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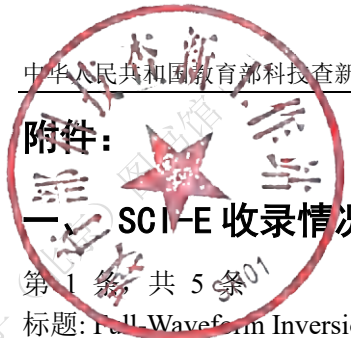
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第 1 条, 共 5 条

标题: Full-Waveform Inversion With Denoising Priors Based on Graph Space Sinkhorn Distance

作者: Tan, ZJ (Tan, Zhoujie); Yao, G (Yao, Gang); Zhang, F (Zhang, Feng); Wu, D (Wu, Di)

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作者: Fang, XY (Fang, Xin-Yu); Yao, G (Yao, Gang); Zheng, QQ (Zheng, Qing-Qing); Zhang, PM (Zhang, Ping-Min); Wu, D (Wu, Di); Niu, FL (Niu, Feng-Lin)

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### 第 3 条, 共 5 条

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作者: Wu, B (Wu, Bo); Yao, G (Yao, Gang); Ma, X (Ma, Xiao); Chen, HM (Chen, Hanming); Wu, D (Wu, Di); Cao, JJ (Cao, Jingjie)

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标题: Pseudo-Helmholtz decomposition for an elastic VTI wavefield based on wavefront phase direction

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作者: Yao, G (Yao, Gang); Wu, B (Wu, Bo); da Silva, NV (da Silva, Nuno V.); Debens, HA (Debens, Henry A.); Wu, D (Wu, Di); Cao, JJ (Cao, Jingjie)

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# Full-Waveform Inversion With Denoising Priors Based on Graph Space Sinkhorn Distance

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**Abstract**—Full-waveform inversion (FWI) is a critical geophysical imaging technique, renowned for its ability to generate high-precision subsurface structural models. However, FWI is a highly nonlinear and ill-posed inverse problem, necessitating appropriate regularization to incorporate prior information. Recently, the plug-and-play (PnP) method has shown promise in addressing various inverse problems by leveraging pretrained deep learning (DL)-based denoisers as priors, thus eliminating the need for explicit regularization functions. Building on this approach, we employ a pretrained DRUNet denoiser from the field of computer vision to implement regularization constraints for FWI via the PnP method. We propose a novel FWI framework (FWISD-DRU) that integrates graph space Sinkhorn distance (GS-SD) with the DRUNet denoiser to enhance FWI quality. By utilizing a bias-free denoising network architecture and additional noise-level map inputs, our approach improves the adaptability of the pretrained network to various geological images. Numerical tests on typical geological models validate the universality and effectiveness of our method. The experimental results demonstrate that our approach, incorporating the DRUNet denoiser, produces more accurate and higher resolution inversion results than total variation (TV) regularization and the denoising convolutional neural network (DnCNN) and FFDNet denoisers. This advantage is particularly pronounced under challenging conditions such as poor initial models, noisy observed data, and missing low-frequency components.

**Index Terms**—Deep denoiser prior, full-waveform inversion (FWI), geophysics, nonlinear, plug-and-play (PnP), regularization, Sinkhorn distance (SD).

## I. INTRODUCTION

FULL-WAVEFORM inversion (FWI) [1], [2] is an advanced geophysical imaging technique that utilizes the complete waveform information in seismic data to achieve more accurate reconstruction of geophysical parameters compared to other methods [3], [4]. Typically, FWI starts with an initial model, simulates the seismic wavefield by solving the wave equation, and iteratively optimizes the subsurface model

by minimizing an objective function that quantifies the difference between simulated and observed waveforms.  $\ell_2$ -norm is commonly used for data fitting due to its simplicity and effectiveness. The gradient of FWI is usually computed using the adjoint-state method [5], [6], guiding model parameter updates along the gradient descent direction.

Over decades, FWI has significantly improved in accuracy and computational efficiency, with innovations like reflection FWI [7], [8] enhancing inversion results. However, FWI remains a highly nonlinear and ill-posed problem, particularly when using the  $\ell_2$ -norm, where cycle skipping is a major challenge [9]. In addition, seismic data acquisition limitations, such as environmental noise [10], limited data coverage [11], and bandwidth [12] can also hinder FWI, leading to lower resolution models and artifacts.

To address the cycle-skipping issue, multiscale inversion [13], [14] has been proposed, starting from the lowest available frequency and progressively incorporating higher frequencies to mitigate cycle skipping. However, its effectiveness relies on the availability of low-frequency data, often unavailable due to acquisition limitations. Low-frequency extrapolation [15] is a means to create lower frequency signals artificially. Sun and Demanet [12] proposed a more efficient low-frequency extrapolation method in the framework of deep learning (DL). Alternatively, envelope inversion [16], [17] approximates low-frequency information using amplitude envelopes. Multiscale envelope inversion [18] further enhances stability and accuracy.

Beyond multiscale strategies, alternative objective functions [19] have shown promise in reducing cycle skipping by shaping a more convex misfit landscape, which directly impacts the accuracy and convergence of FWI. Among these approaches, the integration of optimal transport theory [20], [21] into seismic inversion has been pivotal. Engquist and Froese [22] introduced optimal transport theory to seismic inversion, using the convexity of the Wasserstein distance to address cycle skipping [23], [24]. Métivier et al. [25], [26] and Métivier and Brossier [27] proposed graph space-based strategies using the linear sum assignment problem (LSAP) [28] for mismatch computation, offering stronger convexity than the Wasserstein distance while preserving signal geometry. However, the high computational complexity of LSAP challenges FWI. Cuturi [29] proposed the entropically regularized Sinkhorn distance (SD), which transforms the original linear programming problem into a smooth convex optimization problem through entropy regularization. This allows for

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rapid convergence using the Sinkhorn–Knopp algorithm [30], significantly reducing computational costs compared to LSAP.

In addition, regularization techniques [31], [32], [33] play a critical role in counteracting the ill-posed nature of FWI due to incomplete or noisy data. Traditional methods such as Tikhonov regularization [34] and total variation (TV) regularization [35] suppress noise and artifacts by constraining the solutions of FWI, but may be limited in practical applications due to discrepancy between their assumption and the reality and potential for over-smoothing. Recently, plug-and-play (PnP) priors [36], [37] have gained attention for their potential in regularized inverse problems. Unlike traditional methods, PnP incorporates pretrained denoisers into iterative inversion algorithms as regularizers. Venkatakrishnan et al. [38] introduced the concept of using a denoiser as a PnP prior, and Chan et al. [39] embedded block matching and 3-D filtering (BM3D) denoiser into the alternating direction multiplier method (ADMM) algorithm, demonstrating its effectiveness for super-resolution images. The development of DL techniques has propelled denoising methods based on convolutional neural networks (CNNs) [40]. The introduction of the proximal gradient method (PGM) [41] provides an effective means for addressing convex optimization problems with nondifferentiable objective functions, enabling the application of intelligent denoisers as PnP regularizers. Liu et al. [42] utilized a spectral normalized (SN) denoising CNN (DnCNN) as a denoiser in the PnP method for compressed sensing image recovery, outperforming the batch normalized (BN) DnCNN. Yang and Ma [43] employed a pretrained DnCNN as the regularizer with a learned gradient, significantly improving inversion performance in high-contrast geological models compared to TV-regularized FWI. Although DnCNN is widely regarded as a PnP denoising solution, it has limitations when addressing signals with varying noise levels, necessitating the training of separate models for each specific noise level. To address this, researchers have explored fixed denoisers for low noise levels [44] and transfer learning [45], but these often involve extensive iterations and multimodel testing. Notably, although the ADMM-based FWI framework used by Sun et al. [46] has demonstrated effectiveness in mitigating the tendency of FWI to fall into local minima, it requires retraining on different seismic images using transfer learning to fine-tune the parameters of the pretrained DnCNN denoiser before use. This is an additional time-consuming process. Zhang et al. [47] introduced fast and flexible DnCNN (FFDNet), which is capable of handling different noise levels with a single model, but its denoising performance is comparable to DnCNN. To address the performance issues of FFDNet, Zhang et al. [48] proposed a new denoising network architecture called DRUNet by stacking multiple residual blocks on the U-net architecture to enhance the network's learning capabilities, and introducing the half quadratic splitting (HQS) variable splitting algorithm [49]. This architecture not only handles a wide range of noise levels with a single pretrained model but also demonstrates significant advantages in network modeling and denoising performance.

Furthermore, FWI often uses local optimization methods due to the high computational cost of solving the wave equation. However, local gradient methods like limited-memory Broyden Fletcher Goldfarb Shanno (L-BFGS) [50] may struggle with slow convergence or even divergence in noisy data [51]. DL techniques have achieved state-of-the-art performance across various fields [52], [53], [54], offering new update strategies for FWI. Currently, techniques like the adaptive moment estimation (Adam) gradient optimization algorithm [55] and automatic differentiation [56] have been widely adopted in FWI [57], [58], [59] to boost efficiency and accuracy. To address the issue of rapid decay in the effective step size when dealing with scale-invariant weights in Adam, Heo et al. [60] proposed the adaptive momentum projection estimation (AdamP) algorithm, which removes the radial component from the update vector during each optimization iteration, thereby slowing down the decay of the effective step size. Compared to Adam, it can maintain a more stable convergence rate and better performance.

In this study, we integrate an advanced denoising algorithm from computer vision into FWI using the PnP method's HQS algorithm. Through iterative denoising, this approach effectively incorporates the denoising prior to geological images, which helps reduce noise and artifacts in the iterative inversion process and prevents FWI from getting trapped in local minima. We first outline the principles of conventional FWI and the graph space SD (GS-SD). Subsequently, we provide a detailed introduction to the DL-based FWI update strategy we employ and the architecture of the DRUNet denoiser, as well as our proposed HQS-based FWI method, FWISD-DRU, which integrates GS-SD with DRUNet. Finally, we apply our method to three geophysical models. The key contributions of this article include: 1) introducing the PnP-HQS algorithm into FWI, using the pretrained DRUNet denoiser for regularization, while combining optimal transport theory and DL-based variable update strategies, proposing a novel and efficient FWI framework; 2) using a bias-free pretrained network with a noise level map, eliminating the need for retraining on geological images; 3) introducing a balance term and tradeoff coefficients to preserve the inverted model structure and high-resolution features; and 4) using AdamP to optimize Adam algorithm allows for more flexible step size adjustments when handling gradients, improving the stability and convergence speed of FWI.

## II. THEORY AND METHOD

In this section, we briefly review conventional FWI using the  $\ell_2$ -norm and TV regularization, then introduce the data fitting term of GS-SD and the DL-based variable update strategy. Next, we detail the FWI method based on the HQS algorithm, as well as the integrated DRUNet denoiser. Finally, we elaborate on the workflow of the proposed method.

### A. Overview of Conventional FWI

In a density-constant isotropic medium, which belongs to the spatial domain  $\Omega$ , the 2-D scalar acoustic wave equation

is represented as

$$\frac{1}{v(\mathbf{x})^2} \frac{\partial^2 u(\mathbf{x}_s, t)}{\partial t^2} - \nabla^2 u(\mathbf{x}_s, t) = q(\mathbf{x}_s, t) \quad (1)$$

where  $\mathbf{x} = (x, z)$  denotes the spatial coordinates,  $t$  stands for the time sampling point,  $\nabla^2$  indicates the Laplace operator, and  $q$  is the source term located at the source position  $\mathbf{x}_s$ .  $u(\mathbf{x}_s, t)$  represents the wavefield amplitude, which is the solution of (1). Typically, (1) can be simplified as a vector-matrix formation

$$\mathbf{A}(\mathbf{v})\mathbf{u} = \mathbf{q} \quad (2)$$

where  $\mathbf{A}$  is formed by discretizing the operator of the acoustic wave equation,  $(1/v^2)(\partial^2/\partial t^2) - \nabla^2$ .  $\mathbf{v}$  represents the subsurface velocity model. The seismic data  $\mathbf{d}$  is given by  $d(\mathbf{x}_r, t; \mathbf{v}) = \mathbf{R}u(\mathbf{x}_r, t)$ , where  $\mathbf{R}$  is the extraction operator at the receiver position  $\mathbf{x}_r$ . For simplicity, we redefine  $\mathbf{d}$  as

$$\mathbf{d} = \mathbf{F}(\mathbf{v}) \quad (3)$$

where  $\mathbf{F}$  is the forward modeling operator.

Since FWI for seismic data is an ill-posed optimization problem, a common approach to address this is by introducing a regularization term into the objective function. The optimization problem of FWI can then be formulated as

$$\hat{\mathbf{v}} = \arg \min_{\mathbf{v} \in \Omega} \mathcal{D}(\mathbf{d}^{\text{pre}}(\mathbf{v}), \mathbf{d}^{\text{obs}}) + \mu \mathcal{R}(\mathbf{v}) \quad (4)$$

where  $\mathcal{D}$  represents the data-fitting term,  $\mathbf{d}^{\text{pre}}$  corresponds to the predicted seismic data obtained by forward modeling with the current velocity model,  $\mathbf{d}^{\text{obs}}$  represents the observed seismic data,  $\mathcal{R}$  is the regularization term, and  $\mu > 0$  is the penalty factor for the regularization term. When the  $\ell_2$ -norm is used, the data-fitting term can be expressed as

$$\mathcal{D}(\mathbf{v}) = \frac{1}{2} \sum_{s=1}^{Ns} \sum_{r=1}^{Nr} \int_0^T \|d_s^{\text{pre}}(\mathbf{x}_r, t; \mathbf{v}) - d_s^{\text{obs}}(\mathbf{x}_r, t)\|_2^2 dt \quad (5)$$

where  $T$  represents the maximum recording time,  $Ns$  denotes the total number of shot gathers, and  $Nr$  represents the total number of receivers. Using the adjoint-state method [5], we can effectively derive the gradient of  $\mathcal{D}(\mathbf{v})$  with respect to  $\mathbf{v}$

$$\nabla \mathcal{D}_k(\mathbf{v}) = \frac{\partial \mathcal{D}(\mathbf{v}_k)}{\partial \mathbf{v}_k} = -\frac{2}{\mathbf{v}_k^3} \sum_{s=1}^{Ns} \int_0^T \frac{\partial^2 u(\mathbf{x}_s, t)}{\partial t^2} u^*(\mathbf{x}_s, t) dt \quad (6)$$

where  $u(\mathbf{x}_s, t)$  is the forward wavefield,  $u^*(\mathbf{x}_s, t)$  is the adjoint-state wavefield computed by solving the adjoint-state equation, and  $k$  represents the number of iterations. After knowing the gradient, local optimization algorithms [50] can be used to update the velocity model

$$\mathbf{v}_{k+1} = \mathbf{v}_k - \gamma_k \nabla \mathcal{D}(\mathbf{v}_k) \quad (7)$$

where  $\gamma_k > 0$  is the optimal step length for the  $k$ th iteration.

To enhance the stability of model parameters and prevent overfitting, TV regularization is widely adopted in FWI for constraint. The regularization term can be expressed as

$$\mathcal{R}(\mathbf{v}) = \frac{1}{mn} \sum_{i,j}^{m,n} \sqrt{(\mathbf{v}_{i+1,j} - \mathbf{v}_{i,j})^2 + (\mathbf{v}_{i,j+1} - \mathbf{v}_{i,j})^2} \quad (8)$$

where  $m$  and  $n$  represent the number of discrete points in the distance and depth directions, respectively.

### B. Graph Space SD

The optimal transport theory aims to find the best mapping between two probability distributions while minimizing the cost [61]. For two positive functions  $f(x)$  and  $g(y)$  defined on the spaces  $X$  and  $Y$ , satisfying the mass conservation assumption

$$\int_{\Omega} f(x) dx = \int_{\Omega} g(y) dy = 1. \quad (9)$$

The Wasserstein distance between the probability distributions  $f$  and  $g$  can be calculated by

$$\mathcal{W}(f, g) = \min_{\eta(x,y) \in \Pi_{f,g}} \int_{X \times Y} c(x, y) d\eta(x, y) \quad (10)$$

where  $\Pi_{f,g}$  represents the set of all joint probability distributions between the  $f$  and  $g$ , and  $x$  and  $y$  are a sample from  $f$  and  $g$ , respectively.  $c(x, y)$  is the distance metric function, representing the cost of moving  $x$  to  $y$ , and  $\eta(x, y)$  represents the allocation scheme of transferring mass from  $f$  to  $g$  while minimizing the total cost. By imposing an entropy constraint on the Wasserstein distance, we can obtain the SD, which can be expressed as

$$\mathcal{S}(f, g) = \min_{\eta(x,y) \in \Pi_{f,g}} \int_{X \times Y} c(x, y) d\eta(x, y) + \frac{1}{\lambda} H(\eta) \quad (11)$$

where  $\lambda > 0$  is the regularization factor, and  $H(\eta) = -\int_{X \times Y} \eta(x, y) \log \eta(x, y) dx dy$  is the entropy of  $\eta$ .

To meet the positive mass requirements of optimal transport theory for oscillating seismic signals, we employ a time discretization method to transform the signals into a point cloud in graph space [25]. The discrete graph of single trace seismic data  $\mathbf{d}$  can be defined as a set of  $N$  points, denoted by  $\{(t_n, d_n) \in \mathbb{R}^2, n = 1, \dots, N\}$ . Second, due to the nondifferentiability of the Dirac function, we use a Gaussian distribution function that approximates the Dirac distribution to transform the discrete data into graph space

$$\mathcal{G}[\mathbf{d}](x, t) = \frac{1}{2\pi \delta_t \delta_x N} \sum_{n=1}^N \exp\left(-\frac{(t - t_n)^2}{2\delta_t^2}\right) \times \exp\left(-\frac{(x - d_n)^2}{2\delta_x^2}\right) \quad (12)$$

where  $\delta_t$  and  $\delta_x$  are the scaling factors and  $N$  is the number of discrete time samples. Therefore, the GS-SD objective function can be rewritten as

$$\mathcal{D}(\mathbf{v}) = \sum_{s=1}^{Ns} \sum_{r=1}^{Nr} \sum_{t=1}^{Nt} \mathcal{S}(\mathcal{G}[d_s^{\text{pre}}(\mathbf{x}_r, t; \mathbf{v})], \mathcal{G}[d_s^{\text{obs}}(\mathbf{x}_r, t)]) \quad (13)$$

We then compute the gradient using the mini-batch strategy [58].

In FWI, to ensure numerical stability of wavefield simulation, the time step is normally small, required to satisfy



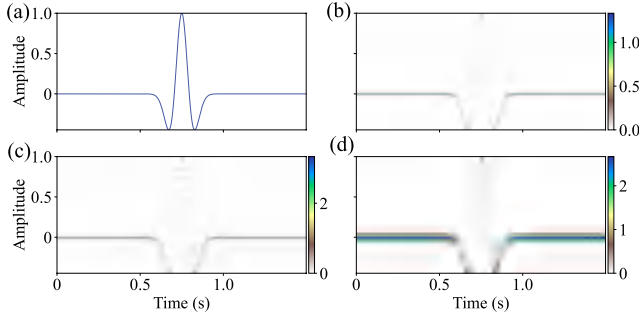


Fig. 1. (a) 5-Hz Ricker wavelet. Representation of this Ricker in the graph space: (b) with  $\delta_t = 1 \times 10^{-3}$ ,  $\delta_x = 5 \times 10^{-3}$ , and 750 discrete points; (c) with  $\delta_t = 1 \times 10^{-3}$ ,  $\delta_x = 5 \times 10^{-3}$ , and 375 discrete points; and (d) with  $\delta_t = 5 \times 10^{-4}$ ,  $\delta_x = 2.5 \times 10^{-3}$ , and 750 discrete points.

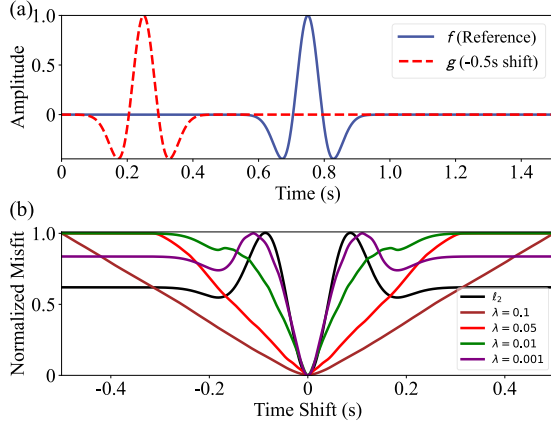


Fig. 2. (a) Observed signal  $f$  and synthetic signal  $g$ . (b) Misfit between the observed and synthetic signals under  $\ell_2$  and GS-SD functions. A small regularization factor leads the GS-SD close to  $\ell_2$  function.

the Courant–Friedrichs–Lewy (CFL) condition [62]. Therefore, to ease the computational load of GS-SD, signals can be sparsely resampled. Using a 5-Hz Ricker wavelet, as illustrated in Fig. 1(a), we demonstrate the graph transformation of the signal, emphasizing the impact of discretization points and scaling factors ( $\delta_t, \delta_x$ ) on signal representation. As shown in Fig. 1(b), optimizing values like ( $\delta_t = 1 \times 10^{-3}$ ,  $\delta_x = 5 \times 10^{-3}$ ) with 750 discrete points enhances signal representation in the graph space. Using a smaller number of discrete points in Fig. 1(c) results in an overly sparse signal, while using excessively large ( $\delta_t, \delta_x$ ) in Fig. 1(d) may lead to signal blurring. In addition, Fig. 2 shows that GS-SD offers better convexity in misfit computation than the  $\ell_2$ -norm distance, improving with increased regularization parameter  $\lambda$ , which reduces the risk of local minima during the inversion process.

### C. FWI With DL-Based Update Strategy

The various gradient optimization algorithms [55], automatic differentiation techniques [56], and mini-batch strategies [58] of DL frameworks provide efficient computational strategies for FWI. The seismic data  $\mathbf{d}$  includes multidimensions, i.e., the dimensions of shots, receivers, and time. From the data-fitting term (13), the cost function for the  $s$ th shot gathered can be expressed as

$$\mathcal{D}_s(\mathbf{v}) = \mathcal{S}(\mathcal{G}[\mathbf{d}_s^{\text{pre}}(\mathbf{v})]), \mathcal{G}[\mathbf{d}_s^{\text{obs}}]). \quad (14)$$

When employing the mini-batch strategy, the approximate gradient of the mini-batch is represented as follows:

$$\bar{\nabla} \mathcal{D}(\mathbf{v}) = \frac{1}{n} \sum_{i=1}^n \nabla \mathcal{D}_{s_i}(\mathbf{v}) \quad (15)$$

where  $n$  represents the number of shots within a batch, satisfying  $1 \leq n \leq N_s$ , and  $s_i$  denotes a randomly chosen index uniformly distributed over  $\{1, 2, \dots, N_s\}$ .

Then, we use the AdamP gradient optimization algorithm to update the model parameters. In the classical Adam algorithm, the calculation formula for the first moment estimation of the gradient is

$$\hat{\mathbf{s}}_k = \frac{\beta_1 \mathbf{s}_{k-1} + (1 - \beta_1) \bar{\nabla} \mathcal{D}_k}{(1 - \beta_1^k)} \quad (16)$$

$$\hat{\mathbf{r}}_k = \frac{\beta_2 \mathbf{r}_{k-1} + (1 - \beta_2) \bar{\nabla} \mathcal{D}_k \odot \bar{\nabla} \mathcal{D}_k}{(1 - \beta_2^k)} \quad (17)$$

where  $\hat{\mathbf{s}}_k$  is the biased first-moment estimation of the gradient for the  $k$ th iteration,  $\hat{\mathbf{r}}_k$  is the biased second raw moment estimate of the gradient for the  $k$ th iteration,  $\hat{\mathbf{s}}_0 = \hat{\mathbf{r}}_0 = 0$ ,  $\odot$  represents element-wise multiplication, and  $\beta_1$  and  $\beta_2$  are hyperparameters controlling the exponential decay rates for the averages of the gradient and the squared gradient terms, respectively. Based on the Adam algorithm, the update step direction  $\mathbf{m}$  is

$$\mathbf{m}_k = \frac{\hat{\mathbf{s}}_k}{\sqrt{\hat{\mathbf{r}}_k + \varepsilon}} \quad (18)$$

where  $\varepsilon$  is a constant, typically set to  $1 \times 10^{-8}$ . Different from Adam, the AdamP optimization algorithm needs to apply a projection operation  $\Gamma_{\mathbf{v}_k}$  to  $\mathbf{m}_k$  to eliminate its radial component in the weight space [60]

$$\Gamma_{\mathbf{v}_k}(\mathbf{m}_k) = \mathbf{m}_k - \frac{\langle \mathbf{m}_k, \mathbf{v}_k \rangle}{\|\mathbf{v}_k\|_2^2} \mathbf{v}_k \quad (19)$$

then, the velocity model is updated with

$$\mathbf{v}_{k+1} = \mathbf{v}_k - \gamma_k \Gamma_{\mathbf{v}_k}(\mathbf{m}_k) \quad (20)$$

where  $\mathbf{v}_k$  represents the current model parameters,  $\gamma$  is the step size of the AdamP optimizer.

### D. Plug-and-Play Priors

PnP priors efficiently address nonlinear inverse problems by incorporating a pretrained denoiser into the optimization process, thus introducing image priors into the system. In the PnP framework, the ADMM [39] and HQS [49] algorithms are commonly used variable splitting methods, with HQS favored for its simplicity and fast convergence.

In Section II-B, we introduced the GS-SD, which serves as an effective measure of data fitting. Utilizing this concept, we can reconstruct the optimization problem of FWI in (4) as follows:

$$\hat{\mathbf{z}} = \arg \min_{\mathbf{z}} \mathcal{S}(\mathcal{G}[\mathbf{F}(\mathbf{z})], \mathcal{G}[\mathbf{y}]) + \mu \mathcal{R}(\mathbf{z}) \quad (21)$$

where  $\mathbf{z}$  represents the unknown velocity model,  $\mathbf{y}$  represents the observed seismic data, the data-fitting term  $\mathcal{D} =$

$\mathcal{S}(\mathcal{G}[\mathbf{F}(\mathbf{z})], \mathcal{G}[\mathbf{y}])$ ,  $\mu$  is the regularization parameter, and  $\mathcal{R}$  is the regularization term, which is typically TV regularization. As shown in Fig. 2, we have demonstrated that  $\mathcal{D}$  is smooth and convex. However, due to the nonsmoothness of  $\mathcal{R}$ , this composite optimization problem cannot be solved using gradient-based methods. In this study, we employ the PnP-HQS to address the nonsmoothness of  $\mathcal{R}$ .

The PnP-HQS algorithm obtains a constrained optimization problem by introducing an auxiliary variable  $\mathbf{v}$

$$\hat{\mathbf{z}} = \arg \min_{\mathbf{z}} \mathcal{S}(\mathcal{G}[\mathbf{F}(\mathbf{z})], \mathcal{G}[\mathbf{y}]) + \mu \mathcal{R}(\mathbf{v}), \quad \text{s.t. } \mathbf{v} = \mathbf{z}. \quad (22)$$

Then, we can formulate this constrained optimization problem into its augmented Lagrangian function form

$$L(\mathbf{z}, \mathbf{v}) = \mathcal{S}(\mathcal{G}[\mathbf{F}(\mathbf{z})], \mathcal{G}[\mathbf{y}]) + \mu \mathcal{R}(\mathbf{v}) + \frac{\tau}{2} \|\mathbf{v} - \mathbf{z}\|_2^2 \quad (23)$$

where  $\tau$  is the penalty factor. Such problem can be solved by alternating iterations to solve the subproblems for  $\mathbf{z}$  and  $\mathbf{v}$

$$\begin{aligned} \mathbf{z}_k &= \text{prox}_{\tau \mathcal{D}}(\mathbf{v}_{k-1}) \\ &= \arg \min_{\mathbf{z}} \mathcal{S}(\mathcal{G}[\mathbf{F}(\mathbf{z})], \mathcal{G}[\mathbf{y}]) + \frac{\tau}{2} \|\mathbf{z} - \mathbf{v}_{k-1}\|_2^2 \end{aligned} \quad (24)$$

$$\mathbf{v}_k = \text{prox}_{\mu \mathcal{R}}(\mathbf{z}_k) = \arg \min_{\mathbf{v}} \frac{1}{2(\sigma)^2} \|\mathbf{v} - \mathbf{z}_k\|_2^2 + \mathcal{R}(\mathbf{v}) \quad (25)$$

where prox denotes the proximal operator, which typically has a closed-form solution, and  $\sigma = \sqrt{\mu/\tau}$ . By alternating solving (24) and (25), the original problem in (21) is solved.

The PnP-HQS algorithm decouples  $\mathcal{D}$  and  $\mathcal{R}$  into two independent subproblems. Specifically, due to the high computational cost associated with calculating the proximal operator  $\text{prox}_{\tau \mathcal{D}}$  for FWI, we can employ the PGM [41], [46] to find the proximal point  $\mathbf{z}_k$  of  $\mathbf{v}_{k-1}$  in the subproblem (24), which only requires the use of automatic differentiation technology to compute the gradient of  $\mathbf{v}_{k-1}$ . From a Bayesian perspective, the subproblem of (25) corresponds to Gaussian denoising on  $\mathbf{z}_k$  with a noise level of  $\sigma$ . Consequently, any Gaussian denoiser can be embedded into the alternating iterations to solve (25). Furthermore, to balance the impact of denoiser updates on FWI, a new variable  $\mathbf{u}$  is introduced,  $\mathbf{u}_0 = \mathbf{v}_0$ , and the gradient  $\nabla \mathcal{D}$  is optimized using AdamP optimizer. Thus, the algorithm based on the HQS-FWI framework can be described as

$$\mathbf{z}_k = \mathbf{u}_{k-1} - \gamma_{k-1} \Gamma_{\mathbf{u}_{k-1}}(\mathbf{m}(\nabla \mathcal{D}(\mathbf{u}_{k-1}))) \quad (26)$$

$$\mathbf{v}_k = \text{Denoiser}(\mathbf{z}_k, \sigma) \quad (27)$$

$$\mathbf{u}_k = \omega \mathbf{v}_k + (1 - \omega) \mathbf{z}_k \quad (28)$$

where  $\omega$  is the tradeoff parameter,  $0 \leq \omega \leq 1$ .

### E. Deep Denoiser Prior Model

In the implementation of the HQS-FWI framework, we employ DRUNet denoiser [48], [63], which is pretrained on a natural image set with noise levels in the range (0, 50) and originates from the field of computer vision, to replace the traditional explicit regularization term. DRUNet combines the image transformation capabilities of UNet with the deep network modeling capabilities of ResNet, thereby enhancing the denoising performance of the network. In addition, the design of DRUNet takes into account the input of noise level

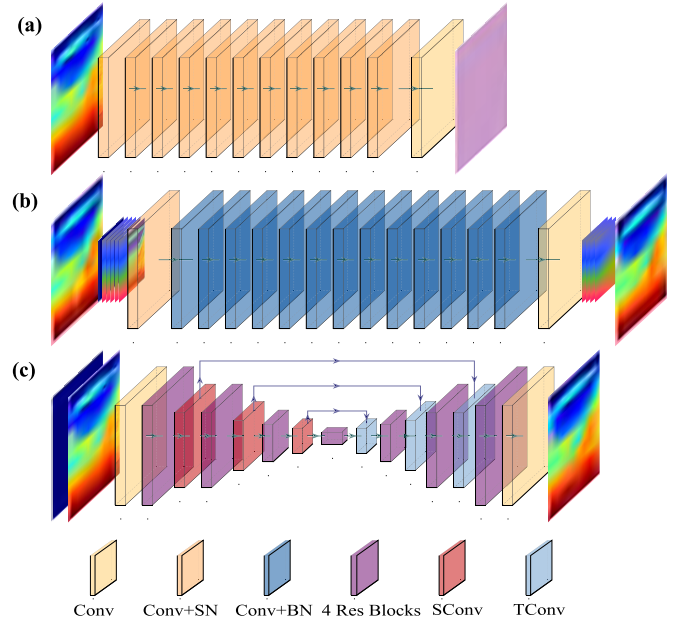


Fig. 3. Architecture of (a) DnCNN, (b) FFDNet, and (c) DRUNet denoisers. Unlike DnCNN, both FFDNet and DRUNet take additional noise level maps as input, and output a clean image rather than noise.

maps, effectively recognizing and adapting to various noise characteristics. The network architecture of DRUNet mainly consists of four scales, where  $2 \times 2$  strided convolution (SConv) is used for downscaling and  $2 \times 2$  transposed convolution (TConv) for upscaling, with identity skip connections between them to facilitate information exchange across scales. From the first to the fourth scale, the number of channels in each layer increases sequentially to 64, 128, 256, and 512. Each scale connects four successive residual blocks with downscaling and upscaling. The first and last convolutional layers, as well as the SConv and TConv layers, do not use activation functions, each residual block contains only a rectified linear unit (ReLU) activation function, and no bias is used throughout the DRUNet, which helps enhance the network's generalization ability. Furthermore, we also use a DnCNN [42], [43], [46] pretrained on natural images with a noise level of 10, and FFDNet [47] with an input noise map level of 15 to compare with the DRUNet, testing their denoising performance on the real noise generated during the iterative process of FWI. The three network architectures are shown in Fig. 3.

### F. Implementation of the Proposed Method

Based on the analysis in Sections II-D and II-E, we combine the GS-SD with DRUNet denoiser to formulate the proposed method FWISD-DRU, achieving efficient inversion through a two-stage optimization process. As illustrated in Fig. 4, the inversion starts from an initial velocity model  $\mathbf{v}_0$  and generates predicted data  $\mathbf{d}^{\text{pre}}$  using the wave equation, while the observed data  $\mathbf{d}^{\text{obs}}$  consists of real seismic records. Throughout the iteration process, both  $\mathbf{d}^{\text{pre}}$  and  $\mathbf{d}^{\text{obs}}$  are mini-batch processed, leveraging automatic differentiation to compute the gradient of the data-fitting term, and employing the AdamP algorithm to update the velocity model. Subsequently, the optimized



**Algorithm 1** FWISD-DRU Algorithm

**Input:** Initial velocity model  $\mathbf{v}_0$ , forward modeling operator  $\mathbf{F}$ , observed record  $\mathbf{d}^{obs}$ , number of iterations  $K$ , number of shots  $n$ , optimizer parameters  $\beta_1, \beta_2$ , regularization Parameter  $\lambda$ , noise level  $\sigma$ , tradeoff parameter  $\omega$ , deep denoiser prior model.

**Output:** Final inverted velocity model  $\mathbf{v}$ .

*Initialization:*  $\mathbf{u}_0 = \mathbf{v}_0$ .

```

1: for  $k = 1, 2, \dots, K$  do
2:   randomly select  $n$  shot gathers from  $\mathbf{d}^{obs}$ ;
3:    $\bar{\nabla}\mathcal{D}(\mathbf{u}_k) = 1/n \sum_{i=1}^n \nabla(S(\mathcal{G}[\mathbf{F}_i(\mathbf{u}_k)], \mathcal{G}[\mathbf{d}_i^{obs}])$ ;
4:    $\hat{\mathbf{s}}_k = (\beta_1 \mathbf{s}_{k-1} + (1 - \beta_1) \bar{\nabla}\mathcal{D}_k) / (1 - \beta_1^k)$ ;
5:    $\hat{\mathbf{r}}_k = (\beta_2 \mathbf{r}_{k-1} + (1 - \beta_2) \bar{\nabla}\mathcal{D}_k \odot \bar{\nabla}\mathcal{D}_k) / (1 - \beta_2^k)$ ;
6:    $\mathbf{m}_k = \hat{\mathbf{s}}_k / (\sqrt{\hat{\mathbf{r}}_k} + \varepsilon)$ ;
7:    $\mathbf{z}_{k+1} = \mathbf{u}_k - \gamma_k \Gamma_{\mathbf{u}_k}(\mathbf{m}_k)$ ;
8:    $\mathbf{v}_{k+1} = \text{Denoiser}(\mathbf{z}_{k+1}, \sigma)$ ;
9:    $\mathbf{u}_{k+1} = \omega \mathbf{v}_{k+1} + (1 - \omega) \mathbf{z}_{k+1}$ ;
10: end for
11: return  $\mathbf{v}$ 

```

model is fed into the DRUNet to extract more accurate model features. Upon reaching a predefined threshold for the objective function, the algorithm outputs the final inverted result. The FWISD-DRU workflow operates entirely within a DL framework, enhancing both the efficiency and accuracy of inversion. Algorithm 1 shows more details of FWISD-DRU.

### III. NUMERICAL EXPERIMENTS

In this section, we first use the Camembert velocity model for inversion testing to demonstrate the regularization effect of a DL-based denoiser in the inversion process. Then, experiments are conducted on two famous synthetic models: the Overthrust model, and the 2004 BP model to validate the effectiveness of the FWISD-DRU method in inversion tasks across different geological models. The experiments first compare the FWI based on  $\ell_2$ -norm ( $\text{FWI}_{\ell_2}$ ) with FWI using GS-SD (FWISD) to demonstrate the advantages of optimal transport theory. Subsequently, we compare the inversion results of FWISD-DRU with FWI methods using traditional TV regularization (FWISD-TV) and two denoisers, DnCNN and FFDNet (FWISD-DnCNN and FWISD-FFD). Our FWI framework is built on the PyTorch 2.0.1 environment using an RTX 3090 GPU with 24 GB of memory. The open-source Deepwave [64] toolbox is employed for wavefield simulation.

#### A. Inversion Parameters and Result Measurement

To accurately simulate the propagation of seismic waves, we employ a finite difference method with second-order accuracy in time and eighth-order accuracy in space for forward modeling. Perfectly matched layers (PMLs) [65] are applied as absorbing boundary conditions on the left, right, and bottom sides of the model. The PML thickness is set to 40 grid points. A free-surface boundary is imposed at the top to simulate wave propagation in a half-space medium. In all FWI frameworks, the AdamP optimizer is utilized with parameters  $\beta_1 = 0.5$ ,  $\beta_2 = 0.7$ ,  $\varepsilon = 10^{-8}$ , and the weight decay is set to

0 for updating the model parameters. For TV regularization, the optimal penalty coefficient  $\mu$  is selected from the set  $\{1 \times 10^{-5}, 1 \times 10^{-4}, 5 \times 10^{-4}, 1 \times 10^{-3}\}$ . The regularization parameter for GS-SD is set to 0.05. When setting the noise level of DRUNet denoiser, we will only discuss the impact of the noise level  $\sigma$ ,  $\sigma$  is chosen optimally from  $\{1, 3, 5, 7, 10, 15\}$ , and the tradeoff parameter  $\omega$  balancing the data-fitting term and the prior term is selected from  $\{0.05, 0.07, 0.1, 0.4, 0.7, 1.0\}$ . When calculating the gradient using automatic differentiation techniques, the batch size  $n$  is set to 2. In FWI  $\ell_2$ , data are normalized to the range  $[-1, 1]$  with a learning rate (lr) of 50, whereas, in FWISD, data are not normalized with a learning rate of 10. The sampling rate for the discrete point cloud data of the graph transformation is set to 2, and the  $(\delta_r, \delta_x)$  for the Gaussian function is  $(1 \times 10^{-3}, 5 \times 10^{-3})$ . All FWI methods iterate 100 epochs with the learning rate decaying to 0.75 of its original value every 20 epochs. Note that in each epoch, the number of iterations is given by  $Ns/n$ , where one epoch will go through all the shot gathers. Therefore, the total number of iterations  $K = 100 \times (Ns/n)$ .

To evaluate the performance of the proposed FWI method, we employ a suite of evaluation metrics to measure the discrepancy between the inverted velocity model  $\mathbf{v}$  and the true velocity model  $\hat{\mathbf{v}}$ . These metrics include the relative error (RE), signal-to-noise ratio (SNR), and structural similarity index (SSIM)

$$\text{RE}(\hat{\mathbf{v}}, \mathbf{v}) = \frac{\|\mathbf{v} - \hat{\mathbf{v}}\|_2}{\|\mathbf{v}\|_2} \quad (29)$$

$$\text{SNR}(\hat{\mathbf{v}}, \mathbf{v}) = 10 \log_{10} \frac{\|\mathbf{v}\|_2^2}{\|\hat{\mathbf{v}} - \mathbf{v}\|_2^2} \quad (30)$$

$$\text{SSIM}(\hat{\mathbf{v}}, \mathbf{v}) = \frac{(2\mu_v \mu_{\hat{v}} + c_1) + (2\sigma_{v\hat{v}} + c_2)}{(\mu_v^2 + \mu_{\hat{v}}^2 + c_1)(\sigma_v^2 + \sigma_{\hat{v}}^2 + c_2)} \quad (31)$$

where  $\mu_v$ ,  $\mu_{\hat{v}}$ ,  $\sigma_v$ , and  $\sigma_{\hat{v}}$  represent the local mean and standard deviation of the true velocity model and the inverted velocity model, and  $\sigma_{v\hat{v}}$  denotes their covariance.  $c_1$  and  $c_2$  are constants introduced to avoid division by zero and to ensure computational stability, commonly set to  $c_1 = 1 \times 10^{-4}$  and  $c_2 = 9 \times 10^{-4}$ . It is evident that the inversion quality is better when the value of RE is lower, the value of SNR is higher, and the value of SSIM is closer to 1.

#### B. Camembert Model Test

Camembert velocity model [see Fig. 5(a)] has a depth of 2 km and a width of 2 km, with a grid spacing of  $10 \times 10$  m. The background velocity is 3 km/s, containing a circular high-velocity anomaly with a radius of 0.6 km and a velocity of 3.6 km/s. A 10-Hz Ricker wavelet is used as the source, with a temporal sampling interval of 1 ms. There are 20 sources evenly distributed at a depth of 10 m with a horizontal spacing of 100 m, and 200 receivers evenly distributed at a depth of 2 km with a horizontal spacing of 10 m.

Fig. 5(c)–(h) shows the Camembert model inversion results. The  $\text{FWI}_{\ell_2}$  method [see Fig. 5(c)] encounters difficulties with

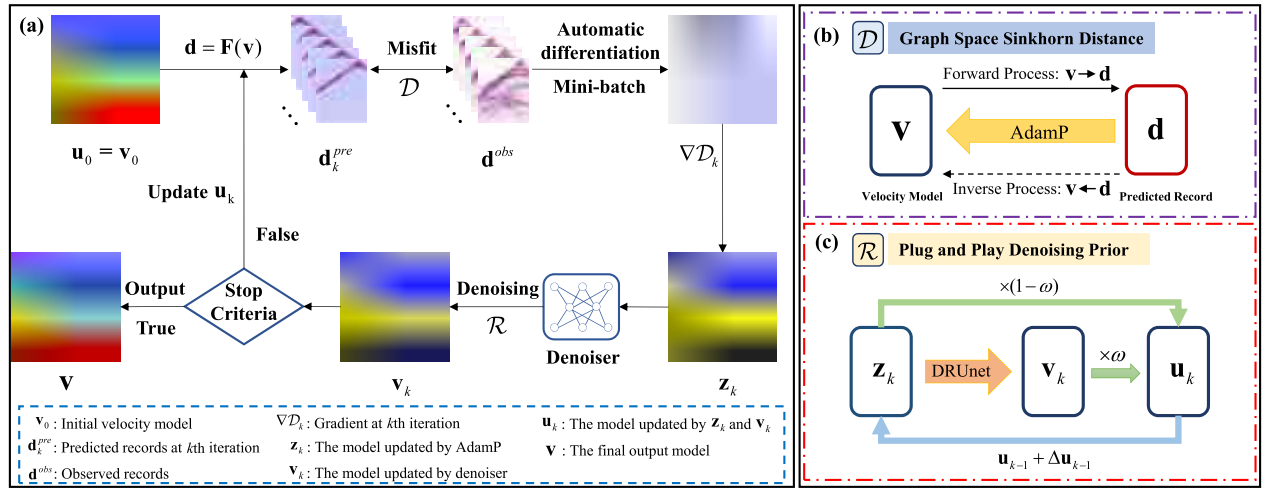


Fig. 4. (a) Workflow of the FWISD-DRU method based on data fitting and deep denoising priors. (b) GS-SD is used as a data-fitting term to measure the misfit between predicted data and observed data. (c) Pretrained DRUNet denoiser is utilized as a regularization term to eliminate noise and artifacts generated during the iterative inversion process.

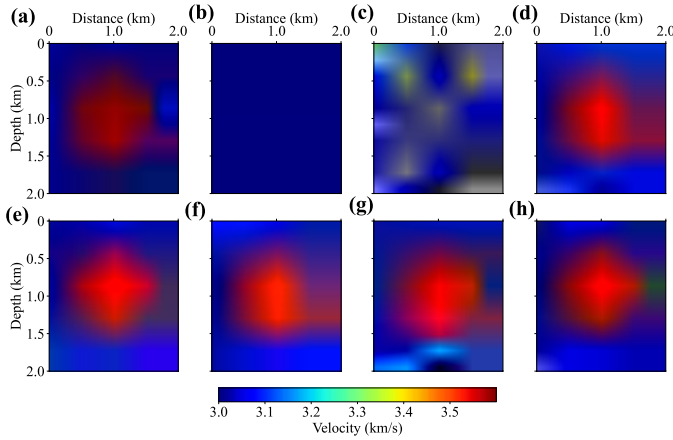


Fig. 5. Results of the Camembert model test with different inversion methods. (a) True model. (b) Initial model. The inverted model from (c) FWI<sub>l2</sub>, (d) FWISD, (e) FWISD-TV, (f) FWISD-DnCNN, (g) FWISD-FFD, and (h) proposed FWISD-DRU.

local minima when the initial model differs from the true model significantly. FWISD [see Fig. 5(d)], using the GS-SD as the misfit term, partially mitigates this issue, recovering the anomaly's overall structure but introducing artifacts and noise at its top and bottom. FWISD-TV [see Fig. 5(e)] reduces artifacts and improves velocity continuity within the anomaly using TV regularization but has challenges with artifacts below the anomaly. FWISD-DnCNN [see Fig. 5(f)] and FWISD-FFD [see Fig. 5(g)], employing DL-based denoisers, better suppress artifacts, but minor residual artifacts persist. FWISD-DRU [see Fig. 5(h)], using the DRUNet denoiser, delivers a high-resolution recovery of the anomaly, significantly reducing background artifacts and enhancing boundary details. Moreover, Table I's quantitative metrics (RE, SNR, and SSIM) also demonstrate the superior performance of FWI-DRU.

### C. Overthrust Model Test

The Overthrust model is a 3-D geological model featuring a central reverse fault anticline, with external monocline and flat zones. For inversion testing, we extract a 2-D slice [see Fig. 6(a)] from the center of this 3-D model. The true velocity

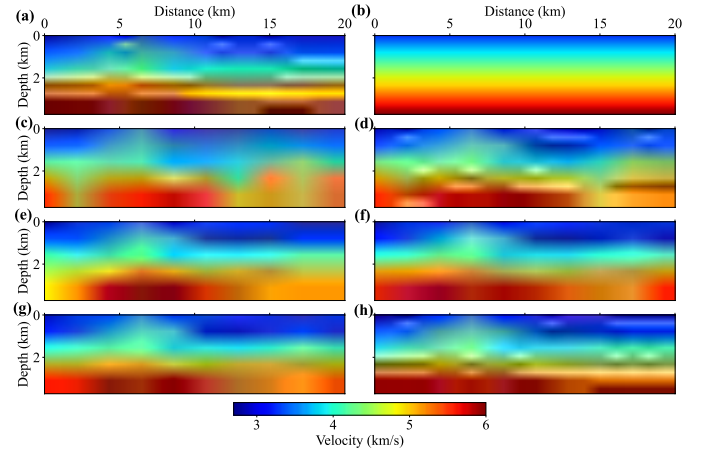


Fig. 6. Results of the Overthrust model with different inversion methods. (a) True model. (b) Initial model. The inverted model from (c) FWI<sub>l2</sub>, (d) FWISD, (e) FWISD-TV, (f) FWISD-DnCNN, (g) FWISD-FFD, and (h) proposed FWISD-DRU.

model measures 4.7 km deep and 20 km wide with 20 by 20 m grid spacing, and velocity values range from 2.36 to 6 km/s. The initial model [see Fig. 6(b)] features a linear velocity profile. A 5-Hz Ricker wavelet is used as the source term, with 40 sources and 500 receivers evenly spaced at a depth of 20 m.

Fig. 6(c)–(h) displays the inversion results of various FWI methods. The baseline FWI<sub>l2</sub> [see Fig. 6(c)] struggles with local minima, failing to recover key structural features. FWISD [see Fig. 6(d)] reduces this issue, producing more accurate velocity distributions and geological structures, though imprecise updates in the flat right area and artifacts persist. FWISD-TV [see Fig. 6(e)] incorporates TV regularization to suppress noise and enhance flat layers and fault structures, but excessive smoothing blurs geological boundaries. FWISD-DnCNN [see Fig. 6(f)] and FWISD-FFD [see Fig. 6(g)], using DL denoisers, deliver higher resolution results with improved structural detail. FWISD-DnCNN reduces noise but leaves artifacts in high-velocity contrast regions. FWISD-FFD achieves similar performance but introduces artificial shallow

TABLE I  
EVALUATION OF INVERTED MODELS AND COMPUTATION TIME OF ONE EPOCH

| Model(size)                | Metric  | $\ell_2$ | SD     | SD-TV  | SD-DnCNN | SD-FFD | SD-DRU        |
|----------------------------|---------|----------|--------|--------|----------|--------|---------------|
| Camembert<br>(201 × 201)   | RE      | 0.1527   | 0.0251 | 0.0209 | 0.0221   | 0.0210 | <b>0.0181</b> |
|                            | SNR(dB) | 16.321   | 31.021 | 33.571 | 32.925   | 33.541 | <b>34.827</b> |
|                            | SSIM    | 0.3443   | 0.7069 | 0.9283 | 0.9220   | 0.9102 | <b>0.9440</b> |
|                            | Time(s) | 2.1      | 3.0    | 3.0    | 3.6      | 3.8    | 5.0           |
| Overthrust<br>(235 × 1000) | RE      | 0.1642   | 0.1163 | 0.0729 | 0.0548   | 0.0605 | <b>0.0463</b> |
|                            | SNR(dB) | 15.692   | 19.689 | 23.737 | 26.213   | 25.362 | <b>27.681</b> |
|                            | SSIM    | 0.2850   | 0.4558 | 0.7296 | 0.7537   | 0.7089 | <b>0.7820</b> |
|                            | Time(s) | 8.0      | 10.0   | 10.0   | 11.5     | 12.0   | 14.0          |
| Modified BP<br>(192 × 701) | RE      | 0.1577   | 0.1289 | 0.1228 | 0.0689   | 0.0746 | <b>0.0385</b> |
|                            | SNR(dB) | 16.042   | 17.725 | 18.011 | 23.236   | 21.252 | <b>28.280</b> |
|                            | SSIM    | 0.3494   | 0.3828 | 0.6338 | 0.7150   | 0.7620 | <b>0.8205</b> |
|                            | Time(s) | 11.0     | 13.0   | 13.0   | 15.0     | 16.0   | 19.0          |

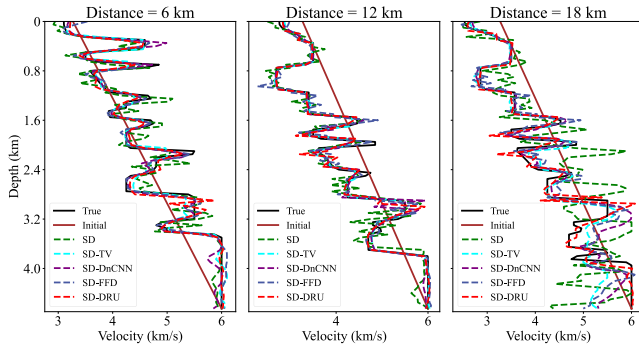


Fig. 7. Vertical velocity profiles at a distance of 6, 12, and 18 km from the inversion results of the Overthrust model.

layers. The proposed FWISD-DRU [see Fig. 6(h)], leveraging the DRUNet denoiser, optimizes noise levels and weighting coefficients to improve inversion quality. It recovers shallow and deep velocity variations, suppresses artifacts, enhances boundary resolution, and achieves high model fidelity. The vertical velocity profile (see Fig. 7) and metrics in Table I confirm FWISD-DRU's superiority. Compared to FWI $\ell_2$ , FWISD reduces the model reconstruction error by approximately 29%, while FWISD-DRU further improves reconstruction fidelity by 63% based on FWISD.

#### D. Modified 2004 BP Model Test

The 2004 BP model is based on a complex geological cross section of the western Gulf of Mexico, characterized by two high-velocity salt bodies with strong lateral variation, which increases the nonlinearity of FWI, potentially trapping the inversion in local minima. The modified 2004 BP model [see Fig. 8(a)] has a size of 3.84 km in depth and 14.02 km in width with a grid spacing of 20 × 20 m. Velocity values range from 1.49 to 4.79 km/s. A 5-Hz Ricker wavelet is employed as the source wavelet, with 50 sources and 700 receivers evenly distributed horizontally at a depth of 0.2 km, with intervals of 0.28 and 0.02 km, respectively. The initial model features a linear velocity profile [see Fig. 8(b)].

Fig. 8(c)–(h) displays the inversion results of various FWI methods. The FWI $\ell_2$  method [see Fig. 8(c)] gets stuck in local minima, failing to recover the salt dome structure. FWISD [see Fig. 8(d)] alleviates cycle skipping by using the GS-SD, improving salt dome recovery. However, there are still errors in the velocity updates at the bottom of the salt dome. FWISD-TV [see Fig. 8(e)] reduces noise and artifacts.

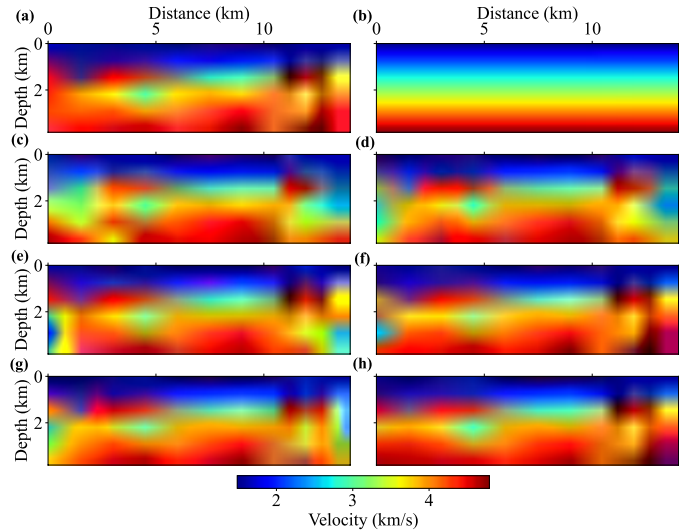


Fig. 8. Results of the modified 2004 BP model with different inversion methods. (a) True model. (b) Initial model. The inverted model from (c) FWI $\ell_2$ , (d) FWISD, (e) FWISD-TV, (f) FWISD-DnCNN, (g) FWISD-FFD, and (h) proposed FWISD-DRU.

However, excessive smoothing limits its ability to recover complex salt dome boundaries. FWISD-DnCNN [see Fig. 8(f)] and FWISD-FFD [see Fig. 8(g)] achieve higher resolution and preserve structural details, but both methods still have incorrect low-velocity artifacts at the edges of the model. In contrast, the FWISD-DRU method [see Fig. 8(h)] achieves high-resolution recovery of the salt dome structure at different depths, especially excelling in the complex velocity variations of the salt cavity on the right side, indicating a superior balance of noise suppression and detail recovery. The vertical velocity profiles (see Fig. 9) and the metrics in Table I highlight the advantages of FWISD-DRU. Compared to FWI $\ell_2$ , FWISD decreases the model reconstruction error by approximately 18%, while FWISD-DRU further enhances reconstruction accuracy by 70% over FWISD. These results demonstrate its capability to overcome local minima and achieve high-quality inversion in complex high-contrast models.

In addition, as illustrated in Fig. 10, the FWISD-DRU method achieves faster and smoother convergence compared to FWISD with the other three constraints and without constraints across the three models: Camembert, Overthrust, and the modified 2004 BP model. The convergence curve demonstrates that the DRUNet denoiser effectively suppresses inversion artifacts without degrading the inversion results.



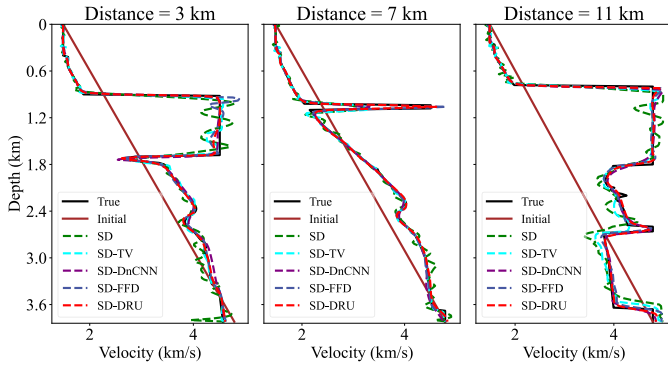


Fig. 9. Vertical velocity profiles at a distance of 3, 7, and 11 km from the inversion results of the modified 2004 BP model.

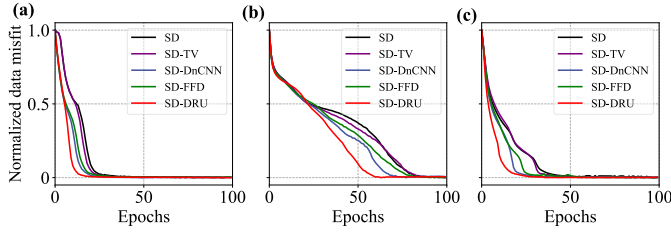


Fig. 10. Misfit convergence curves of different algorithms on (a) Camembert, (b) Overthrust, and (c) modified 2004 BP models.

#### IV. DISCUSSION

We propose an effective FWI method, termed FWISD-DRU, whose superior performance over traditional methods and other denoising approaches has been demonstrated in previous numerical tests. This section explores the key factors affecting the performance of FWISD-DRU, based on the modified 2004 BP model test results.

##### A. Noisy Observed Records

When observed data contain noise, it increases data uncertainty and affects the stability of the inversion algorithm. We add AWGN to noise-free records to obtain noisy records with an SNR of 10 dB (see Fig. 11) and test the noise sensitivity of various FWI methods. As shown in Fig. 12,  $\text{FWI}\ell_2$  is prone to local minima, generating noise and artifacts with noisy data. While FWISD captures the overall model structure, it is still significantly affected by noise, especially when updating the right-side salt body. FWISD-TV, FWISD-DnCNN, and FWISD-FFD also give degraded performance with noise, creating artificial low-velocity zones. In contrast, FWISD-DRU demonstrates greater accuracy and robustness, with results similar to the noise-free case.

Fig. 13 further illustrates the changes in  $\mathbf{z}_k$  and  $\mathbf{v}_k$  across different iterations of FWISD-DRU. As the iterations progress, the SNR of  $\mathbf{v}_k$  gradually improves, the RE of  $\mathbf{z}_k$  and  $\mathbf{v}_k$  decreases, and the range of the removed noise is also reduced.

##### B. Optimization Algorithms

In the FWI process, different optimization algorithms vary in convergence speed, stability, and ability to find global optimal solutions. We assess the performance of L-BFGS, stochastic gradient descent (SGD), Adam, and AdamP within the FWISD-DRU framework and analyze AdamP's performance at different learning rates. Fig. 14 shows the results:

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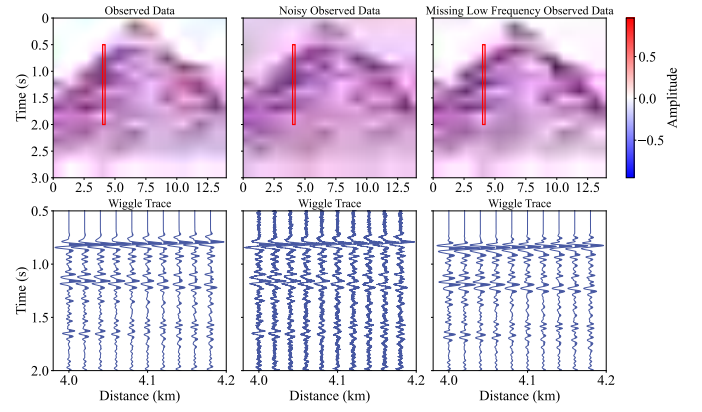


Fig. 11. Comparison of observed data generated from the modified 2004 BP model under the condition of a free surface at the top. The first row, in order, presents: the original observed data (first column), observed data with additive white Gaussian noise (second column), where the SNR of the noisy data is 10 dB, and observed data missing frequency components below 3 Hz (third column). The second row shows the wiggle trace extracted from the red rectangular areas.

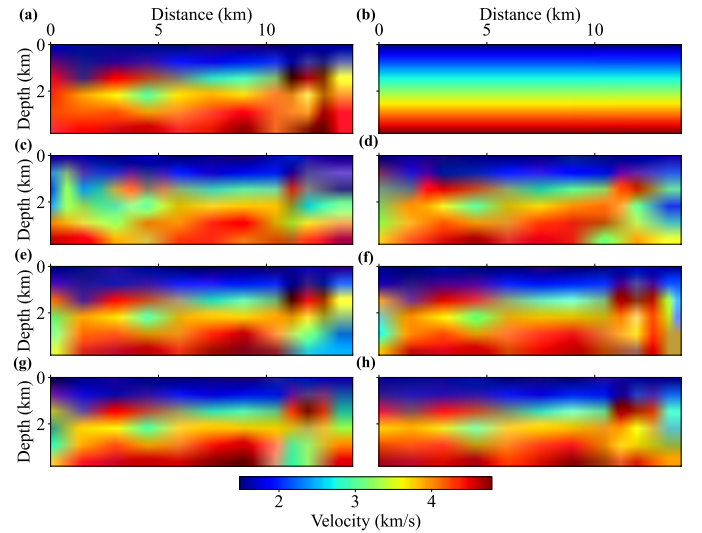


Fig. 12. Inversion results of different inversion methods to the modified 2004 BP model with noisy observed data. (a) True model. (b) Initial model. Inverted model from (c)  $\text{FWI}\ell_2$ , (d) FWISD, (e) FWISD-TV, (f) FWISD-DnCNN, (g) FWISD-FFD, and (h) proposed FWISD-DRU, respectively.

L-BFGS fails to recover the salt body structure, creating erroneous low-velocity zones. SGD struggles with the high-velocity salt body on the right. Adam restores the overall model but causes slight distortions in the left-side salt body, resulting in smoother outcomes. AdamP provides more stable and accurate results than Adam. The learning rate significantly affects AdamP's performance: too low causes insufficient updates, while too high leads to errors in the subsalt area. Through a comprehensive analysis of the model recovery results and the RE curves (see Fig. 15), we find that the AdamP algorithm with lr of 10 achieves the smallest inversion error. Compared to Adam with the same lr, AdamP reduces the model error by about 16%.

##### C. Noise Level of DRUNet

We systematically analyze the noise level map input to the DRUNet, using  $\sigma$  values from 1 to 15. Fig. 16 shows that the best FWI results occur at a noise level of 5. When  $\sigma$

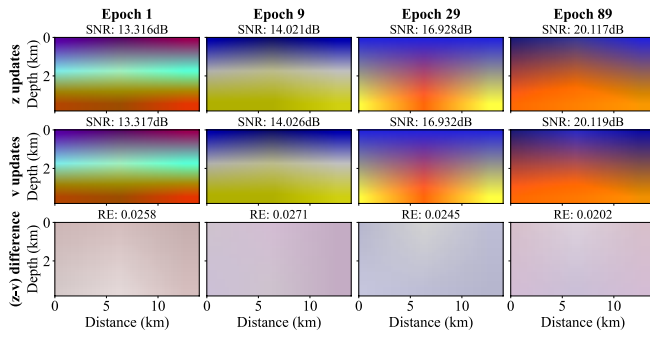


Fig. 13. Intermediate steps of inversion and denoising in FWISD-DRU. (First row) Estimated values of  $z$  obtained from the inversion of the data-fitting term. (Second row) Estimated values of  $v$  obtained after the denoiser removes noise from  $z$ . (Third row) Removed noise.

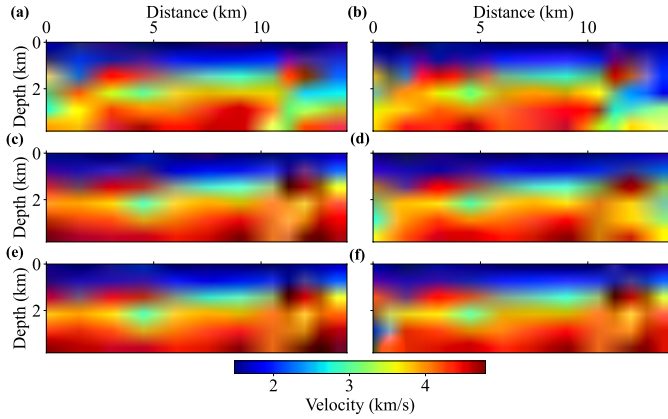


Fig. 14. Inversion results of the modified 2004 BP model using different optimization algorithms. (a) L-BFGS, (b) SGD, (c) Adam with lr of 10, (d) AdamP with lr of 4, (e) AdamP with lr of 10, and (f) AdamP with lr of 20.

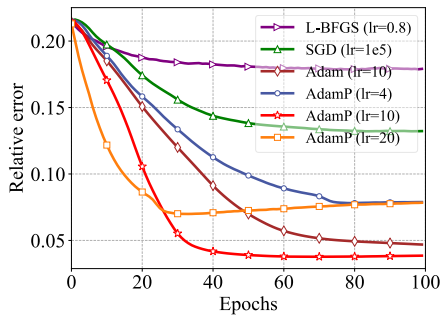


Fig. 15. RE values of different optimization algorithms, against the epoch number. The purple, green, brown, blue, red, and orange curves represent L-BFGS, SGD, Adam with lr of 10, and AdamP with lr of 4, 10, and 20, respectively.

is below 5, inversion results improve with increasing noise levels, likely because moderate noise enhances the denoiser's ability to adapt and accurately remove noise. However, when  $\sigma$  exceeds 5, the recovered model loses detail, and the interface becomes overly smooth, suggesting that high noise levels make it difficult for the denoiser to distinguish between geological structures and noise, reducing accuracy. At  $\sigma = 15$ , the denoising process severely disrupts the structures, leading to significant deviations from reality. The test confirms that a moderate noise level improves FWI performance, while too low or too high levels reduce image quality. Fig. 17 shows the variation of RE and SNR with the number of iterations,

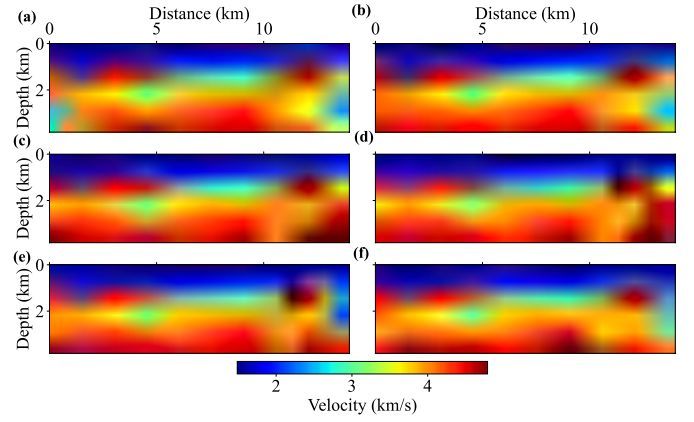


Fig. 16. Inverted models from different noise levels corresponding to the modified 2004 BP model. (a)  $\sigma = 1$ , (b)  $\sigma = 3$ , (c)  $\sigma = 5$ , (d)  $\sigma = 7$ , (e)  $\sigma = 10$ , and (f)  $\sigma = 15$ .

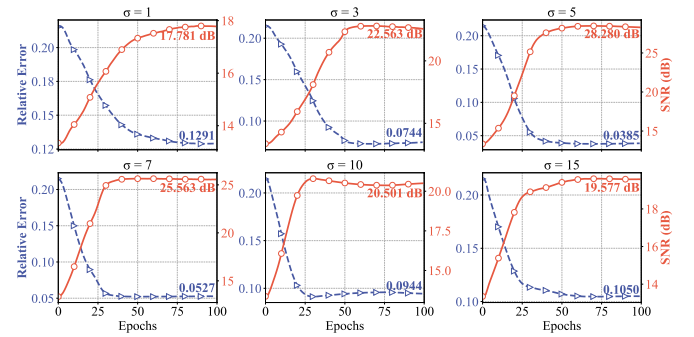


Fig. 17. RE (blue) and SNR (orange) of the recovered models using FWISD-DRU with different noise levels.

further confirming that an appropriate noise level can improve the performance of FWI,  $\sigma = 5$  produces the lowest RE and highest SNR.

#### D. Tradeoff Parameter

In the FWISD-DRU framework, the update of the model  $\mathbf{u}_k$  depends on  $\mathbf{z}_k$  and  $\mathbf{v}_k$ , which are iteratively updated by the data-fitting term and the denoiser, respectively. The combination is significantly affected by the tradeoff parameter  $\omega$ . To assess its impact on FWISD-DRU performance, we tested six values of  $\omega$ : 0.05, 0.07, 0.1, 0.4, 0.7, and 1.0. Fig. 18 shows that at  $\omega = 0.4$ , FWISD-DRU achieves optimal inversion, accurately recovering underground structures without low-speed errors or artifacts. At  $\omega = 0.05$ , artifacts appear in the subsalt area, which are reduced as  $\omega$  increases. However, the inversion overly smooths the model at  $\omega = 0.7$ , losing details; the denoiser misinterprets the model updates as noise at  $\omega = 1.0$ . Thus, an appropriate tradeoff parameter balances the data-fitting term and the denoiser, leading to more accurate results.

#### E. Missing Low-Frequency Data

The lack of low-frequency data often traps FWI in local minima, affecting its convergence and accuracy severely. We analyze the performance of different DL-based FWI methods with the observed data missing low frequencies. In Fig. 11, a noise-free observed seismic record is processed using a sixth-order high-pass Butterworth filter to remove frequencies

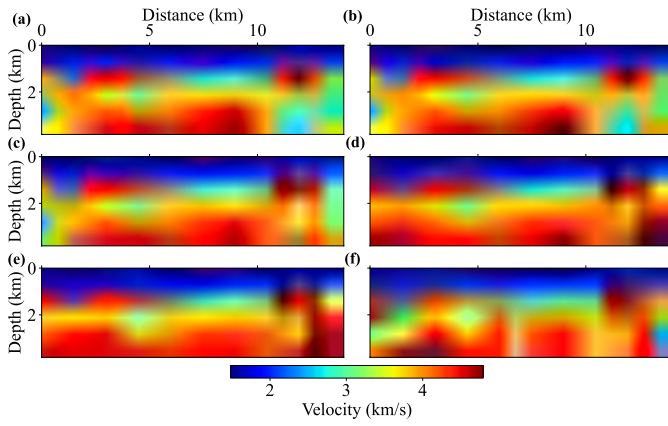


Fig. 18. Inversion results of the modified 2004 BP model with different tradeoff parameters. (a)  $\omega = 0.05$ , (b)  $\omega = 0.07$ , (c)  $\omega = 0.1$ , (d)  $\omega = 0.4$ , (e)  $\omega = 0.7$ , and (f)  $\omega = 1.0$ .

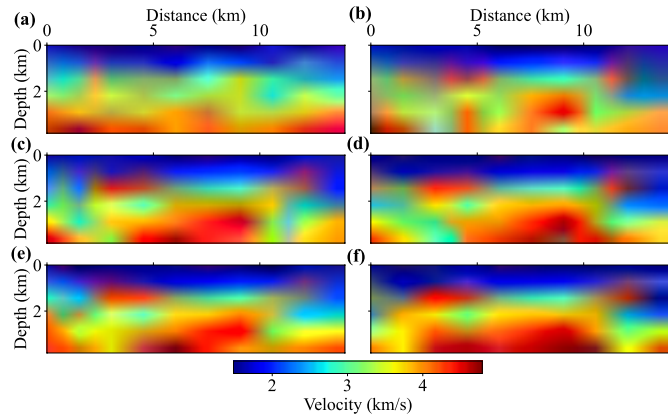


Fig. 19. Inversion results of the modified 2004 BP model with missing low-frequency observed data using different inversion methods. (a)  $\text{FWI}\ell_2$ , (b) FWISD, (c) FWISD-TV, (d) FWISD-DnCNN, (e) FWISD-FFD, and (f) proposed FWISD-DRU.

below 3 Hz, and the inversion results are shown in Fig. 19.  $\text{FWI}\ell_2$  fails to update the model, and FWISD only captures the general model structure. FWISD-TV, FWISD-DnCNN, and FWISD-FFD show significant low-velocity errors, whereas FWISD-DRU effectively recovers stratigraphic boundaries and salt structures, proving its robustness against low-frequency deficiencies and high-frequency artifacts.

#### F. Comparison Between Multiscale Inversion and Denoiser-Assisted Inversion

To mitigate the issue of FWI getting trapped in local minima, common strategies also include multiscale inversion. We applied  $\ell_2$ -norm multiscale inversion to sequential frequency bands (0–2, 2–4, 4–8, and 8–16 Hz) with 25 epochs of iteration for each and compared its results with  $\ell_2$ -norm inversion using the DRUNet denoiser (without multiscale), which processes full-bandwidth data directly (see Fig. 20). While multiscale inversion mitigates local minima by progressively incorporating higher frequencies, it struggles to recover detailed stratigraphy and exhibits significant artifacts beneath the salt bodies. In contrast, the DRUNet-based inversion achieves higher resolution, more accurately reconstructs the salt structure on the left, and suppresses the overall noise and artifacts in the model. These findings show that the

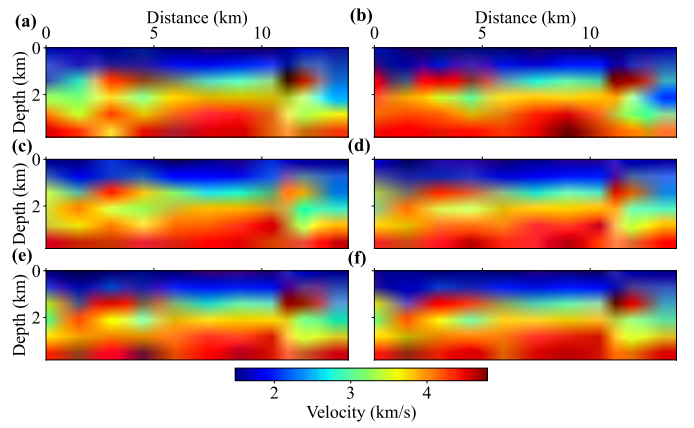


Fig. 20. Inversion results of the modified 2004 BP model using different inversion strategies. (a)  $\text{FWI}\ell_2$ , (b)  $\text{FWI}\ell_2$  with DRUNet, (c)–(f) Multiscale  $\text{FWI}\ell_2$  results at 0–2, 2–4, 4–8, and 8–16 Hz, respectively.

DRUNet denoiser effectively mitigates local minima risks without frequency decomposition and enhances model resolution in challenging inversions, offering a viable alternative to multiscale methods.

#### G. Remaining Challenge and Future Work

First, Table I presents performance metrics and time expenditure per iteration for various methods. Although FWISD-DRU requires the longest processing time due to the DRUNet's complexity, its performance gains justify this cost. Second, the GS-SD shows potential for velocity model recovery but increases computational demands as data size grows. Signal resampling can mitigate this, but high sampling rates risk inaccurate signal estimation. Third, the effectiveness of the denoiser hinges on the careful selection of the noise level  $\sigma$  and tradeoff parameter  $\omega$ , as improper settings of  $\sigma$  and  $\omega$  can lead to structure loss or excessive smoothing. Finally, although DL frameworks enhance FWI efficiency, their memory demands may limit application in large-scale seismic exploration.

Researchers have explored various DL-based strategies to address the convergence of FWI to local minima, including constructing large-scale velocity model datasets [66] to learn the mapping relationship between seismic records and velocity models, unsupervised learning [53], low-frequency extrapolation [12], and multiscale strategies [14]. Despite these advancements in DL methodologies, there is a growing emphasis on developing FWI approaches that are robust and grounded in physical principles, ensuring results align with geological and physical wave propagation laws. Physics-informed neural networks (PINNs) [67] and neural operators [68], which embed physical laws within neural networks, offer promising improvements in FWI's efficiency and accuracy. In addition, to further enhance the practicality and efficiency of FWI-DRU, reducing the number of tunable parameters is a key area of focus. Generative denoisers like the Diffusion model [69] provide learned prior constraints, eliminating the need for manual noise level tuning, which is inevitable in traditional CNN-based denoisers. Finally, extending FWISD-DRU to elastic FWI and 3-D geological models is a crucial direction for future research.



## V. CONCLUSION

In this article, we propose an effective PnP FWI framework called FWISD-DRU, which integrates a DL-based pretrained DRUNet denoiser from the field of computer vision into the FWI process as a regularization term. Compared with traditional regularization methods, such as TV regularization, FWISD-DRU significantly reduces the noise and artifacts that arise during the iterative inversion process due to factors such as inaccurate initial models, poor data quality, and data bandwidth limitations. Our framework provides denoising prior information for each iteration of FWI, effectively avoiding the inversion from falling into local minima, thereby restoring the high-fidelity and high-resolution features of different geological models. Furthermore, by utilizing the SD in graph space as a data fitting term, we effectively alleviate the cycle skipping issues, which are prone to happen with the  $\ell_2$ -norm. Combining the automatic differentiation technology of DL and the AdamP gradient optimization algorithm, FWISD-DRU achieves high computational efficiency and accuracy. Although our proposed method is demonstrated on 2-D acoustic FWI, its principles, and strategies can be extended to both elastic and 3-D FWI easily, offering new avenues for accurate underground imaging with seismic data.

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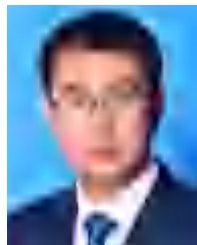
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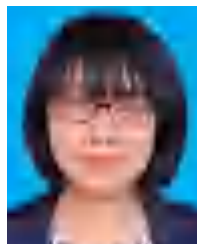
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Original Paper

# Helmholtz decomposition with a scalar Poisson equation in elastic anisotropic media



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## abstract

P- and S-wave separation plays an important role in elastic reverse-time migration. It can reduce the artifacts caused by crosstalk between different modes and improve image quality. In addition, P- and S-wave separation can also be used to better understand and distinguish wave types in complex media. At present, the methods for separating wave modes in anisotropic media mainly include spatial non-stationary filtering, low-rank approximation, and vector Poisson equation. Most of these methods require multiple Fourier transforms or the calculation of large matrices, which require high computational costs for problems with large scale. In this paper, an efficient method is proposed to separate the wave mode for anisotropic media by using a scalar anisotropic Poisson operator in the spatial domain. For 2D problems, the computational complexity required by this method is 1/2 of the methods based on solving a vector Poisson equation. Therefore, compared with existing methods based on pseudo-Helmholtz decomposition operators, this method can significantly reduce the computational cost. Numerical examples also show that the P and S waves decomposed by this method not only have the correct amplitude and phase relative to the input wavefield but also can reduce the computational complexity significantly.

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## 1. Introduction

The P- and S-waves are coupled during their propagation in the Earth. Thus, crosstalk artifacts will occur when imaging directly with the mixed wavefields, affecting the imaging quality (Zhang and Shi, 2019; Xie et al., 2021). Through wave-mode separation, the PP, PS, SS and SP waves can be imaged separately, which can reduce wave-mode crosstalk artifacts and improve imaging quality (Sun et al., 2006; Yan and Sava, 2008; Zhou et al., 2019; Yang et al., 2019; Li et al., 2021; Li and Qu, 2022; Zhang et al., 2022; Zuo et al., 2022). The application of wave mode separation in full-waveform inversion can reduce the nonlinearity and crosstalk problem between multi-parameters and improve the accuracy of inversion (Ren and Liu, 2016; Qu et al., 2018; Luo et al., 2020; Hu et al., 2022).

So P- and S-wave separation is very important in imaging and full-waveform inversion for elastic isotropic and anisotropic media.

The key to wavefield separation is the polarization directions of the P and S waves. In isotropic media, the wave travels in the same direction as the polarization of the P-wave and perpendicular to the polarization of the S-wave, so the P and S waves can be separated by applying divergence and curl directly to the input wavefield. However, the resulting amplitude and phase of the P and S waves are incorrect (Sun et al., 2004). Separating the input wavefield using Helmholtz decomposition (Morse and Feshbach, 1953; Aki and Richards, 2002) can solve this problem effectively. However, directly solving scalar and vector potentials requires calculating triple integrals, resulting in high costs. To solve this problem, the Helmholtz decomposition based methods for vector decomposing wavefield in the space domain and the wavenumber domain are proposed successively (Zhang and McMechan, 2010; Zhu, 2017). Yang et al. (2018) and Zhao et al. (2018) propose to integrate the source wavelet and achieve the wavefield decomposition by scaling

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the decomposition operator. This method avoids the calculation of Poisson equation and improves the efficiency of wavefield decomposition. Using the relationship between the divergence, curl, gradient, and exterior derivative operations (Morse and Feshbach, 1953), Zheng and Yao (2023) proposed a method for decomposing wavefields in isotropic media based on a scalar Laplacian operator. Different from the existing Helmholtz decomposition based method, this method only requires solving a scalar Poisson equation, not a vector Poisson equation, resulting in much higher computational efficiency.

In anisotropic media, the polarization directions of P and S waves are neither parallel nor perpendicular to the wave propagation direction. Therefore, it is necessary to obtain the polarization di-

S-wave by subtracting the vector P-wave directly from the input full wavefield. There is no curl operation on a certain auxiliary wavefield, which can further reduce the computation costs when compared with existing pseudo-Helmholtz decomposition methods.

## 2. Method

### 2.1. Review of the pseudo-Helmholtz decomposition operator for 2D VTI media

The elastic wave equation in the 2D VTI media is as follows:

$$\begin{cases} \rho(\mathbf{x}) \frac{\nabla^2 u_x(\mathbf{x}; t)}{\nabla t^2} = c_{11}(\mathbf{x}) \frac{\nabla^2 u_x(\mathbf{x}; t)}{\nabla x^2} + c_{55}(\mathbf{x}) \frac{\nabla^2 u_x(\mathbf{x}; t)}{\nabla z^2} + (c_{13}(\mathbf{x}) + c_{55}(\mathbf{x})) \frac{\nabla^2 u_z(\mathbf{x}; t)}{\nabla x \nabla z} \\ \rho(\mathbf{x}) \frac{\nabla^2 u_z(\mathbf{x}; t)}{\nabla t^2} = c_{55}(\mathbf{x}) \frac{\nabla^2 u_z(\mathbf{x}; t)}{\nabla x^2} + c_{33}(\mathbf{x}) \frac{\nabla^2 u_z(\mathbf{x}; t)}{\nabla z^2} + (c_{13}(\mathbf{x}) + c_{55}(\mathbf{x})) \frac{\nabla^2 u_x(\mathbf{x}; t)}{\nabla x \nabla z} \end{cases} \quad (1)$$

rections of P and S waves through the Christoffel equation (Dellinger and Etgen, 1990), and then project the vector of wave displacement or particle velocity into the polarization directions of P and S waves to achieve wave mode separation. Dellinger and Etgen (1990) and Dellinger (1991) obtained the polarization directions of P and S waves by solving the Christoffel equation in the wavenumber domain and then returned to the spatial domain to obtain the anisotropic wavefield separation operator. However, since this method directly applies the separation operator to the wavefield, the amplitude and the phase obtained are incorrect. Moreover, this method is only accurate for homogeneous media. To solve these problems, Zhang and McMechan (2010) proposed a vector decomposition method of elastic wavefield in the wavenumber domain, which can obtain the correct amplitude and phase. Yan and Sava (2009) proposed a non-stationary filter to separate P- and S-wave in anisotropic heterogeneous media. Their method needs to solve the Christoffel equation of local media parameters to obtain the local polarization direction for constructing the non-stationary filter, which leads to high computational costs. To reduce computational costs, many scholars have proposed other approaches, such as low-rank approximation (Cheng and Fomel, 2014; Sripanich et al., 2017), LU decomposition (Yang et al., 2019), ani-Helmholtz decomposition in the wavenumber domain and the spatial domain (Zhang et al., 2022, 2023). In addition, Zhou and Wang (2017) used the Poynting vector to estimate the deviation angle between the vector of wave displacement and the P-wave polarization direction and then separated the P and S waves by rotating the wave vector to the P-wave polarization direction. Lu et al. (2019) used the Poynting vector to achieve wave-mode separation in the angle domain.

In this paper, we extend the method proposed by Zheng and Yao (2023) to separate the anisotropic elastic wavefields by using the pseudo-gradient operator (Zuo et al., 2022). For the resulting method, we only need to solve an scalar anisotropic Poisson equation. Compared with the methods that require solving vector anisotropic Poisson equations, our method can greatly reduce the computational cost. Precisely, in the case of 2D wavefields, our method can save half of the computational cost. Like the methods proposed by Du et al. (2017) and Zhong et al. (2021), we obtain the

where  $\mathbf{x}$  is spatial position coordinates,  $u_x(\mathbf{x}; t)$  and  $u_z(\mathbf{x}; t)$  denote horizontal and vertical components of the displacement or particle velocity wavefields, respectively.  $\rho(\mathbf{x})$  represents density, and  $c_{11}(\mathbf{x})$ ,  $c_{13}(\mathbf{x})$ ,  $c_{33}(\mathbf{x})$ ,  $c_{55}(\mathbf{x})$  are the elements of the elastic coefficient matrix.

Taking the Fourier transform of Eq. (1) by assuming the local homogenous medium, the Christoffel equation is obtained:

$$\rho \mathbf{u}^2 \begin{bmatrix} U_x \\ U_z \end{bmatrix} = \begin{bmatrix} c_{11}k_x^2 + c_{55}k_z^2 & (c_{13} + c_{55})k_x k_z \\ (c_{13} + c_{55})k_x k_z & c_{55}k_x^2 + c_{33}k_z^2 \end{bmatrix} \begin{bmatrix} U_x \\ U_z \end{bmatrix} \quad (2)$$

where  $\mathbf{u}$  is the angular frequency,  $U_x$  and  $U_z$  are the corresponding wavefields of  $u_x$  and  $u_z$  after the Fourier transform, respectively. Moreover,  $k_x$  and  $k_z$  are the wavenumbers in the  $x$  and  $z$  directions, respectively. Denoting

$$\mathbf{A} = \begin{bmatrix} c_{11}k_x^2 + c_{55}k_z^2 & (c_{13} + c_{55})k_x k_z \\ (c_{13} + c_{55})k_x k_z & c_{55}k_x^2 + c_{33}k_z^2 \end{bmatrix} \text{ and } \mathbf{a} = \begin{bmatrix} U_x \\ U_z \end{bmatrix} \quad (3)$$

Then  $\mathbf{l} = \rho \mathbf{u}^2 = \rho k^2 V^2$ , where  $V$  is the phase velocity,  $\mathbf{l}$  and  $\mathbf{a}$  are the eigenvalue and eigenvector of matrix  $\mathbf{A}$ , respectively. The matrix  $\mathbf{A}$  has two eigenvalues, and the eigenvectors corresponding to the large and small eigenvalues are the polarization directions of the P and S waves, respectively. Moreover, the elastic coefficient matrix elements in Eq. (3) can be represented by Thomsen parameters (Thomsen, 1986) as follows:

$$\begin{aligned} c_{11} &= \rho(1 + 2\varepsilon)v_p^2; c_{33} = \rho v_p^2; c_{55} = \rho v_s^2 \\ c_{13} &= \rho \sqrt{[(1 + 2d)v_p^2 - v_s^2][v_p^2 - v_s^2]} - \rho v_s^2 \end{aligned} \quad (4)$$

where  $\varepsilon$  and  $d$  are the Thomsen anisotropy parameters,  $v_p$  and  $v_s$  denote the P and S velocities along the axis of symmetry, respectively. Therefore, the eigenvalue of matrix  $\mathbf{A}$  is

$$l_{1,2} = r \frac{\left[ (1+2\varepsilon)v_p^2 + v_s^2 \right] k_x^2 + \left[ v_p^2 + v_s^2 \right] k_z^2}{2} \pm r \frac{\left[ (1+2\varepsilon)v_p^2 - v_s^2 \right] k_x^2 + \left[ v_p^2 - v_s^2 \right] k_z^2}{2} \times \sqrt{1 + \frac{8(d-\varepsilon)v_p^2(v_p^2 - v_s^2)k_x^2 k_z^2}{\left[ ((1+2\varepsilon)v_p^2 - v_s^2)k_x^2 + (v_p^2 - v_s^2)k_z^2 \right]^2}} \quad (5)$$

Utilizing the zero-order Taylor expansion (Zuo et al., 2022), the eigenvalues and eigenvectors of  $\mathbf{A}$  can be approximately expressed as

$$l_1 = rv_p^2 \left[ (1+2\varepsilon)k_x^2 + k_z^2 \right]; \quad l_2 = rv_s^2 \left[ k_x^2 + k_z^2 \right]$$

$$\mathbf{a}_1 = \begin{bmatrix} k_x \\ \sqrt{\frac{[(1+2d)v_p^2 - v_s^2](v_p^2 - v_s^2)}{(1+2\varepsilon)v_p^2 - v_s^2}} k_z \end{bmatrix} \quad (6)$$

$$\mathbf{a}_2 = \begin{bmatrix} \sqrt{\frac{[(1+2d)v_p^2 - v_s^2](v_p^2 - v_s^2)}{(1+2\varepsilon)v_p^2 - v_s^2}} k_z \\ -k_x \end{bmatrix}$$

By denoting (Zuo et al., 2022)

$$r = \frac{\sqrt{[(1+2d)v_p^2 - v_s^2](v_p^2 - v_s^2)}}{(1+2\varepsilon)v_p^2 - v_s^2} \quad (7)$$

the corresponding formulas of Eq. (6) in the spatial domain are

$$\mathbf{a}_1(\mathbf{x}) = \begin{bmatrix} v_x \\ r(\mathbf{x})v_z \end{bmatrix}$$

$$\mathbf{a}_2(\mathbf{x}) = \begin{bmatrix} r(\mathbf{x})v_z \\ -v_x \end{bmatrix} \quad (8)$$

$$r(\mathbf{x}) = \frac{\sqrt{[(1+2d(\mathbf{x}))v_p^2(\mathbf{x}) - v_s^2(\mathbf{x})](v_p^2(\mathbf{x}) - v_s^2(\mathbf{x}))}}{(1+2\varepsilon(\mathbf{x}))v_p^2(\mathbf{x}) - v_s^2(\mathbf{x})}$$

where,  $v_x$  and  $v_z$  are the first-order spatial derivatives in  $x$  and  $z$  directions, respectively. Physically,  $\mathbf{a}_1(\mathbf{x})$  and  $\mathbf{a}_2(\mathbf{x})$  denote the polarization directions of the P- and S-wave, respectively. Since zero-order Taylor expansion is applied to obtain the eigenvalues and eigenvectors of  $\mathbf{A}$ , the resulting eigenvalues in Eq. (6) and eigenvectors in Eq. (8) are accurate for elliptical anisotropy media, i.e.,  $\varepsilon = d$ . When the difference between  $\varepsilon$  and  $d$  is large, the accuracy of zero-order Taylor expansion decreases.

According to Eq. (8), which gives approximated eigenvectors of  $\mathbf{A}$ , the following operator gives a pseudo-gradient operator in anisotropic media:

$$\bar{\nabla} = \begin{bmatrix} v_x \\ r(\mathbf{x})v_z \end{bmatrix} \quad (9)$$

Since the P- and S-wave polarization directions are

perpendicular to each other, the decomposition formulas of P and S waves can be obtained from the zero-order pseudo-Helmholtz decomposition operator:

$$\mathbf{u}^p = \bar{\nabla}(\bar{\nabla} \cdot \mathbf{w}); \quad \mathbf{u}^s = -\bar{\nabla} \times (\bar{\nabla} \times \mathbf{w}) \quad (10)$$

The vector wavefield  $\mathbf{w}$  satisfies the following anisotropic Poisson equation:

$$\frac{v^2 \mathbf{w}(\mathbf{x})}{v_x^2} + r^2(\mathbf{x}) \frac{v^2 \mathbf{w}(\mathbf{x})}{v_z^2} = \mathbf{u}(\mathbf{x}) \quad (11)$$

Eqs. (9) and (11) are the anisotropic wavefield decomposition formulas. When the anisotropy parameter is 0, Eq. (9) reduces to a gradient operator. Therefore, the approximate gradient operator of Eq. (9) is an improvement on the counterpart in Yang et al. (2019). Eq. (11) indicates that  $\mathbf{w}$  is obtained by solving a vector Poisson equation, which contains multiple scalar Poisson equations. When the scale of  $\mathbf{u}$  increases, the computational cost of solving the vector Poisson equation (Eq. (11)) will increase significantly.

## 2.2. A scalar anisotropic Poisson operator

By using relationships among the gradient, divergence, curl, and exterior derivative operations, Zheng and Yao (2023) proposed the method of using a scalar Poisson equation to decompose the isotropic wavefield. In this section, we extend this method to decompose anisotropic wavefields. By introducing an auxiliary function, we present a scalar anisotropic Poisson equation based on the pseudo-divergence, pseudo-gradient, and pseudo-curl operators.

For anisotropic media, the input wavefield vector can be projected to the polarization directions of P and S waves according to the Helmholtz decomposition theory. Here, the obtained spatial domain approximate P-wave polarization direction is used to replace the P-wave polarization direction. The pseudo-gradient operator given by Eq. (9) is consistent with the polarization direction of the P-wave and orthogonal to the polarization direction of the S-wave. Therefore, the following formula in the spatial domain is obtained after projecting the vector wavefields  $\mathbf{u}$ ,  $\mathbf{u}^p$  and  $\mathbf{u}^s$  onto the obtained polarization vectors  $\mathbf{a}_1(\mathbf{x})$ ,  $\mathbf{a}_2(\mathbf{x})$ :

$$\mathbf{u} = \mathbf{u}^p + \mathbf{u}^s$$

$$\bar{\nabla} \cdot \mathbf{u} = \bar{\nabla} \cdot \mathbf{u}^p; \quad \bar{\nabla} \times \mathbf{u} = \bar{\nabla} \times \mathbf{u}^s$$

$$\bar{\nabla} \times \mathbf{u}^p = 0; \quad \bar{\nabla} \cdot \mathbf{u}^s = 0 \quad (12)$$

More details can be seen in Zhang et al. (2022). Here,  $\mathbf{u}$ ,  $\mathbf{u}^p$  and  $\mathbf{u}^s$  are the input vector wavefield, vector P-wave, and vector S-wave, respectively.

For the general VTI anisotropic media, the gradient and curl operators are complex. Thus, we obtain them by applying zero-order Taylor expansion to the exact eigenvalue of  $\mathbf{A}$ . Applying the pseudo-gradient operator to Theorem 1 of Zheng and Yao (2023) and combining it with the properties of P and S waves in Eq. (12),



the following equation can be obtained:

$$\mathbf{u} - \mathbf{u}^s = \bar{\nabla} f \quad (13)$$

Applying the pseudo-divergence operator to both sides of Eq. (13) results in

$$\bar{\nabla}^2 f = \bar{\nabla} \$ (\bar{\nabla} f) = \bar{\nabla} \$ \mathbf{u} \quad (14)$$

which can be rewritten as

$$\frac{v^2 f(\mathbf{x})}{v_x^2} + r^2(\mathbf{x}) \frac{v^2 f(\mathbf{x})}{v_z^2} = \bar{\nabla} \$ \mathbf{u}(\mathbf{x}) \quad (15)$$

Therefore, the P- and S-wavefield decomposition equations for VTI anisotropic media are

$$\mathbf{u}^p = \bar{\nabla} f; \quad \mathbf{u}^s = \mathbf{u} - \mathbf{u}^p \quad (16)$$

From Eqs. (15) and (16), it can be seen that the computational complexity of implementing wavefield decomposition is mainly reflected in solving the scalar anisotropic Poisson Eq. (15). By contrast, the separation presented by Yang et al. (2019) needs to solve the vector anisotropic Poisson equation (e.g., Eq. (11)). For the 2D case, two anisotropic Poisson equations need to be solved. The method proposed in this paper only requires solving one Poisson equation. Theoretically, the computational cost of our proposed method is almost 1/2 of that of Yang et al. (2019) for 2D problems. An extension of this method for 3D cases can be found in Appendix A.

### 2.3. Numerical implementation

According to Eqs. (14) and (16), the proposed wavefield decomposition method includes four steps: (1) calculate  $\bar{\nabla} \$ \mathbf{u}$ ; (2) solve the scalar anisotropic Poisson equation; (3) compute  $\bar{\nabla} f$  to produce the

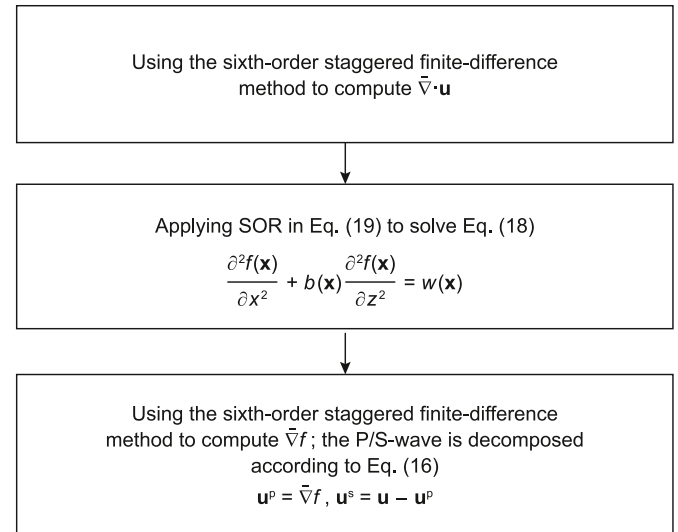


Fig. 1. Flowchart of P/S-wave decomposition.

spatial derivative of the function is computed with the sixth-order central finite difference.

By denoting

$$b(\mathbf{x}) = r^2(\mathbf{x}); \quad w(\mathbf{x}) = \bar{\nabla} \$ \mathbf{u}(\mathbf{x}) \quad (17)$$

Eq. (15) can be expressed as

$$\frac{v^2 f(\mathbf{x})}{v_x^2} + b(\mathbf{x}) \frac{v^2 f(\mathbf{x})}{v_z^2} = w(\mathbf{x}) \quad (18)$$

The SOR iteration format for Eq. (18) is as follows:

$$f_{i,j}^{(k+1)} = b \frac{w_{i,j} - \frac{1}{D_x^2} \sum_{n=1}^3 c_n \left( f_{i+n,j}^{(k)} + f_{i-n,j}^{(k+1)} \right) - \frac{b_{i,j}}{D_z^2} \sum_{n=1}^3 c_n \left( f_{i,j+n}^{(k)} + f_{i,j-n}^{(k+1)} \right)}{c_0 \left( \frac{1}{D_x^2} + \frac{b_{i,j}}{D_z^2} \right)} + (1-b) f_{i,j}^{(k)} \quad (19)$$

P-wave; (4) compute the S-wave by subtracting the P-wave from the full wavefield.

Usually, staggered finite-difference methods are used to solve the VTI elastic wave equations, resulting in a half-grid shift of the velocity and stress components. In the first step, we use the staggered grid finite difference to compute  $\bar{\nabla} \$ \mathbf{u}$ . The obtained scalar field is located at the grid points of normal stresses. The calculation in the second step operates on the grid points of normal stresses. In the third and fourth steps, the P-wave is obtained by solving  $\bar{\nabla} f$  using finite difference, and then the S-wave is obtained by subtracting the P-wave from the full wavefield. Therefore, the separated P/S waves are still in the original grid position.

In the second step, the successive over-relaxation (SOR) iterative method (Kincaid and Young, 1972) is used to solve the scalar anisotropic Poisson equation (Eq. (15)). Here, the second-order

where  $f_{i,j}^{(k)}$  represents the value of  $f$  on the grid point  $(i, j)$  of the  $k$ -th iteration,  $b$  is the relaxation factor of the SOR iterative method, and  $c_n$  is the finite-difference coefficient. The convergence condition of this iterative method is  $0 < b < 2$ . In the numerical experiments of this paper, the relaxation factor  $b$  of the SOR iterative is obtained through trial and error in the interval  $[0, 2]$ , which is taken as 1.9. To speed up the convergence, we adopt the SOR iteration with alternating sweeping orderings (Zhao, 2005) to solve the scalar Poisson equation. The four alternating sweeping orderings in the entire domain are as follows:

$$\begin{aligned} \text{(i)} \quad & i = 1:I; \quad j = 1:J; & \text{(ii)} \quad & i = I:1; \quad j = 1:J \\ \text{(iii)} \quad & i = I:1; \quad j = J:1; & \text{(iv)} \quad & i = 1:I; \quad j = J:1 \end{aligned} \quad (20)$$

Eq. (20) indicates the update order of Eq. (19). One iteration uses

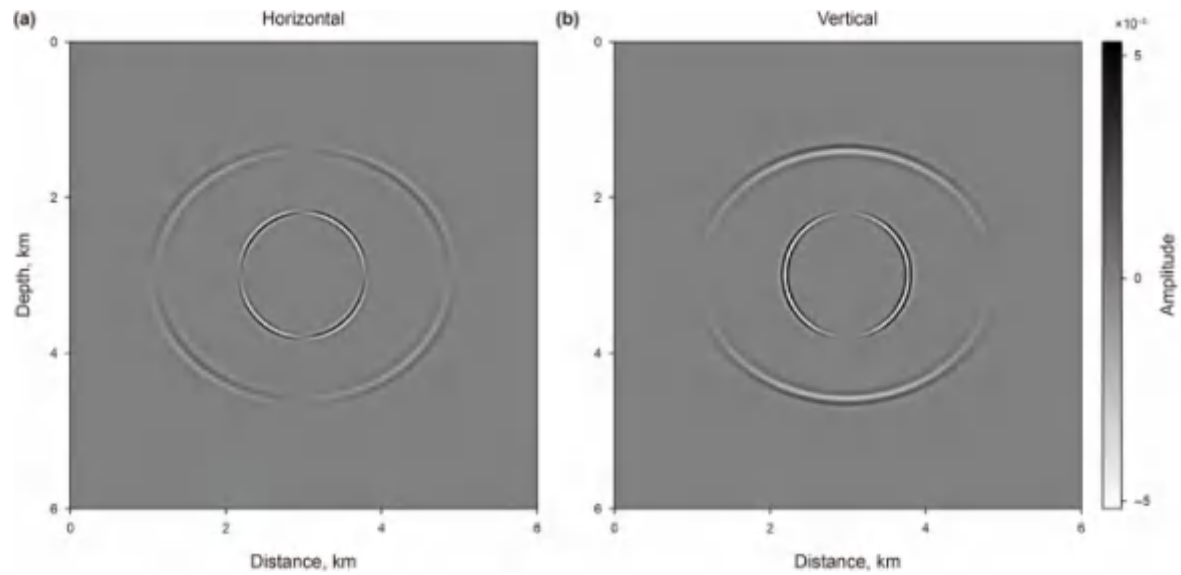


Fig. 2. The horizontal (a) and vertical (b) components of particle velocity for the elliptical anisotropic homogeneous model.

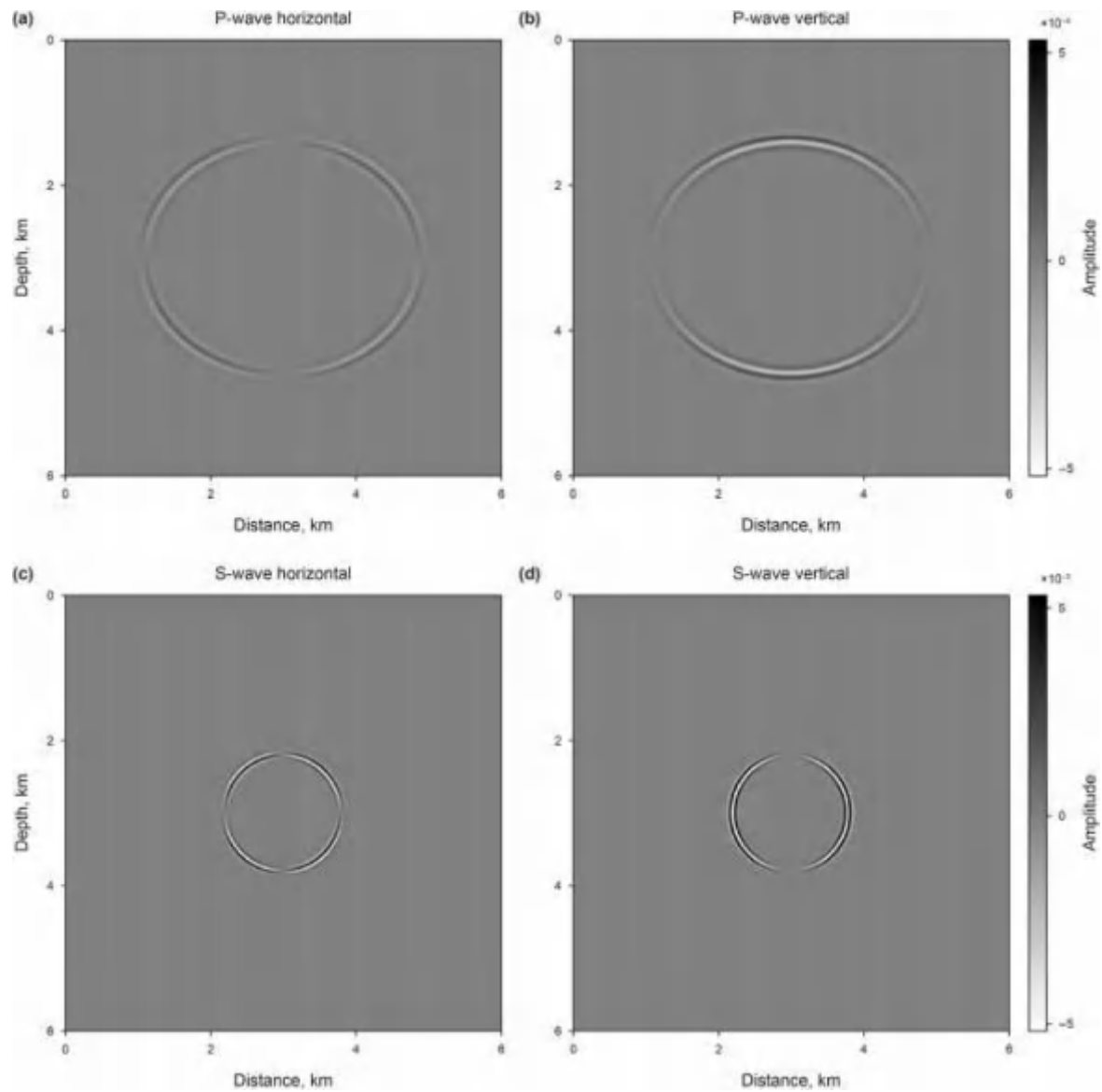


Fig. 3. The separated wavefields for the elliptical anisotropic homogeneous model. Horizontal (a) and vertical (b) components of P-wave. Horizontal (c) and vertical (d) components of S-wave.

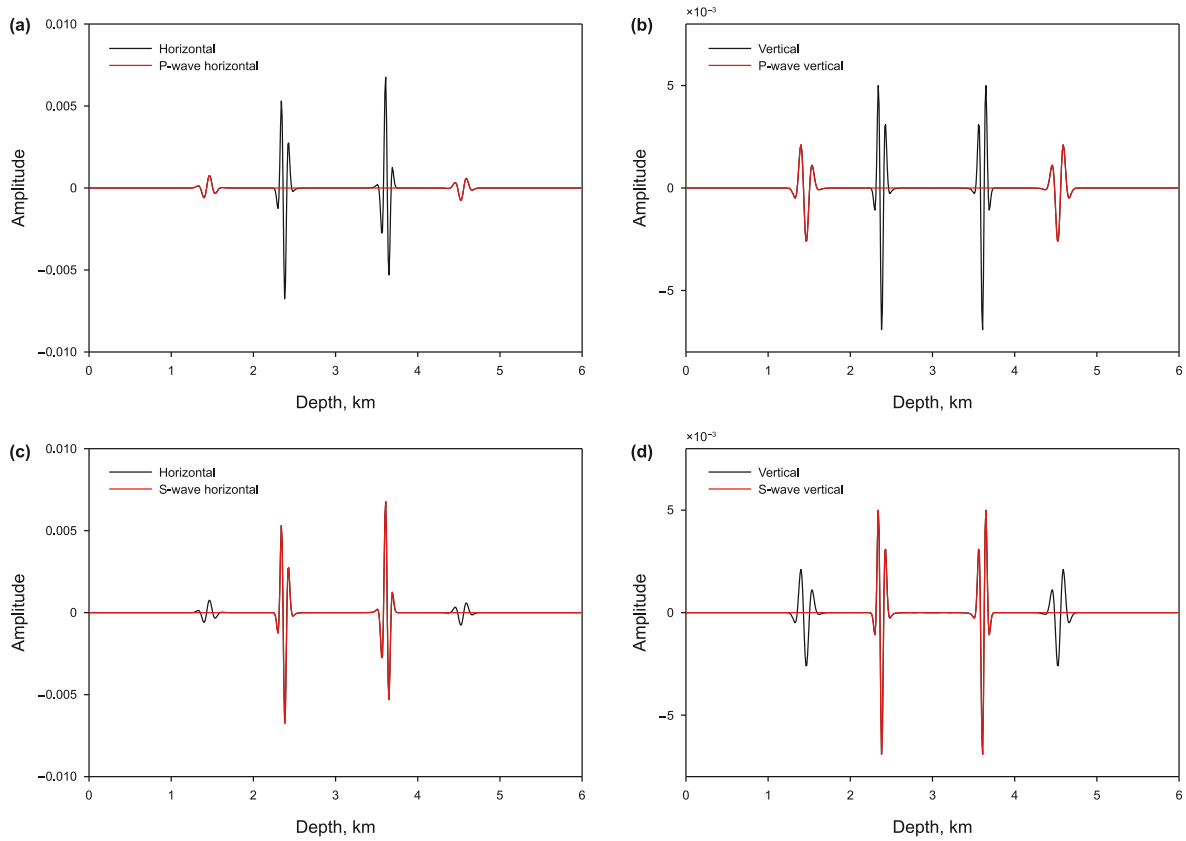


Fig. 4. The wiggle display of the 350th trace (distance = 3.5 km) for the experiment of the elliptical anisotropic homogeneous model. The black curves show the original waveform while the red curves show the separated P/S waves.

the order of (i), and the next three iterations follows the order of (ii) e (iv), and then repeat the order of (i) and so on. The solution obtained in each iteration is used as the initial value of the next iteration. Based on the description in this section, Fig. 1 is presented to show the working flowchart.

### 3. Examples

In this section, four numerical examples are presented to demonstrate the effectiveness of our proposed method for decomposing the wavefields in anisotropic media.

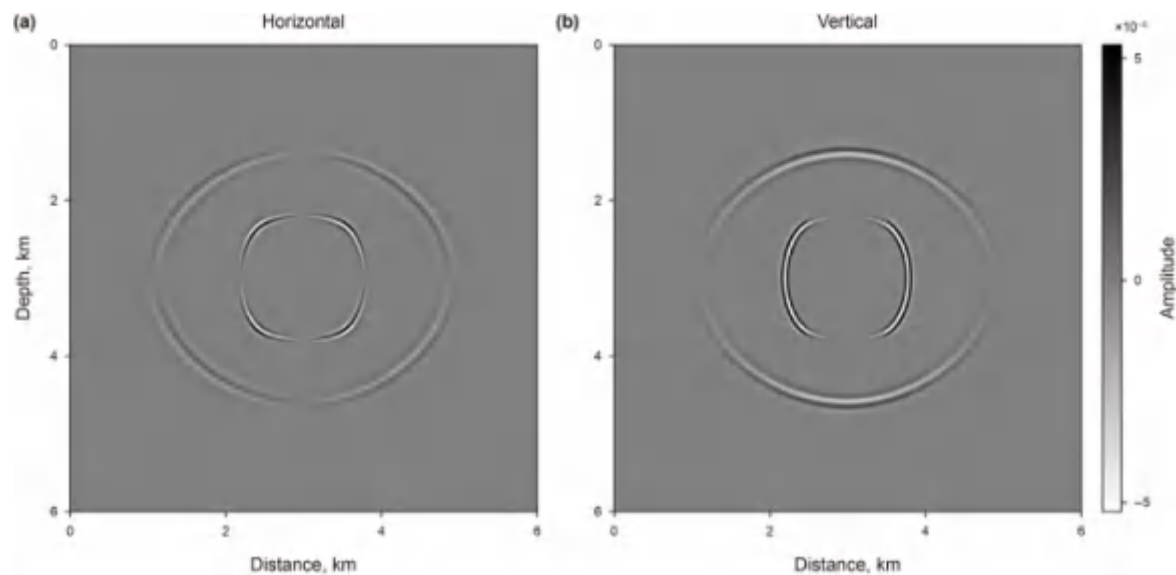


Fig. 5. The horizontal (a) and vertical (b) components of particle velocity for the non-elliptical anisotropic homogeneous model.

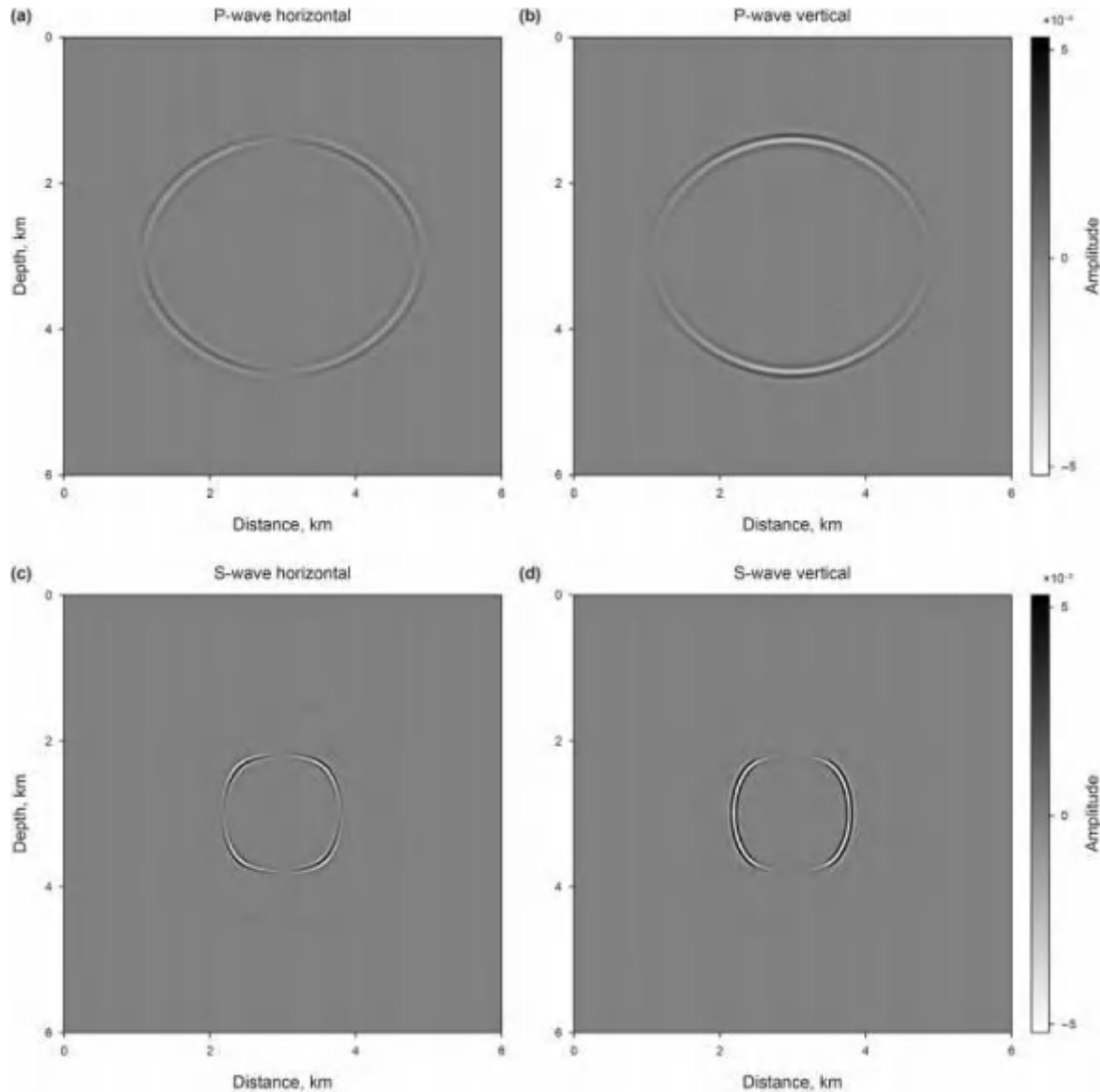


Fig. 6. The separated wavefields for the non-elliptical anisotropic homogeneous model. Horizontal (a) and vertical (b) components of P-wave. Horizontal (c) and vertical (d) components of S-wave.

### 3.1. Elliptical anisotropic homogeneous model

The first example is the elliptical anisotropic homogeneous model. A 15 Hz Ricker wavelet is used as the vertical body-force source excitation, and the source location is at the center of the model. The parameters of the model are  $v_p = 3000$  m/s,  $v_s = 1500$  m/s,  $\rho = 1000$  kg/m<sup>3</sup>,  $\epsilon = 0.2$  and  $d = 0.2$ . Moreover, the model is discretized into a grid of  $600 \times 600$  with a 10 m grid interval.

The horizontal and vertical particle velocity wavefields are shown in Fig. 2. Fig. 3 shows the horizontal and vertical components of P and S waves obtained by using the decomposition method proposed in this paper, i.e., Eqs. (14)e(16). As can be seen from Fig. 3, P- and S-wavefield can be separated completely for an elliptical anisotropic model. The wiggle comparison of the 350th trace is shown in Fig. 4. It can be seen from Fig. 4 that the horizontal and vertical components of P and S waves obtained by the proposed method match well with the amplitude and phase of the input velocity wavefields. This further demonstrates the effectiveness of

the proposed method.

### 3.2. Non-elliptical anisotropic homogeneous model

In this experiment, we test the performance of the proposed zero-order method for a non-elliptical anisotropic homogeneous media. The test parameters are the same as that of the previous elliptical anisotropic model except for  $d = 0.1$ . The horizontal and vertical particle velocity wavefields are shown in Fig. 5. Fig. 6 shows the horizontal and vertical components of P and S waves.

It can be seen from Fig. 6 that there is a small amount of S-wave leaking into the separated P-wave, and there is also some P-wave residual in the S-wave. Furthermore, according to the wiggle display in Fig. 7, the residual is about 3% in terms of the amplitude ratio. This is because the polarization directions of the P and S waves shown in Eq. (8) are exact in elliptical anisotropic media but are an approximation in non-elliptical anisotropic media, so there will be some residuals when decomposing non-elliptical anisotropic wavefield. The amplitude of the residual is

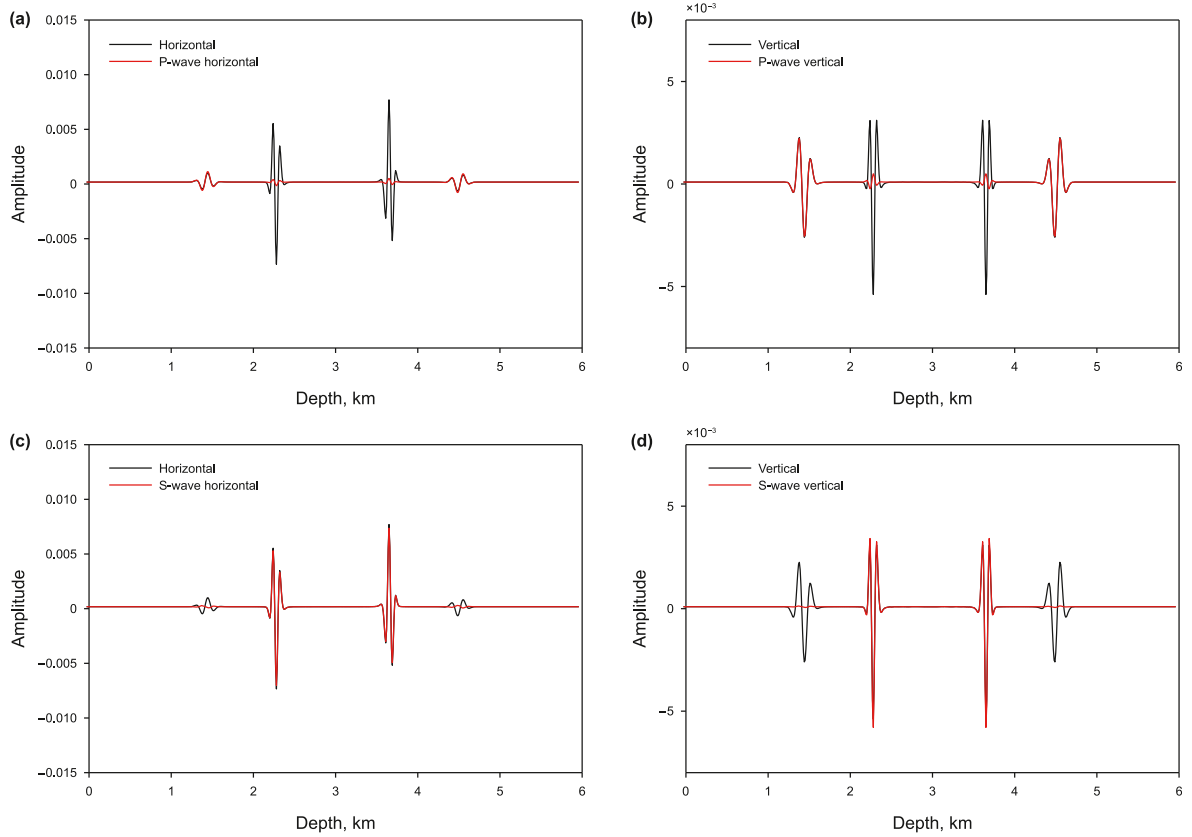


Fig. 7. The wiggle display of the 350th trace (distance = 3.5 km) for the experiment of the non-elliptical anisotropic homogeneous model. The black curves show the original waveform while the red curves show the separated P/S waves.

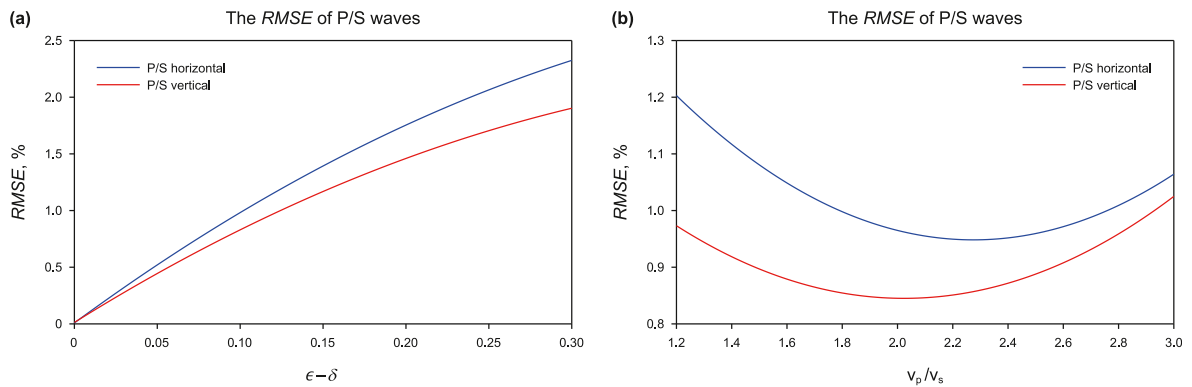


Fig. 8. Root mean square errors (RMSE) of the P/S waves obtained by using the proposed method relative to the accurate P/S waves with different influential factors: (a) anisotropic parameter difference, i.e.,  $\varepsilon - \delta$  and (b) the ratio of P-wave to S-wave velocities, i.e.,  $v_p/v_s$ .

proportional to the difference between  $\varepsilon$  and  $\delta$ . Although the leakage exists, previous studies (Yang et al., 2019; Zhang et al., 2022; Zuo et al., 2022) suggest that the zero-order pseudo-Helmholtz decomposition method fulfills the quality requirement of elastic migration.

Because accurate P/S wavefields can be obtained by cutting through a homogeneous model, we take homogeneous non-elliptical media as an example to further analyze the accuracy of this method. By keeping other parameters fixed, we separately change the anisotropic parameter difference, i.e.,  $\varepsilon - \delta$  and the ratio of P-wave to S-wave velocities, i.e.,  $v_p/v_s$ . We then calculate the root mean square error (RMSE) of the P/S waves obtained by using the

method proposed in this paper relative to the accurate P/S waves. The results are shown in Fig. 8.

When  $v_p/v_s = \sqrt{3}$ ;  $v_p = 3000 \text{ m/s}$ ;  $v_s = 1732 \text{ m/s}$ ;  $r = 1000 \text{ kg/m}^3$ ;  $d = 0.1$  and the range of  $\varepsilon - \delta$  is  $[0, 0.3]$ , the RMSE of P/S waves obtained using the proposed approach are shown in Fig. 8(a). As can be seen, when other parameters are fixed, the RMSE is directly proportional to  $\varepsilon - \delta$ . Furthermore, the RMSE of the vertical component is smaller than that of the horizontal component.

When  $v_p = 3000 \text{ m/s}$ ;  $r = 1000 \text{ kg/m}^3$ ;  $\varepsilon = 0.2$ ;  $d = 0.1$ , the RMSE relative to  $v_p/v_s$  is shown in Fig. 8(b). As can be seen, when  $v_p/v_s$  is between 1.2 and 3, the RMSE is less than 1.2 %. The horizontal component has a relatively larger error than the vertical



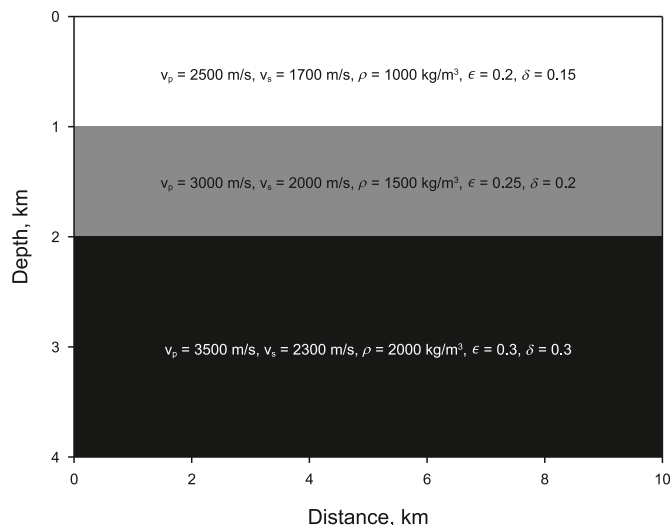


Fig. 9. The non-elliptical VTI layered model.

component. Besides, the variation in  $\epsilon - \delta$  has a slightly greater influence on the accuracy of wavefield separation than  $v_p = v_s$ . However, Fig. 8 indicates that even in strongly anisotropic media, e.g.,  $\epsilon - \delta = 0.3$ , the RMSE is about 2.3%. This suggests that the new method has a high level of accuracy and can be applied to most anisotropic media.

### 3.3. VTI layered model

In this example, we consider the VTI layered model, and the model parameters are shown in Fig. 9. The source is located at (5 km, 0.8 km) and is excited with a P-wave source of a 15-Hz Ricker wavelet. The grid spacing is 10 m in both horizontal and vertical directions.

The horizontal and vertical components of the particle velocity wavefields are shown in Fig. 10. The separated P and S waves are shown in Fig. 11. As can be seen, the leakage is weak. This implies that the proposed method is suitable for the VTI layered model.

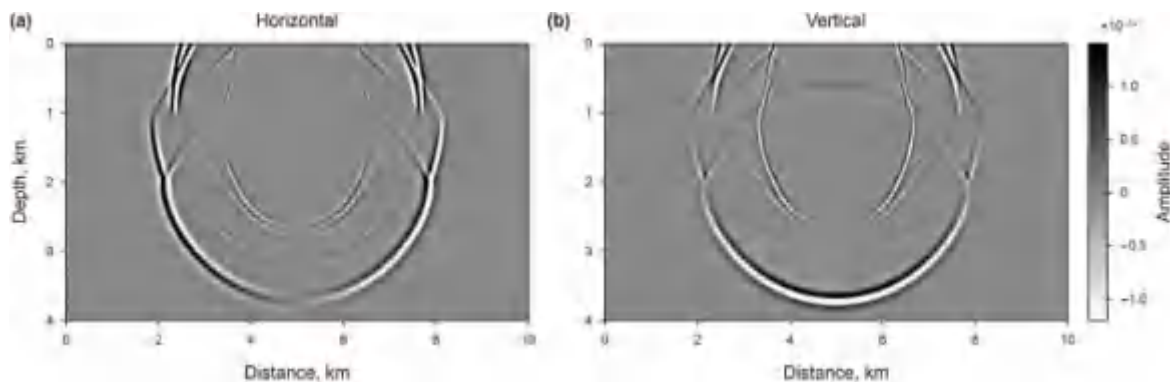


Fig. 10. The horizontal (a) and vertical (b) components of particle velocity for the non-elliptical VTI layer model.

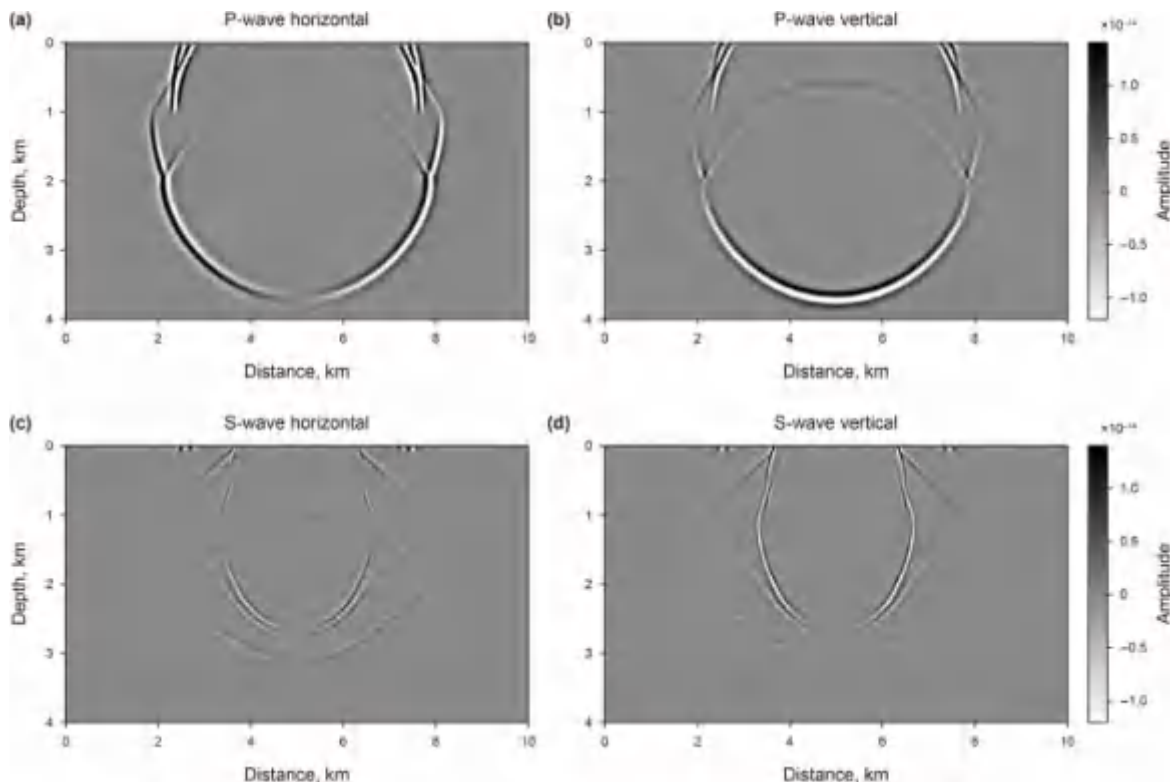


Fig. 11. The separated wavefields for the non-elliptical VTI layer model. Horizontal (a) and vertical (b) components of P-wave. Horizontal (c) and vertical (d) components of S-wave.

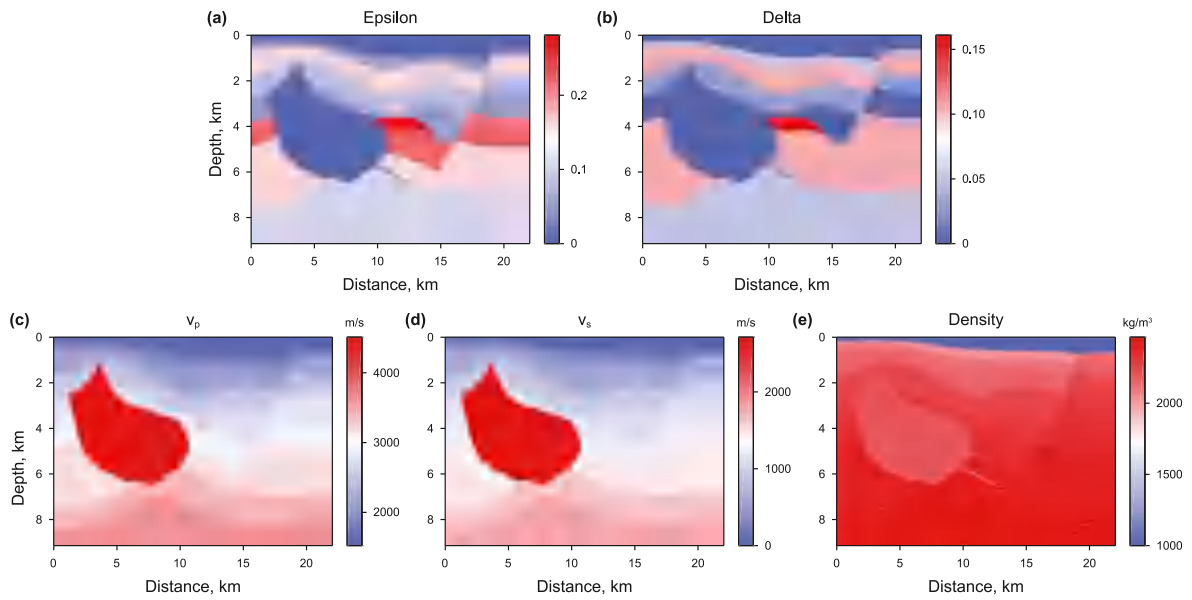


Fig. 12. Hess model parameters.

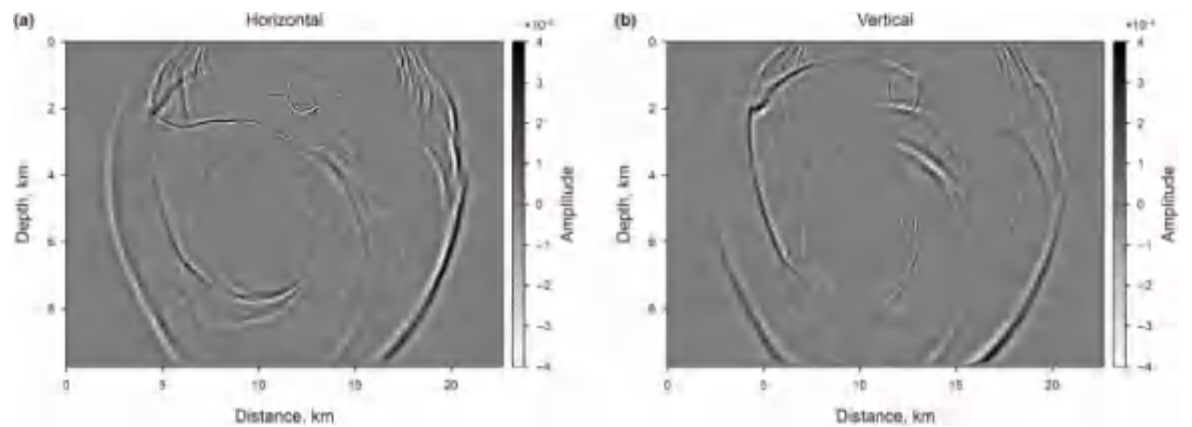


Fig. 13. The horizontal (a) and vertical (b) components of particle velocity wavefields in the Hess model.

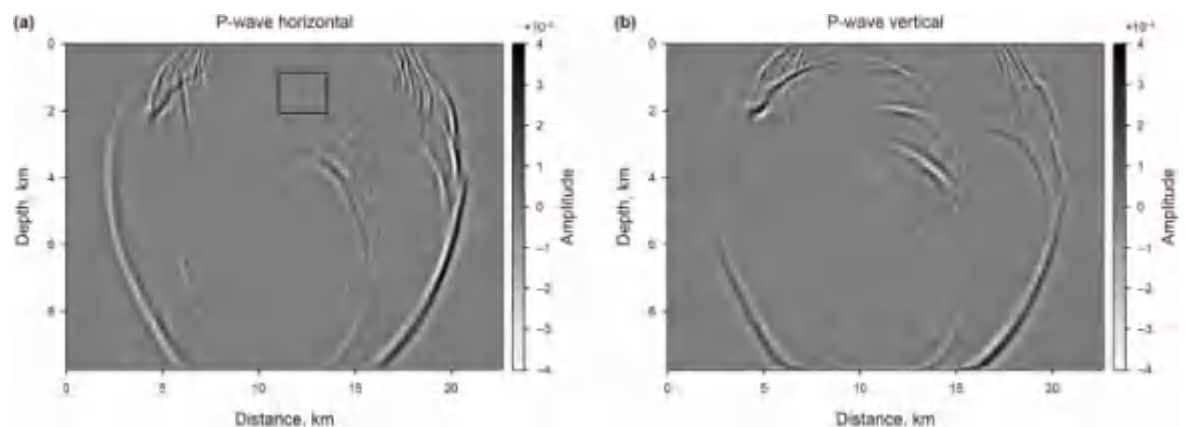


Fig. 14. The horizontal (a) and vertical (b) components of P-wave using the method of [Yang et al. \(2019\)](#).

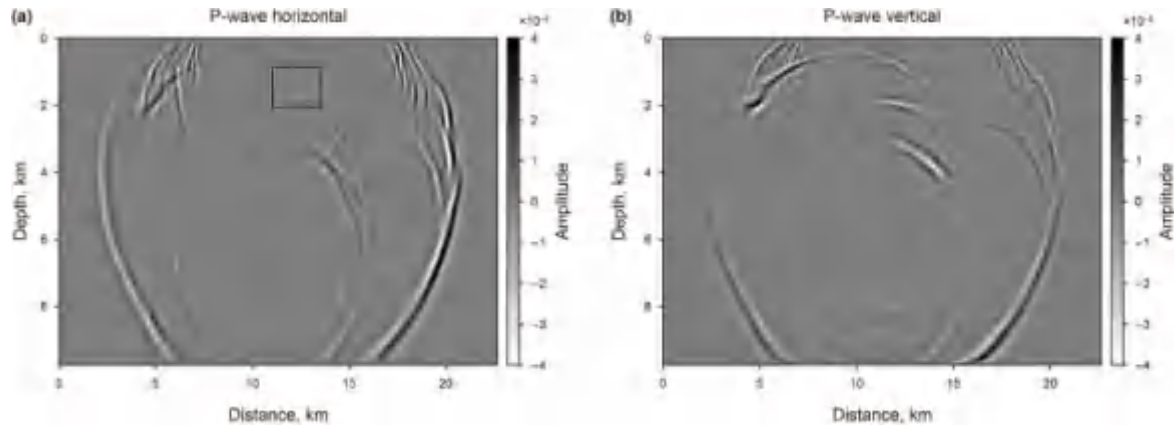


Fig. 15. The horizontal (a) and vertical (b) components of P-wave by using our method.

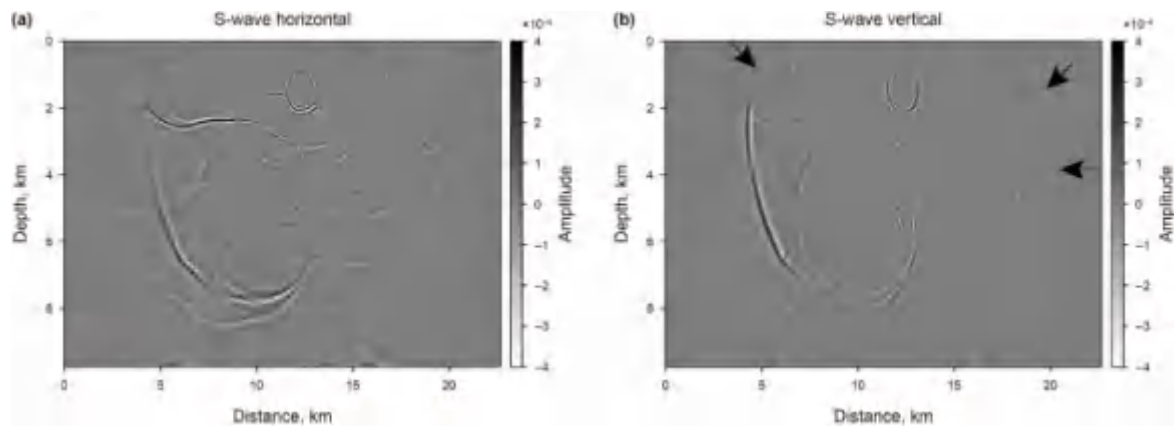


Fig. 16. The horizontal (a) and vertical (b) components of S-wave by using the method of Yang et al. (2019).

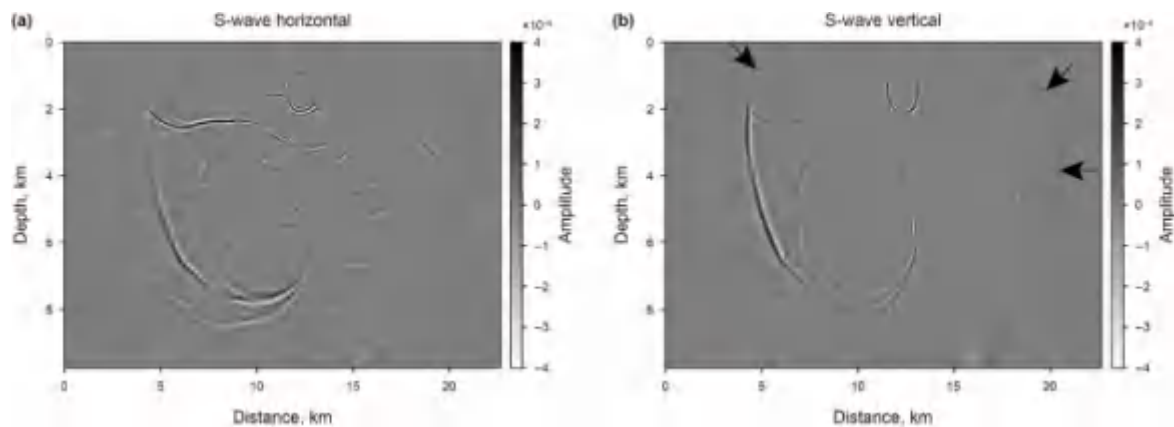


Fig. 17. The horizontal (a) and vertical (b) components of S-wave by using our method.

### 3.4. Hess model

The Hess model is further used to show the effectiveness of the proposed method in heterogeneous media. The model has a grid of  $2205 \times 915$ . The grid interval is 10 m. A 5-Hz Ricker wavelet is used as the vertical body-force source excitation. The source is placed at (12 km, 0.5 km). The input wavefield contains an absorbing

boundary area. The model parameters are shown in Fig. 12(a)e(e).

Fig. 13 shows the horizontal and vertical components of particle velocity wavefields obtained through simulation. As a comparison, we first use the method of Yang et al. (2019) to separate P/S-waves. The results are shown in Fig. 14(a) and (b). As can be seen from Fig. 14(a), there is a faint S-wave residual indicated by the black box in the extracted P-wave. The S-wave residual almost cannot be seen

Table 1  
The CPU times of the proposed method and that of Yang et al. (2019).

| Model             | Time cost of Yang's method | Time cost of the proposed method |
|-------------------|----------------------------|----------------------------------|
| Homogeneous model | 6.22 s                     | 3.13 s                           |
| Layered model     | 6.61 s                     | 3.41 s                           |
| Hess model        | 43.05 s                    | 21.82 s                          |

in the extracted P-wave obtained by the method we proposed (Fig. 15(a)).

Figs. 16 and 17 show the separation results for S-wave. As can be seen, there are P-wave residuals in both S-waves, but Fig. 16(b) has more remnants than Fig. 17(b), which are indicated by the black arrows. The reason why a tiny amount of P-waves remains in S-waves in Figs. 16 and 17 is that these two methods are based on zero-order Taylor expansion to the exact eigenvalues, and therefore the resulting polarization direction is accurate when  $\varepsilon = d$ , and is an approximation when  $\varepsilon \neq d$ . But, in general, the pseudo-Helmholtz decomposition based on zero-order Taylor expansion achieves good wave separation for the Hess model, which is a representative model of the real world. In addition, previous studies have shown that the wavefield separation results obtained by using zero-order Taylor expansion can meet the needs of elastic migration imaging (Yang et al., 2019; Zhang et al., 2022; Zuo et al., 2022). The reason why our method is slightly better than Yang et al. (2019) is that, for 2D problems, Yang's method requires solving two anisotropic Poisson equations when computing the auxiliary vector wavefield, and requires a pseudo-divergence and a pseudo-gradient to obtain the P-wave. In addition, Yang's method requires two pseudo-curl operators to compute the S-wave. Errors will occur when using pseudo-gradient, pseudo-divergence, and pseudo-curl operators for approximating the corresponding exact operators. However, our algorithm only uses one anisotropic Poisson equation to compute the scalar auxiliary function and uses a pseudo-gradient operator to obtain the P-wave. Another reason is that the pseudo-derivative operator proposed by Yang et al. (2019) does not reduce into a derivative operator when the anisotropic parameters are zero. This tends to cause more errors.

To further show the efficiency of the proposed method, we compare the CPU time of the new method with that of Yang et al. (2019) for the homogeneous elliptical anisotropy model, the layered model, and the Hess model in the previous numerical examples. The running time is shown in Table 1. As can be seen, the computational cost of the proposed method is about 1/2 of that of Yang et al. (2019) for 2D problems.

4. Discussion

Zheng and Yao (2023) used the relationships between the gradient, divergence, curl, and exterior derivative operators to construct the isotropic scalar Poisson equation. In this paper, the anisotropic scalar Poisson equation was derived by constructing the pseudo-divergence, pseudo-gradient, and pseudo-curl operators through the polarization directions of P and S waves. The scalar anisotropic Poisson equation is an extension of the scalar isotropic Poisson equation. When the anisotropic parameter is zero, the pseudo-divergence, pseudo-gradient, and pseudo-curl operators reduce to the divergence, gradient, and curl operators in the isotropic media. In this case, the scalar anisotropic Laplace operator reduces to the scalar isotropic Laplace operator.

The scalar isotropic Poisson equation can be solved in the wavenumber domain, but the coefficients of the anisotropic

Poisson equation vary in space, so the equation cannot be solved in the wavenumber domain directly by using FFT. In this paper, we propose to solve the scalar anisotropic Poisson equation in the spatial domain by using SOR iteration with alternating sweeping orderings. Eq. (19) is used to compute the scalar auxiliary function  $f$  without the need to construct a large coefficient matrix, which can significantly reduce the computational cost, as well as implementation complexity, compared with the matrix-based methods, e.g., LU decomposition. In our numerical experiment, the SOR method takes 15 iterations for the homogeneous media. For a more complex model, we can increase the iteration numbers for a more accurate solution of the function  $f$ , for instance, 60 iterations are used for the Hess model study.

5. Conclusion

In this paper, a new scalar anisotropic Poisson equation for pseudo-Helmholtz decomposition is proposed using pseudo-divergence, pseudo-gradient, and pseudo-curl operators. The vector P and S waves are decomposed by solving the scalar anisotropic Poisson equation. Thus, compared with the existing approaches based on solving the vector anisotropic Poisson equation, the proposed method saves the computational cost by half for 2D problems, respectively. The resulting separated P and S waves keep the correct amplitude and phase. The numerical experiments demonstrate the effectiveness of the methods we proposed. Especially, the Hess model shows that the pseudo-Helmholtz decomposition based zero-order Taylor expansion can achieve an effective wave separation, which can basically meet the needs of reverse-time migration imaging. This proposed method can be extended to 3D problems straightforwardly, which saves 2/3 of the cost.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Wavefield decomposition for 3D anisotropic media using scalar anisotropic Poisson operators.

The elastic wave equation in the 3D VTI media is as follows:

$$\begin{cases} r \frac{v^2 u_x}{v t^2} = \left( c_{11} \frac{v^2}{v x^2} + c_{66} \frac{v^2}{v y^2} + c_{44} \frac{v^2}{v z^2} \right) u_x + (c_{11} - c_{66}) \frac{v^2 u_y}{v x v y} + (c_{13} + c_{44}) \frac{v^2 u_z}{v x v z} \\ r \frac{v^2 u_y}{v t^2} = (c_{11} - c_{66}) \frac{v^2 u_x}{v x v y} + \left( c_{66} \frac{v^2}{v x^2} + c_{11} \frac{v^2}{v y^2} + c_{44} \frac{v^2}{v z^2} \right) u_y + (c_{13} + c_{44}) \frac{v^2 u_z}{v y v z} \\ r \frac{v^2 u_z}{v t^2} = (c_{13} + c_{44}) \frac{v^2 u_x}{v x v z} + (c_{13} + c_{44}) \frac{v^2 u_y}{v y v z} + \left( c_{44} \frac{v^2}{v x^2} + c_{44} \frac{v^2}{v y^2} + c_{33} \frac{v^2}{v z^2} \right) u_z \end{cases} \quad (\text{A.1})$$

where  $u_x, u_y, u_z$  are two horizontal and one vertical components of the displacements in Cartesian coordinates, respectively. They are functions of time and space.  $c_{11}, c_{13}, c_{33}, c_{44}$  and  $c_{66}$  are the elements of the elastic coefficient matrix, and  $r$  represents density. They are functions of space. Under the assumption of local homogeneity, the elastic coefficient matrix elements can be represented by Thomsen parameters (Thomsen, 1986):

$$\begin{aligned} c_{11} &= r(1 + 2\varepsilon)v_p^2; c_{33} = r v_p^2 \\ c_{44} &= c_{55} = r v_s^2; c_{66} = r(1 + 2g)v_s^2 \\ c_{13} &= r \sqrt{[(1 + 2d)v_p^2 - v_s^2][v_p^2 - v_s^2]} - r v_s^2 \end{aligned} \quad (\text{A.2})$$

where  $\varepsilon, d$  and  $g$  are the Thomsen anisotropy parameters,  $v_p$  and  $v_s$  denote the P-wave and S-wave velocities along the axis of symmetry, respectively.

Like the 2D media, the polarization directions of the P and S waves can be obtained by using the Christoffel equation. See Zu et al. (2022) for more details. For a 3D problem, we can define the pseudo-gradient operator with the polarization direction of the P-wave by

$$\nabla = \begin{bmatrix} v_x \\ v_y \\ r(x)v_z \end{bmatrix} \quad (\text{A.3})$$

where  $r(x)$  is defined in Eq. (8). Then, the P- and S-wavefield decomposition equations for 3D anisotropic media are

$$u^p = \nabla f; \quad u^s = u - u^p \quad (\text{A.4})$$

Here the scalar auxiliary function  $f$  satisfies the following anisotropic Poisson equation:

$$\frac{v^2 f(x)}{v x^2} + \frac{v^2 f(x)}{v y^2} + r^2(x) \frac{v^2 f(x)}{v z^2} = \nabla \cdot \nabla u(x) \quad (\text{A.5})$$

By denoting

$$b(x) = r^2(x); \quad w(x) = \nabla \cdot \nabla u(x) \quad (\text{A.6})$$

Eq. (A.5) then can be expressed as

$$\frac{v^2 f(x)}{v x^2} + \frac{v^2 f(x)}{v y^2} + b(x) \frac{v^2 f(x)}{v z^2} = w(x) \quad (\text{A.7})$$

Similarly, the 3D anisotropic Poisson equation (Eq. (A.7)) can also be solved using SOR iterative with alternating sweeping orderings. When  $i = 1:L; l = 1:L; j = 1:J$ , SOR iteration format is as

follows, and iteration formats under other sequential iterations can also be analogized:

$$\begin{aligned} f_{i,l,j}^{(k+1)} &= \frac{b}{c_0 \left( \frac{1}{D_x^2} + \frac{1}{D_y^2} + \frac{b_{i,l,j}}{D_z^2} \right)} \left( w_{i,l,j} - \frac{1}{D_x^2} \sum_{n=1}^3 c_n \left( f_{i+n,l,j}^{(k)} + f_{i-n,l,j}^{(k+1)} \right) \right. \\ &\quad \left. - \frac{1}{D_y^2} \sum_{n=1}^3 c_n \left( f_{i,l+n,j}^{(k)} + f_{i,l-n,j}^{(k+1)} \right) \right. \\ &\quad \left. - \frac{b_{i,l,j}}{D_z^2} \sum_{n=1}^3 c_n \left( f_{i,l,j+n}^{(k)} + f_{i,l,j-n}^{(k+1)} \right) \right) \\ &\quad + (1-b)f_{i,l,j}^{(k)} \end{aligned} \quad (\text{A.8})$$

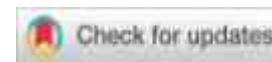
Based on Eqs. (A.1)–(A.8), the wavefield decomposition method based on the proposed scalar anisotropic Poisson equation for 3D VTI media is briefly discussed in this section. The existing 3D anisotropic wavefield decomposition method proposed by Zu et al. (2022) requires solving the anisotropic Poisson equation three times, whereas our method only requires solving it once. In theory, our method can potentially reduce the computational workload by 2/3 compared to the existing approaches.

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# Least-squares reverse time migration of simultaneous sources with deep-learning-based denoising

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## ABSTRACT

Least-squares reverse time migration (LSRTM) is currently one of the most advanced migration imaging techniques in the field of geophysics. It uses least-squares inversion to fit the observed data, resulting in high-resolution imaging results with more accurate amplitudes and better illumination compensation than conventional reverse time migration (RTM). However, noise in the observed data and the Born approximation forward operator can result in high-wavenumber artifacts in the final imaging results. Moreover, iteratively solving LSRTM leads to one or two orders of computational cost higher than conventional RTM, making it challenging to apply extensively in industrial applications. Simultaneous source acquisition technology can reduce the computational cost of LSRTM by reducing the number of wavefield simulations. However, this technique also can cause

high-wavenumber crosstalk artifacts in the migration results. To effectively remove the high-wavenumber artifacts caused by these issues, simultaneous source and deep learning are combined to speed up LSRTM as well as suppress high-wavenumber artifacts. A deep residual neural network (DR-Unet) is trained with synthetic samples, which are generated by adding field noise to synthesized noise-free migration images. Then, the trained DR-Unet is applied on the gradient of LSRTM to remove high-wavenumber artifacts in each iteration. Compared to directly applying DR-Unet denoising to LSRTM results, embedding DR-Unet denoising into the inversion process can better preserve weak reflectors and improve denoising effects. Finally, the proposed LSRTM method is tested on two synthetic data sets and a land data set. The tests demonstrate that the proposed method can effectively remove high-wavenumber artifacts, improve imaging results, and accelerate convergence speed.

## INTRODUCTION

Migration is an essential technique for imaging subsurface structures using surface-observed data. Reverse time migration (RTM) (Baysal et al., 1983; McMechan, 1983; Whitmore, 1983) is one of the most popular migration methods. It simulates the wavefield propagation process in the subsurface by solving two-way wave equations. Thus, RTM can effectively image complex structures, including strata with steep dip angles (Xu et al., 2011; Shi et al., 2019; Tan et al., 2023). However, in cases for which observed data are

incomplete or sparse, RTM imaging with an optimal migration velocity model may still exhibit migration artifacts (Zhang and Sun, 2009). This issue primarily stems from the fact that RTM uses the adjoint operator of the forward operator rather than the inverse operator.

To solve this issue, least-squares reverse time migration (LSRTM) obtains the approximate inverse operator of the forward operator by fitting predicted data and observed data in a least-squares sense (Dai and Schuster, 2013; Liu, 2013; Yao and Wu, 2015; Zhang et al., 2015; Yao and Jakubowicz, 2016; Yang et al., 2019). Thanks to the application of least-squares inversion, LSRTM has the advantages

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of more accurate amplitude, higher resolution, less noise, and more robust data adaptability than RTM. However, each iteration of LSRTM based on the local optimization algorithm requires at least three wavefield simulations, resulting in a large amount of computational cost. Consequently, it is challenging to apply LSRTM in the industry extensively. The simultaneous source acquisition technology can generate multiple shots at the same time, which can reduce the acquisition cost and time significantly, as well as the computational cost of LSRTM significantly (Beasley, 2008; Hampson et al., 2008). However, interference between adjacent sources generates many crosstalk artifacts, which are a type of high-wavenumber artifact (Herrmann and Li, 2012; Li et al., 2012; Dai and Schuster, 2013; Dai et al., 2013; Chen, 2015; Gan et al., 2016; Zhang et al., 2019; Hu et al., 2022).

Furthermore, noise in the observed data and the Born approximation forward operators can result in high-wavenumber artifacts in the final imaging results. Many studies have worked on removing these high-wavenumber artifacts from LSRTM. One of the mainstream approaches at present is to add regularization constraints to the objective function. Chen et al. (2015) and Xue et al. (2016) incorporated the smoothing filter constrained into LSRTM for suppressing crosstalk artifacts caused by simultaneous-source data or migration artifacts caused by incomplete data. Wu et al. (2016) introduced the sparsity constraint of the  $L_1$ -norm into LSRTM to remove high-wavenumber artifacts and extra sidelobes of reflectors. Li et al. (2017) applied sparsity constraints to the inversion model using singular spectrum analysis technology to remove crosstalk artifacts from LSRTM of simultaneous sources (SLSRTM). Li et al. (2020) proposed LSRTM based on  $L_1$ -norm sparsity constraints in the wavelet domain. This helps to preserve reflectivity when removing high-wavenumber artifacts through multiscale and multiangle analysis. Wu et al. (2022a) proposed an LSRTM based on the sparsity constraint in the curvelet domain, which protects the edge information of the image better than the constraints in the wavelet domain. Yao et al. (2022) introduced the Cauchy constraint to LSRTM to mitigate imaging artifacts in the migration results. Although these sparsity constraints can suppress most high-wavenumber artifacts, it is still a challenge to remove those high-wavenumber artifacts that are similar to the signals.

In recent years, owing to the continuous progress in deep learning, there has been a growing utilization of deep-learning techniques in geophysical inversion. To expedite the convergence rate of inversion, researchers have used deep learning to train neural networks for approximating the Hessian matrix and projecting gradients, thereby significantly reducing the number of iterations (Louboutin et al., 2022; Torres and Sacchi, 2022; Wu et al., 2023). In addition to this, deep learning has been successful in seismic data denoising, thanks to the effectiveness of convolutional neural networks in image processing (Liu et al., 2022; Shao et al., 2022). Klochikhina et al. (2020) addressed the data scarcity problem using seismic field data as a training set. Their experiments demonstrated the great power of deep learning to remove migration artifacts. Wu et al. (2022b) assumed migration noise could be simulated using Gaussian and Poisson noise and then constructed data sets by combining synthetic noise with seismic data, achieving good denoising results on seismic field data. Compared with traditional sparsity constraint methods operated in transformed domains, e.g., wavelet and curvelet domains (Xue et al., 2016; Dutta, 2017; Li et al., 2020), deep-learning denoise methods can better remove high-wavenumber artifacts and preserve weak reflectors. Furthermore, once the network is trained, the denoising

process costs negligible computation compared to the sparse-domain denoising process.

In this paper, instead of reducing the number of iterations by training a neural network as an approximation of the Hessian matrix using deep learning, we reduce the computational burden by SLSRTM while applying an Unet-based neural network (Ma et al., 2024) to the gradients of SLSRTM to remove migration noise. The Unet-based neural network uses deep residual (DR) learning to effectively remove migration artifacts and better preserve amplitudes by learning from training samples. Thus, we call our method the deep residual neural network (DR-Unet).

In the rest of the paper, we first review the principles of SLSRTM and analyze the causes of high-wavenumber artifacts in SLSRTM and LSRTM; second, we introduce the algorithm of SLSRTM with DR-Unet denoising. Third, we present the network architecture of DR-Unet and the preparation of the training data set. Afterward, numerical examples are presented to demonstrate the efficiency of this method. Before the conclusion, three related aspects of SLSRTM are discussed.

## METHODOLOGY

### Least-squares reverse time migration of simultaneous sources

With the Born approximation, the predicted record  $\mathbf{d}$  with simultaneous sources can be expressed as

$$\mathbf{d}(\mathbf{x}_r; \omega) = -\omega^2 \sum_i^n \sum_{\mathbf{x}} \mathbf{G}_r(\mathbf{x}_r | \mathbf{x}; \omega) \mathbf{m}(\mathbf{x}) \mathbf{G}_s(\mathbf{x} | \mathbf{x}_i; \omega) \mathbf{s}(\mathbf{x}_i; \omega); \quad (1)$$

where  $\omega$  denotes the angular frequency;  $n$  represents the number of simultaneous sources;  $\mathbf{m}(\mathbf{x})$  represents the reflectivity at point  $\mathbf{x}$ ;  $\mathbf{s}(\mathbf{x}_i; \omega)$  is the seismic source at  $\mathbf{x}_i$ ;  $\mathbf{G}_s(\mathbf{x} | \mathbf{x}_i; \omega)$  is the Green's function from the source point  $\mathbf{x}_i$  to the subsurface scattering point  $\mathbf{x}$ ; and  $\mathbf{G}_r(\mathbf{x}_r | \mathbf{x}; \omega)$  is the Green's function from the underground scattering point  $\mathbf{x}$  to the receiver point  $\mathbf{x}_r$ .

The traditional RTM uses the adjoint operator of equation 1, which can be expressed as

$$\mathbf{m}(\mathbf{x}) = -\sum_{\omega} \sum_i^n \sum_{\mathbf{x}_r} \omega^2 [\mathbf{G}_r(\mathbf{x}_r | \mathbf{x}; \omega) \mathbf{G}_s(\mathbf{x} | \mathbf{x}_i; \omega) \mathbf{s}(\mathbf{x}_i; \omega)]^\dagger \mathbf{d}(\mathbf{x}_r; \omega); \quad (2)$$

where  $\dagger$  denotes the complex conjugate.

However, the adjoint operator used in RTM generates low-quality migration results when the observed data are truncated, incomplete, and noisy. To further improve the imaging quality, the simultaneous-source imaging process can be formulated in the least-squares framework, which is simultaneous-source LSRTM (SLSRTM). The objective function of SLSRTM can be expressed as

$$\phi_s = \frac{1}{2} \|\mathbf{d} - \mathbf{d}_{\text{obs}}\|^2; \quad (3)$$

where  $\mathbf{d}_{\text{obs}}$  represents the simultaneous-source observed data. To simplify the following derivation process, equation 3 also can be expressed in matrix notation as

$$\phi_S = \frac{1}{2} \|\mathbf{L}\mathbf{m} - \mathbf{d}_{\text{obs}}\|^2; \quad (4)$$

where  $\mathbf{L}$  is the forward Born modeling operator of simultaneous sources. Here,  $\mathbf{L}$  and  $\mathbf{d}_{\text{obs}}$  can be further expressed as

$$\mathbf{L} = \sum_i^n \mathbf{L}_i = -\omega^2 \sum_i^n \sum_{\mathbf{x}} \mathbf{G}_r(\mathbf{x}_r | \mathbf{x}; \omega) \mathbf{G}_s(\mathbf{x} | \mathbf{x}_i; \omega) \mathbf{s}(\mathbf{x}_i; \omega) \quad (5)$$

and

$$\mathbf{d}_{\text{obs}} = \sum_i^n \mathbf{d}_{\text{obs}}^i; \quad (6)$$

Traditional LSRTM uses single-source excitation. Its objective function can be expressed as

$$\phi_L = \frac{1}{2} \sum_i^n \|\mathbf{L}_i \mathbf{m} - \mathbf{d}_{\text{obs}}^i\|^2; \quad (7)$$

By differentiating equations 4 and 7 with respect to the reflectivity model  $\mathbf{m}$ , the gradients of SLSRTM and LSRTM can be expressed, respectively, as

$$\frac{\partial \phi_S}{\partial \mathbf{m}} = \sum_j^n \mathbf{L}_j^T \left( \sum_i^n \mathbf{L}_i \mathbf{m} - \sum_i^n \mathbf{d}_{\text{obs}}^i \right) \quad (8)$$

and

$$\frac{\partial \phi_L}{\partial \mathbf{m}} = \sum_i^n \mathbf{L}_i^T (\mathbf{L}_i \mathbf{m} - \mathbf{d}_{\text{obs}}^i); \quad (9)$$

where  $\mathbf{T}$  denotes the conjugate transpose. When  $i \neq j$ , strong crosstalk artifacts appear in the gradient of SLSRTM, mainly due to the crosscorrelation between different sources within the super shot.

To demonstrate crosstalk artifacts and other high-wavenumber artifacts in the gradient, Figure 1 shows the gradient of the first iteration of the Sigsbee2A model using SLSRTM and LSRTM. There are 70 single-source shots for generating the LSRTM gradient, whereas the SLSRTM gradient is generated with 70 super shots, each of which contains three simultaneous sources. The details of the observation system are described in the example section of the Sigsbee2A model. By comparing Figure 1a and 1b, it is clear that the gradient of SLSRTM has many crosstalk artifacts, which are these steep stripes. In addition, the Born approximation is used to construct the forward operator in SLSRTM and LSRTM, so it is impossible to fit multiples and each event's amplitudes in the observed data. This will cause some high-wavenumber artifacts in the gradient, as indicated by the black arrows in Figure 1b.

According to the analysis and the example in Figure 1, one can conclude that the gradient of SLSRTM in equation 8 is neither an ideal gradient nor an ideal model updating direction because of these high-wavenumber artifacts. There are three reasons: first, crosstalk noise generated by simultaneous sources; second, observation data that cannot be fit completely by the Born approximation operator; and third, random or coherent noise in the data. Therefore, it is necessary to transform the raw gradient into a clean gradient that contains only the reflectors' gradient but does not include other

high-wavenumber artifacts. To achieve this goal, we trained a DR-Unet network to clean the raw gradient, which can be expressed as

$$\tilde{\mathbf{g}} = \text{DR\_Unet} \left( \frac{\partial \phi_S}{\partial \mathbf{m}} \right); \quad (10)$$

where  $\tilde{\mathbf{g}}$  represents the clean gradient, and DR\_Unet denotes the process of DR-Unet denoising. Note that other denoising deep-learning networks should be able to serve this purpose as well.

Minimizing  $\phi_S$  is equivalent to solving

$$\mathbf{L}^T \mathbf{d}_{\text{obs}} = \mathbf{L}^T \mathbf{L} \mathbf{m}; \quad (11)$$

where  $\mathbf{L}^T \mathbf{L}$  is a semipositive-definite matrix. Thus, the zero-eigen values cause noise in the result. The noise lies in the null space because the predicted data do not change, at least not significantly, with or without the noise. The process of DR-Unet denoising removes the noise, which intends to change  $\mathbf{L}^T \mathbf{L}$  into a positive-definite matrix. Therefore, the step of equation 10 improves the imaging quality of LSRTM in a mathematical sense.

To avoid the influence of low-wavenumber artifacts on LSRTM, we use inverse scattering imaging conditions to eliminate low-wavenumber artifacts in the gradients of LSRTM (Whitmore and Crawley, 2012; Fang et al., 2018). Finally, the preconditioned nonlinear conjugate gradient method (Shewchuk, 1994) is used to update the reflectivity model iteratively. The detailed algorithm is provided in Algorithm 1,

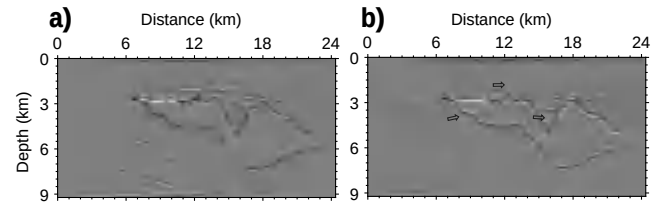


Figure 1. The raw gradient of the first iteration of (a) SLSRTM and (b) LSRTM for the Sigsbee2A model.

#### Algorithm 1: The preconditioned nonlinear conjugate gradient method for SLSRTM.

Input: initial  $\mathbf{m}$ ,  $n_{\text{max}}$

$n = 0, \tilde{\mathbf{g}} = \text{DR\_Unet} \left( \frac{\partial \phi_S}{\partial \mathbf{m}} \right)$

Compute the preconditioner:  $\mathbf{M}$

$\mathbf{r} = -\mathbf{M}^{-1} \tilde{\mathbf{g}}, \mathbf{s} = \mathbf{r}, \delta_{\text{new}} = -\tilde{\mathbf{g}}^T \mathbf{s}$

While  $n < n_{\text{max}}$  do

$\alpha_{\text{opt}} = \arg \min_{\alpha} \phi_S(\mathbf{m} + \alpha \delta \mathbf{m})$ , where

$\delta \mathbf{m}$  is a small perturbation along  $\mathbf{s}$ .

$\mathbf{m} = \mathbf{m} + \alpha_{\text{opt}} \delta \mathbf{m}$

$\tilde{\mathbf{g}} = \text{DR\_Unet} \left( \frac{\partial \phi_S}{\partial \mathbf{m}} \right)$

$\delta_{\text{old}} = \delta_{\text{new}}, \delta_{\text{mid}} = -\tilde{\mathbf{g}}^T \mathbf{r}, \mathbf{r} = -\mathbf{M}^{-1} \tilde{\mathbf{g}}, \delta_{\text{new}} = -\tilde{\mathbf{g}}^T \mathbf{r}$

$\beta = \max((\delta_{\text{new}} - \delta_{\text{mid}}) / \delta_{\text{old}}, 0), \mathbf{s} = \mathbf{r} + \beta \mathbf{s}$

$n = n + 1$

End

for which the preconditioner  $M$  is the stack of the source wavefield energy and the step length  $\alpha_{\text{opt}}$  is computed with a line search.

### DR-Unet denoising

We use our recently proposed DR-Unet to remove the high-wave-number artifacts in the raw gradient. The input of DR-Unet is a noisy seismic image, and the output is a clean seismic image, which are fixed as a size of  $256 \times 256$ . Thus, the raw gradient is divided into patches of size  $256 \times 256$ . The denoised gradient is formed by assembling the patches after denoising. The architecture of DR-Unet is shown in Figure 2. ResNet-18 (He et al., 2016) is used to construct each encoder. ResNets help the gradients of DR-Unet during the training stage flow directly through the skip connections backward from the subsequent layers to the initial layers. This

mechanism mitigates the problem of gradient vanishing when the neural network performs the back-propagation operation.

ResNet-18 consists of several residual blocks. Figure 2b shows the architecture of each residual block. Encoders 1–4 in our denoising network consist of three residual blocks from ResNet-18. The three encoders sequentially down-sample the input seismic image to a size of  $(128, 128)$ ,  $(64, 64)$ ,  $(32, 32)$ , and  $(16, 16)$ . The output of each encoder block is connected to the corresponding decoders through a skip connection. In the decoder part, we use two convolution layers (Figure 2c) to construct decoders 1–4. The kernel size of all the convolution layers in every decoder is  $3 \times 3$ . We use the rectified linear unit (ReLU) activation function to output the denoised seismic image.

To generate sufficient training samples, we synthesize clean seismic images first and then add migration noise from field data to the clean

images to form their labels. The clean seismic images are generated by constructing horizontal reflectivity profiles first and then simulating real geologic structures by introducing folds, as well as faults, and tilting them (Wu et al., 2019). The migration noise of field data is extracted by applying traditional denoising processes to stacked migration images of field data. In this process, the extracted noise should not contain noticeable geologic structural events. As shown in Figure 3, we first divide the extracted noise data into subimages of size  $256 \times 256$ , then multiply the subimages by a coefficient  $\alpha$  to control their amplitude, and finally sum these subimages with synthetic seismic data. There are 10,000 pairs of samples used for training the DR-Unet, of which 8000 pairs are for training and 2000 pairs are for validation. According to our denoising tests, the optimal weight  $\alpha$  is 0.55. Introducing a well-balanced level of noise into clean data helps the training data closely resemble the noisy images generated during the actual migration process. It is worth noting that there is no noise in the synthetic seismic data, so the network can thoroughly learn the noise features. During the application, the input image is

divided into patches in the size of  $256 \times 256$ , and they are glued into the original size after denoising; the normalization and denormalization on the images are applied before and after DR-Unet denoising, respectively. Readers are referred to Ma et al. (2024) for more details on DR-Unet denoising.

## EXAMPLES

### Mamousi2 model

In the first example, we evaluate the effectiveness of the SLRST with DR-Unet denoising using the Mamousi2 model. The simultaneous source seismic data set is generated by solving the two-way acoustic wave equation with the stratigraphic velocity model (Figure 4a). The spatial sampling interval of the velocity model along the horizontal and vertical directions is 6.25 m and 4 m, respectively. The data set contains 48 super shots with three simultaneous sources in each one. The source interval is 3 km in each super shot. Thus, there are 144 single-source shots in total. Each super shot is recorded by 737 receivers with an interval of 12.5 m. The shift between two

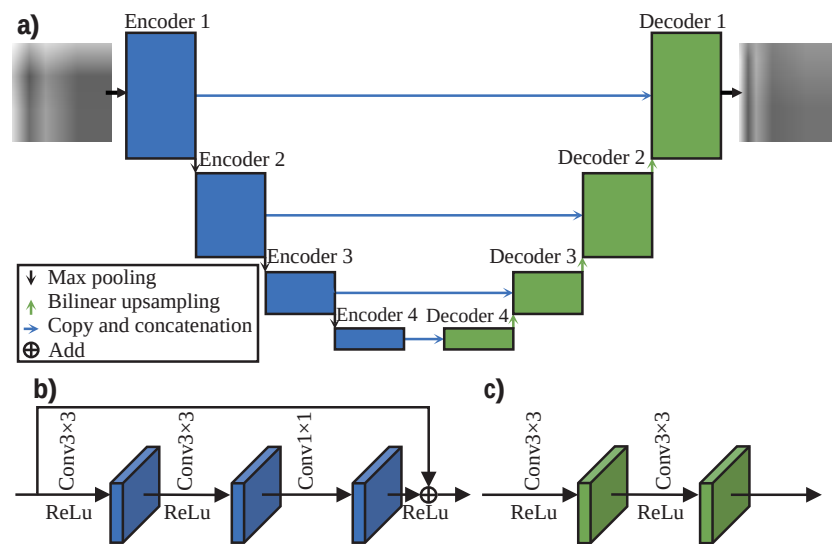


Figure 2. (a) The architecture of DR-Unet consists of an encoder branch and a decoder branch; (b) the architecture of the residual block in each encoder; and (c) the architecture of each decoder includes two convolution layers and a ReLU activation function.

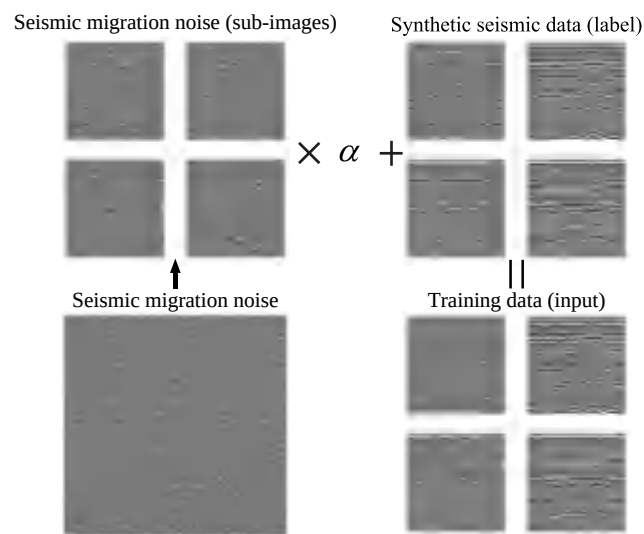


Figure 3. The workflow for generating the training data set.



super shots is 62.5 m. The source is a 30 Hz Ricker wavelet with a sampling interval of 0.4 ms and a recording time of 3.2 s. One super shot is shown in Figure 5. To improve imaging quality, the direct waves of the observed records have been filtered out before migration. The migration velocity model is shown in Figure 4b, which is obtained by smoothing the stratigraphic velocity model.

Figure 6a and 6b shows SRTM results without and with DR-Unet denoising, respectively. It is evident that DR-Unet denoising effectively eliminates high-wavenumber artifacts from the SRTM result. However, there are still some artifacts indicated by the black arrows. In contrast, Figure 6c illustrates the SLSRTM result using the SRTM result (Figure 6a) as the initial reflectivity model. As shown, SLSRTM gives a result with higher resolution and more accurate amplitude than SRTM. However, high-wavenumber artifacts also increase with the number of iterations. To address these issues, DR-Unet denoising is applied to the gradient of SLSRTM to remove the high-wavenumber artifacts. The result is shown in Figure 6d. As

shown, SLSRTM with DR-Unet denoising gives the best result in terms of high resolution and low noise.

Figure 7 shows the gradients at the first and 10th iterations, as well as their respective gradients after DR-Unet denoising. As shown, as iterations progress, the effective information in the gradients gradually decreases. However, crosstalk noise generated by simultaneous sources does not decrease correspondingly, and the DR-Unet network is effective in recognizing and removing this noise. It is worth noting that the training samples for DR-Unet do not contain any information on the Marmousi model or the crosstalk noise. This implies that: first, the trained DR-Unet has a good generalization capacity; second, the crosstalk noise exhibits similar characteristics to those of typical migration noise.

In addition, we also examined the influence of the number and spatial distribution of simultaneous sources on the inversion results. The parameter settings for the eight cases tested are provided in Table 1. The corresponding imaging results are shown in Figure 8. Comparing Figure 8a and 8c, it can be observed that with a fixed number of simultaneous sources, reducing the spatial interval results in less crosstalk noise, as indicated by the white arrows.

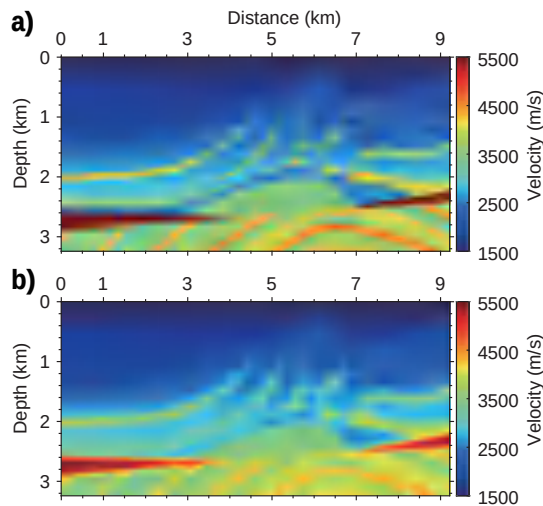


Figure 4. The Marmousi2 model: (a) the true velocity model; (b) the smoothed version of (a). The Seismic Unix command, "smooth2", with the parameter of  $r1 = r2 = 20$ , is used for smoothing.

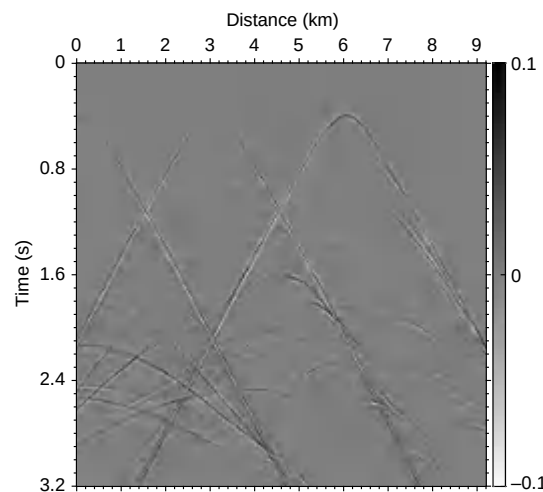


Figure 5. The first super shot gather from the Marmousi2 model.

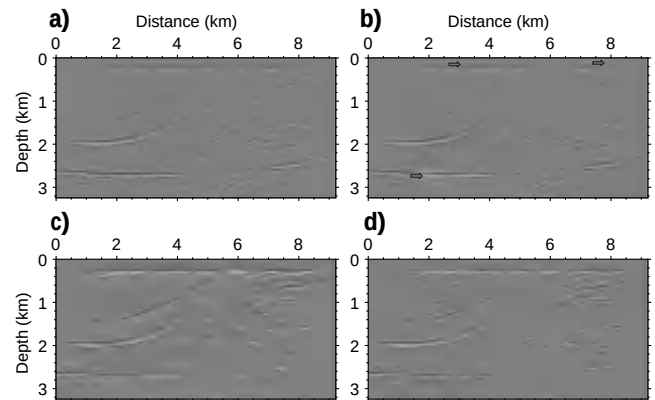


Figure 6. Migration images of Marmousi2: (a) SRTM; (b) SRTM with DR-Unet denoising; (c) SLSRTM; and (d) SLSRTM with DR-Unet denoising. The SLSRTMs have been iterated 10 times. All plots are clipped to the same amplitude range.

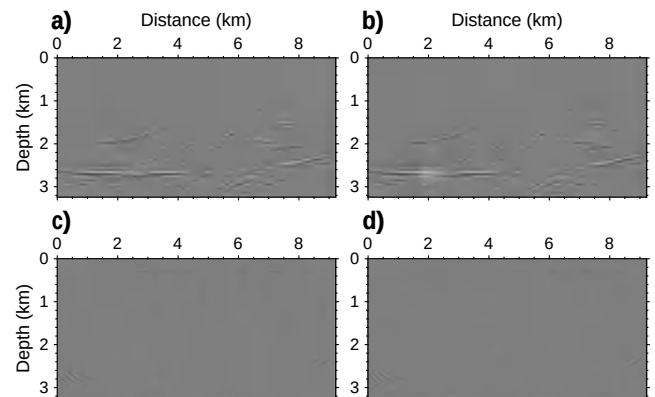


Figure 7. The gradient of SLSRTM for Marmousi2: (a) the gradient at the first iteration; (b) the gradient at the first iteration after DR-Unet denoising; and (c and d) are the counterparts of (a and b) at the 10th iteration, respectively. All plots are clipped to the same amplitude range.

However, imaging quality in complex regions is poorer, as indicated by the black arrows. Contrasting Figure 8a and 8e, it can be seen that increasing the number of simultaneous sources leads to more crosstalk noise and poorer imaging results. In comparison with the SLSRTM results in the left column of Figure 8, SLSRTM with DR-Unet denoising shown in the right column suppresses the migration noise significantly.

In addition, Figure 9 shows the misfit curves for all eight cases. As indicated by Figure 9 and Table 1, SLSRTM with DR-Unet has a better convergence rate than SLSRTM. A comparative analysis reveals that smaller source spacing results in better convergence, primarily because smaller source spacing leads to less variation in the records of different sources within the simultaneous sources. However, less variation also leads to a decrease in the effective information for inversion. Therefore, when the source interval is smaller, the imaging quality is poorer. Furthermore, as the number of sources increases, the inversion converges to a higher value of misfit. However, by comparing the left and right columns in Figure 8, it can be observed that regardless of variations in the number and spatial distribution of sources, SLSRTM with DR-Unet suppresses crosstalk noise significantly. Note that crosstalk and other migration noise stay in the null space, which means that the reduction in data misfit is not as significant as the improvement in imaging quality.

### Sigsbee2A model

In the second example, the Sigsbee2A model was used to further verify the effectiveness of our proposed method. Due to the huge salt body in Sigsbee2A, it is challenging to image the subsalt reflectors. In addition, the strong velocity contrast between the salt body and the sedimentary rocks also can cause significant interbed multiples in the record. These interbed multiples cannot be simulated by the Born forward-modeling operator; therefore, they are eventually converted into high-wavenumber artifacts in the RTM/LSRTM images.

In the test, the observed data set is generated by solving the two-way acoustic wave equation with the true velocity model (Figure 10a). The spatial sampling interval along the horizontal and vertical directions is 11.43 m and 7.62 m, respectively. We generate two data sets. One is the single-source data set, which contains 70 shots with a shot interval of 343 m. The other is the simultaneous-source data set, which contains 70 super shots. Each super shot includes three simultaneous sources with an interval of 8 km. The shift between two consecutive super shots is 114 m. Each simultaneous-source shot and single-source shot are recorded by 1065 receivers with an interval of 22.86 m. The source signature is a 12 Hz Ricker

wavelet with a sampling interval of 1 ms and a recording time of 12 s. Figure 11 shows a super shot gather and a single-source shot gather. The direct waves have been filtered out before migration. The migration velocity shown in Figure 10b is generated by smoothing the stratigraphic velocity model outside the salt body.

Figure 12a and 12b shows the RTM and LSRTM results with the single-source data set, respectively. As shown, LSRTM, after five iterations, gives an image with more accurate amplitude, higher resolution, and better illumination compensation than RTM. However,

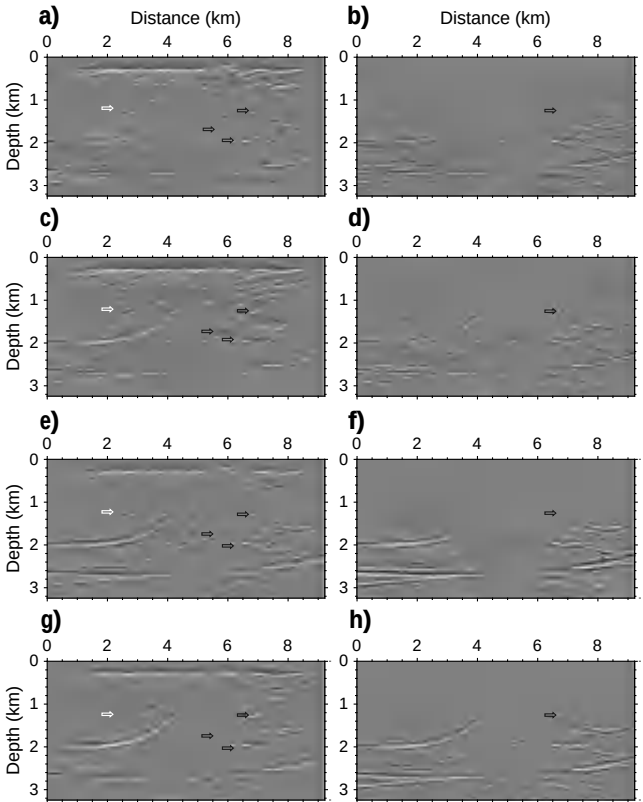


Figure 8. Migration images of Marmousi2: (a–h) correspond to cases 1–8 in Table 1, respectively. All plots are clipped to the same amplitude range. The white arrows indicate a larger simultaneous source interval, which leads to fewer crosstalk artifacts for SLSRTM. However, the imaging quality in complex regions is still poor, as indicated by the black arrows in the left column. SLSRTM with DR-Unet denoising shown in the right column suppresses all the noise significantly.

Table 1. Convergence rate corresponding to different numbers and spatial distributions of simultaneous sources.

|        | Method              | Number | Source interval within simultaneous-source | Convergence rate (%) |
|--------|---------------------|--------|--------------------------------------------|----------------------|
| Case 1 | SLSRTM              | 3      | 62.5 m                                     | 37                   |
| Case 2 | SLSRTM with DR-Unet | 3      | 62.5 m                                     | 32                   |
| Case 3 | SLSRTM              | 3      | 3 km                                       | 42                   |
| Case 4 | SLSRTM with DR-Unet | 3      | 3 km                                       | 36                   |
| Case 5 | SLSRTM              | 5      | 62.5 m                                     | 46                   |
| Case 6 | SLSRTM with DR-Unet | 5      | 62.5 m                                     | 34                   |
| Case 7 | SLSRTM              | 5      | 3 km                                       | 56                   |
| Case 8 | SLSRTM with DR-Unet | 5      | 3 km                                       | 41                   |

because the predicted data with the Born modeling operator cannot fit the observed data entirely, the final image contains some high-wavenumber artifacts, which are indicated by the black arrows in Figure 12b.

Figure 12c and 12d shows the SRTM and SLSRTM results with the simultaneous-source data set, respectively. Due to simultaneous sources, a large amount of crosstalk noise appears in the SRTM result. The crosstalk noise is amplified during the iterative inversion process of SLSRTM. Thus, it is paramount to suppress the crosstalk noise in SLSRTM.

Figure 12e and 12f depicts the results of SRTM and SLSRTM with DR-Unet denoising, respectively. As shown in Figure 12e,

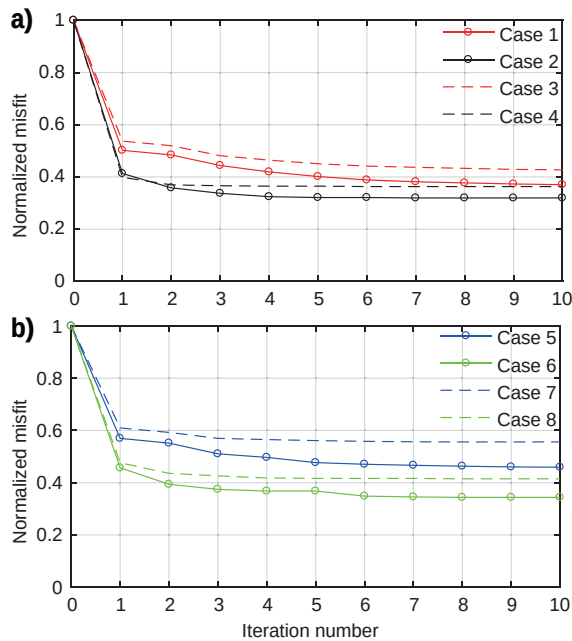


Figure 9. Convergence curves of migration on Marmousi2: (a) Represents the convergence curve for a simultaneous source count of three, whereas (b) represents the convergence curve for a simultaneous source count of five.

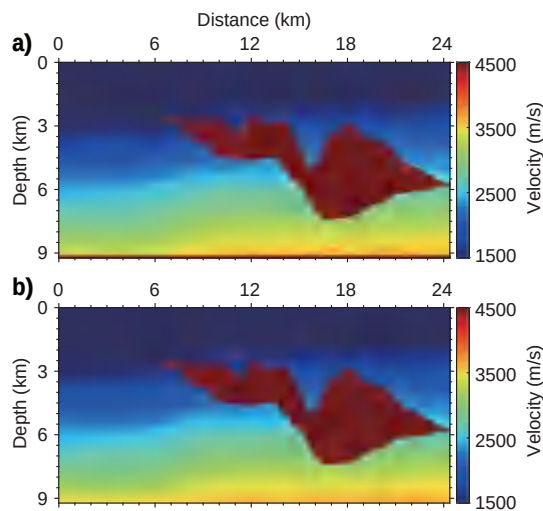


Figure 10. The Sigsbee2A model: (a) the stratigraphic velocity model; and (b) the smoothed version of (a) outside the salt body.

the boundary of the lower part of the salt body indicated by the white arrow is not imaged properly by SRTM with DR-Unet denoising. The amplitude is much weaker than that of the SRTM result in Figure 12c. This implies that directly applying DR-Unet to denoise the SRTM results could remove steep reflectors. In addition, some crosstalk artifacts are not removed, as indicated by the black arrow. In contrast, combining SLSRTM with DR-Unet denoising can suppress high-wavenumber artifacts iteratively and achieve higher-resolution imaging results (Figure 12f). Figure 13 shows an enlarged view of the black box in Figure 12.

## Land data from northwestern China

In the third example, we validated the effectiveness of our method using a land field data set from northwest China. A total of 456

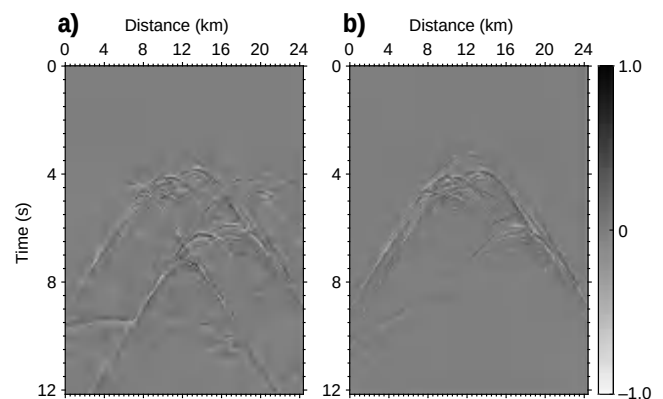


Figure 11. Observed record of Sigsbee2A: (a) a three-simultaneous-source super shot gather; and (b) a single-source shot gather.

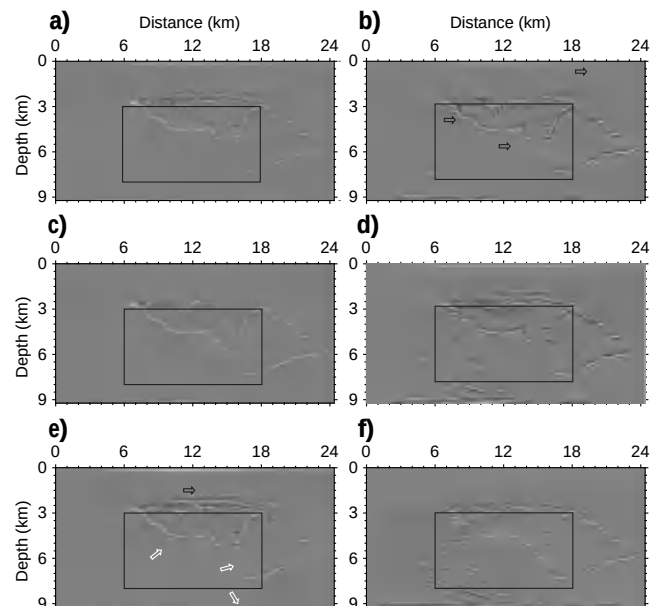


Figure 12. Migration images of Sigsbee2A: (a) RTM image; (b) LSRTM image; (c) SRTM image; (d) SLSRTM image; (e) SRTM image with DR-Unet denoising; and (f) SLSRTM image with DR-Unet denoising. All the LSRTM and SLSRTM contain five iterations. All plots are clipped to the same amplitude range.

receivers are uniformly distributed on the surface with an interval of 50 m. A 12 super shot data set is used for the test. The source interval in a super shot is 4.85 km. The first super shot is shown in Figure 14. The source shift for two consecutive shots is 475 m. For comparison, the test includes other two data sets: 12 single-source shots and 36 single-source shots, which have a shot interval of 1.2 km and 400 m, respectively. Thus, the 12 super shot data set shares the same number of sources as the 36 single-source shot data set. The migration velocity model shown in Figure 15 was obtained through reflection full waveform inversion (Yao and Wu, 2017; Yao et al., 2019).

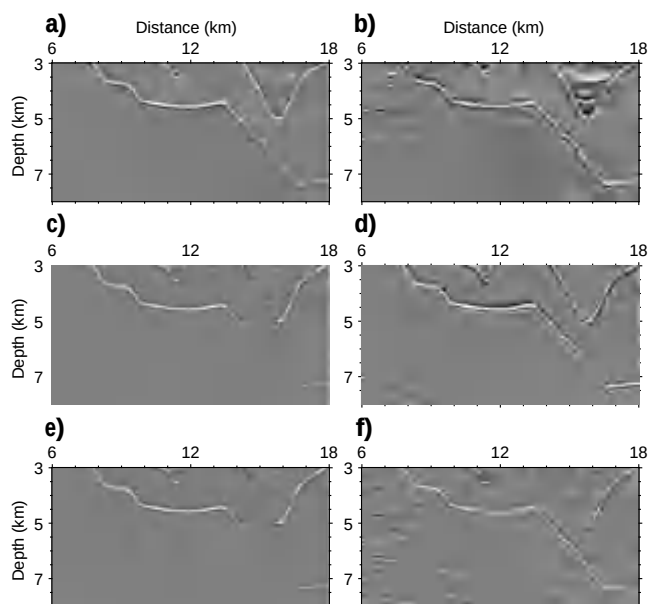


Figure 13. Enlarged view of the migration images. (a–f) corresponds to the black box areas in (a–f) of Figure 12, respectively. All plots are clipped to the same amplitude range.

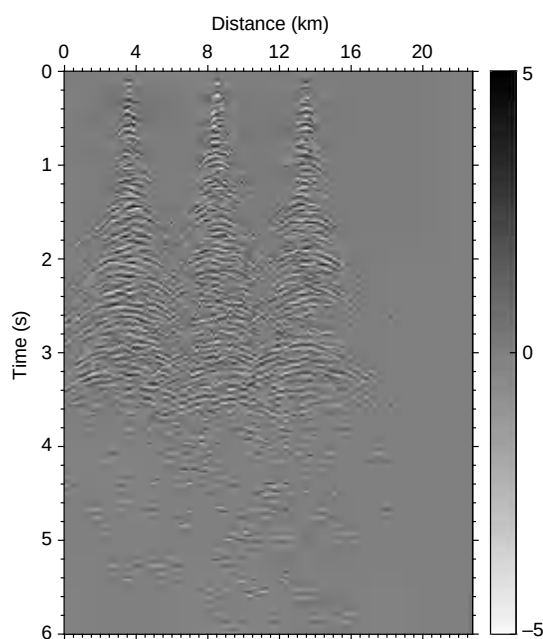


Figure 14. The first super shot gather of the land data.

Figure 16a and 16b depicts the results of RTM for the 12 single-source shots and the 36 single-source shots, respectively. A comparison reveals that insufficient spatial sampling occurs when there are too few sources, making it challenging to effectively stack seismic events, as indicated by the black arrows in Figure 16a. Figure 16c presents the results of LSRTM with the 12 single-source shots, whereas Figure 16d shows the results of SLSRTM with the 12 simultaneous-source shots. A comparison reveals that using the 12 simultaneous-source shots compensates for the issue of insufficient spatial sampling effectively but introduces a significant amount of crosstalk noise. Figure 16e shows the results of LSRTM with the 36 single-source shots, whereas Figure 16f depicts the results of SLSRTM with DR-Net denoising for the 12 simultaneous-source shots. Comparing Figure 16d and 16f highlights that the presented SLSRTM with DR-Net removes crosstalk noise effectively. Moreover, it achieves even better imaging results with just 12 simultaneous-source shots than LSRTM with 36 single-source shots. This means that the SLSRTM method takes one-third of the computation time.

## DISCUSSION

### Comparison of DR-Net denoising and traditional denoising methods

Deep learning can effectively remove certain types of noise by using appropriate training data sets and deep neural networks. Compared with traditional methods, taking the sparsity constraint in the curvelet domain (Candès and Donoho, 2004; Wu et al., 2022a) as an example, deep-learning methods have the following advantages: (1) once the network training is complete, the denoising process has a trivial computational cost, whereas traditional methods still need a significant amount of computation to perform the domain transform and associated computation. (2) Although the sparsity constraint in the curvelet domain protects the edge information better than the sparsity constraint in the wavelet domain, the denoising migration results are still blurred at the edges. In contrast, our tests show that deep-learning methods can avoid the blurring issue, as indicated by the white arrows in Figure 17. (3) Compared with traditional methods, deep-learning methods remove specific noise better than traditional methods, for instance, the steep stripe artifacts. Figure 17a shows the results of SLSRTM with sparsity constraints in the curvelet domain, whereas Figure 17b depicts the results of SLSRTM with DR-Net denoising. As shown, SLSRTM with DR-Net denoising suppresses the high-wavenumber artifacts more effectively than LSRTM with sparsity constraints in the curvelet domain, as indicated by the black arrows. Readers are referred to Ma et al. (2024) for a more detailed comparison of DR-Net denoising

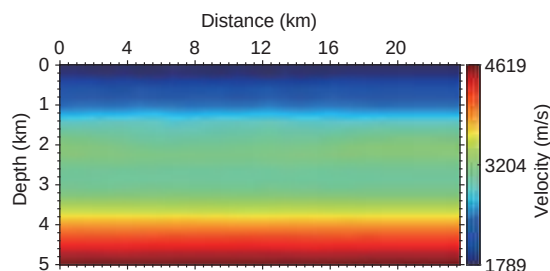


Figure 15. Migration velocity model for the land data.



and curvelet-domain denoising. More results on LSRTM with the curvelet-domain denoising are presented in Wu et al. (2022a).

### Applying DR-Unet denoising on the model versus on the gradient

There are two ways to integrate DR-Unet denoising into SLSRTM. One is to apply it to the reflectivity model,  $\mathbf{m}$ , in each iteration. The other is to perform it on the gradient,  $\partial\phi_S = \partial\mathbf{m}$ , in each iteration. We tested these ways. Figures 18 and 19 show examples of Marmousi2 and Land data. Based on our analysis and the examples, one can conclude that applying DR-Unet denoising to the gradient gives better results in this case. Applying DR-Unet denoising to the reflectivity model leaves more high-wavenumber artifacts in the image, as indicated by the black arrows.

### SLSRTM for in-house blended towed streamer data

Previously, we demonstrated that SLSRTM with DR-Unet is highly effective in suppressing high-wavenumber artifacts for

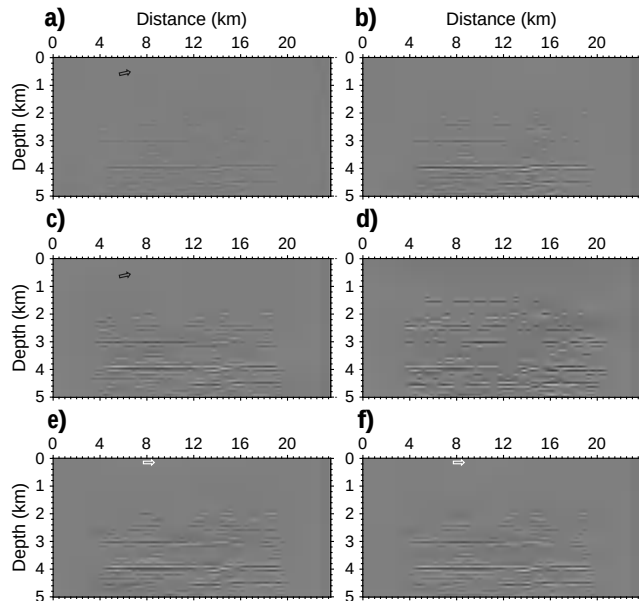


Figure 16. Migration images of the land data: (a) RTM image with 12 single-source shots; (b) RTM image with 36 single-source shots; (c) LSRTM image with 12 single-source shots; (d) SLSRTM image with 12 simultaneous-source shots; (e) LSRTM image with 36 single-source shots; and (f) SLSRTM image with DR-Unet denoising for 12 simultaneous-source shots. All the LSRTM and SLSRTM contain five iterations. All plots are clipped to the same amplitude range.

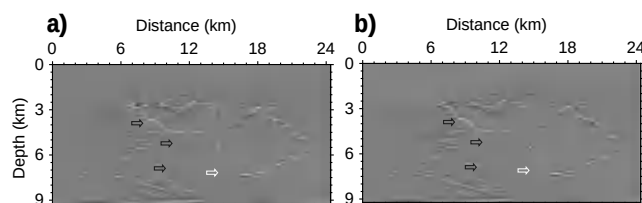


Figure 17. Migration images: (a) SLSRTM image with sparsity constraints in the curvelet domain; and (b) SLSRTM image with DR-Unet denoising.

simultaneous source data, in which multiple sources are fired in each super shot. Thereby, the receiver setting is identical for each single source. There is another scenario: seismic data are acquired with a moving receiver array and a single source in each shot, e.g., the towed streamer acquisition, and then blended in-house before migration (Figure 20). Because the receiver array is moving, the receiver geometry varies from shot to shot. Consequently, the geometry of the predicted data in SLSRTM does not match the geometry of the in-house blended multisource data, which will lead to significantly more arc-shaped artifacts than the simultaneous source data in the SLSRTM image, e.g., Figure 21a versus Figure 6c. Even so, SLSRTM with DR-Unet still achieves a much cleaner image, shown in Figure 21b. However, its quality

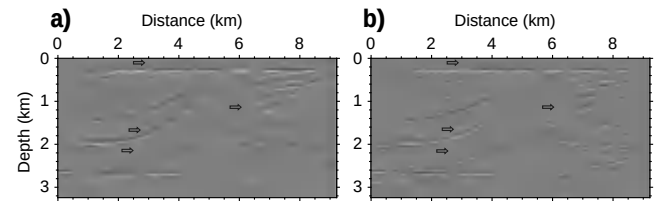


Figure 18. Migration images: (a) SLSRTM image with DR-Unet denoising on the reflectivity model; and (b) SLSRTM with DR-Unet denoising on the gradient.

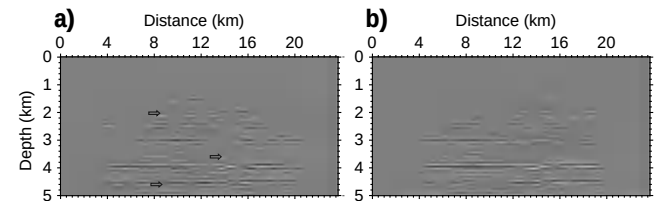


Figure 19. Migration images: (a) SLSRTM with DR-Unet denoising on the reflectivity model; and (b) SLSRTM with DR-Unet denoising on the gradient.

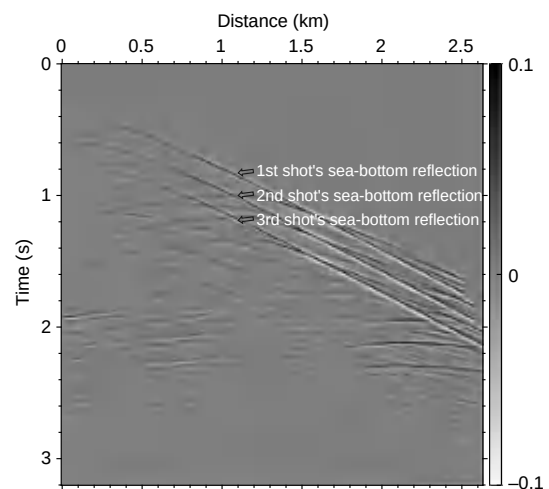


Figure 20. A super shot gather formed by the in-house blending from the Marmousi2 model. Each super shot includes three single-source shots with a sequential delay of 0.2 s. The shot spacing within the super shot is 187.5 m. A total of 49 supergathers are used for SLSRTM.



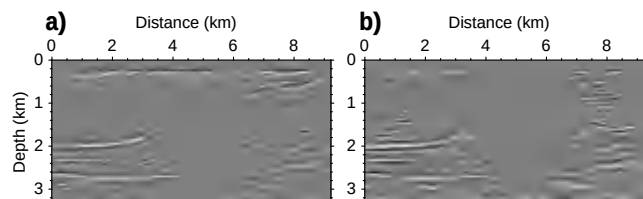


Figure 21. Migration images of the in-house blended seismic data from the Marmousi2 model: (a) SLSRTM; and (b) SLSRTM with DR-Unet denoising. The SLSRTMs have been iterated 10 times.

(Figure 21b) is lower than the image with simultaneous sources (Figure 6d). In addition, the imaging quality is degraded as we increase the blending shot interval. A possible solution is to incorporate a method like the global correlation norm (Choi and Alkhalifah, 2012) into SLSRTM.

## CONCLUSION

The high computational demand for LSRTM is an essential obstacle to its wide industrial application. Reducing the number of wavefield simulations through simultaneous source acquisition can reduce the computational cost of LSRTM significantly, but it also introduces numerous crosstalk artifacts. In addition, LSRTM itself is an ill-posed problem, and the simulated data with the Born approximation are difficult to fit the observed data fully. The two factors lead to high-wavenumber artifacts in the final inversion results. To reduce the computational burden of LSRTM and suppress artifacts, we combine the simultaneous source technique and deep-learning denoising to achieve high-quality migration imaging. A DR-Unet network is trained with synthesized samples. The DR-Unet denoising is applied to remove the high-wavenumber artifacts in the gradient of LSRTM. Synthetic and field data examples demonstrate the good effectiveness of the proposed LSRTM method. Expanding SLSRTM with DR-Unet denoising into 3D models is feasible in theory, although hindered by the significant computational cost.

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## DATA AND MATERIALS AVAILABILITY

Data associated with this research are available and can be obtained by contacting the corresponding author.

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# Pseudo-Helmholtz decomposition for an elastic VTI wavefield based on wavefront phase direction

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## ABSTRACT

P and S waves are coupled when propagating in anisotropic elastic media. The separation of P and S waves helps to study the characteristics of different types of seismic waves as well as mitigating crosstalk artifacts in elastic reverse time migration and elastic full-waveform inversion. At present, the methods of seismic wave mode separation in anisotropic media are mainly built on divergence- and curl-like operations, pseudo-Helmholtz decomposition, and low-rank approximation. We develop a new pseudo-Helmholtz decomposition operator based on eigenform analysis and the wavefront phase direction to decompose vertically transversely isotropic elastic wavefields. The corresponding

P-/S-wave decoupling formulas are also derived in detail. Compared with the divergence- and curl-like methods, the new method does not change the phase of P and S waves. Compared with existing pseudo-Helmholtz decomposition methods based on eigenform analysis, our method achieves more accurate wavefield separation than the zero-order pseudo-Helmholtz decomposition operator. Our method requires solving one vector Poisson equation only, resulting in much less computational cost than the existing first-order pseudo-Helmholtz decomposition methods. In addition, the accuracy of our method is analyzed by providing homogeneous media with different parameter settings. Finally, the numerical examples demonstrate that the new pseudo-Helmholtz decomposition method is effective, efficient, and robust against random noise.

## INTRODUCTION

P and S waves are coupled in the process of elastic wave propagation. Wave mode separation can distinguish different types of waves in complex media, which is conducive to studying the propagation characteristics of different types of waves. Moreover, wave mode separation is a key step in suppressing crosstalk artifacts in elastic reverse time migration (ERTM) (e.g., Sun et al., 2006; Yan and Sava, 2008; Du et al., 2012; Wang and McMechan, 2015) and elastic full-waveform inversion (e.g., Ren and Liu, 2016; Wang and Cheng, 2017).

In isotropic media, the polarization directions of P and S waves are parallel and perpendicular to the direction of wave propagation, respectively. Therefore, the input wavefield can be decomposed using

the divergence and curl operators directly to obtain a scalar P wave and a vector S wave (Dellinger and Etgen, 1990). However, the amplitude and phase of the separated P and S waves are incorrect. To solve this problem, Zhang and McMechan (2010) propose a vector wavefield decomposition method in the wavenumber domain based on Helmholtz decomposition theory, which gives the correct amplitude and phase. They also extend the Helmholtz decomposition theory to vertically transversely isotropic (VTI) media. In contrast, Zhu (2017) also proposes a vector wavefield decomposition method in the spatial domain based on Helmholtz decomposition theory. This method solves a vector Poisson equation with a fast sine transform. The method of Zhu (2017) shares the same fundamental principle as

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the method of Zhang and McMechan (2010), but they are in two different domains. To improve efficiency, Zhao et al. (2018) and Yang et al. (2018) avoid solving the vector Poisson equation by applying a double integral on the source wavelet and a further scaling operation with phase velocities. Inspired by the Zhu (2017) method, Zheng and Yao (2023) propose a wavefield separation method based on the scalar Poisson equation by using the relations among the operations of the gradient, divergence, curl, and external derivative. This method only needs to solve one Poisson equation, which significantly reduces the computational cost compared with the Zhu (2017) method.

In the real world, most of the earth's rocks are anisotropic elastic media. In anisotropic media, P and S waves are neither parallel nor perpendicular to the direction of wave propagation (Tsvankin, 2012). Dellinger and Etgen (1990) present a wavefield separation technique for anisotropic media. They solve the Christoffel equation in the wavenumber domain to obtain the eigenvectors, which indicate the polarization direction of P and S waves for all required wavenumbers. Then, an inverse Fourier transform is applied to form the separation operator in the space domain. However, they only develop this method for homogeneous media. Yan and Sava (2009) propose non-stationary spatial filtering for anisotropic wavefield separation in heterogeneous media. The separation accuracy depends on the length of the local pseudo-derivative operator. The longer the operator is, the higher the accuracy. They present the operator as long as 65. Methods of Dellinger and Etgen (1990) and Yan and Sava (2009) are analog to the divergence and curl operators for the isotropic case. Thus, the phase and amplitude are incorrect.

To obtain the correct amplitude and phase of P and S wavefields, Zhang and McMechan (2010) propose a VTI vector wavefield decomposition method based on the Helmholtz theory and the Christoffel equation in the wavenumber domain. The method was carried out block by block for heterogeneous media. Each block is treated as homogeneous. Cheng and Fomel (2014) use the low-rank approximation to improve the efficiency of separating anisotropic wavefields in the mixed domain, i.e., spatial and wavenumber domains, but it still requires multiple Fourier transforms.

Yang et al. (2019) propose zero- and first-order pseudo-Helmholtz decomposition operators to decompose anisotropic wavefields in the spatial domain based on eigenform analysis, wherein the auxiliary wavefield is obtained by solving the Poisson equation using lower-upper (LU) decomposition. This auxiliary wavefield can also be approximated by applying the first-order Taylor expansion to the reciprocal of the square of the modulus of the pseudo-gradient operator in the mixed domain (Zhang et al., 2022), where one forward fast Fourier transform (FFT) and two inverse FFTs are used for each component at each time step of the 2D case. Zuo et al. (2022) derive the zero-order pseudo-Helmholtz decomposition operator in the 3D case based on eigenform analysis. The zero-order pseudo-Helmholtz decomposition operator can perfectly decompose the P and S waves for an elliptic anisotropic media. However, for non-elliptic anisotropic media, there are noticeable wavefield residuals, especially when  $|\epsilon - \delta|$  is large. Methods based on eigenform analysis solve the Christoffel equation analytically to obtain a mathematical formula for the eigenvectors. In contrast, the separation methods in the previous paragraphs solve the Christoffel equation for the eigenvectors numerically. Therefore, when the model parameter changes, the computation is repeated. One advantage of these numerical methods is that they work for weak and strong anisotropy.

In this paper, we propose a new pseudo-Helmholtz decomposition operator based on the wavefront's phase direction. There are

three advantages of the proposed wavefield decomposition method: first, an approximated anisotropic Poisson equation is derived in the space domain by making use of the phase direction. The accuracy of the proposed anisotropic Poisson equation is higher than that of the first-order pseudo-Helmholtz decomposition based on the assumption of  $k_x^2 = k_z^2$  (Yang et al., 2019). Second, there are no mixed high-order derivatives in the proposed decomposition operator; therefore, it has less computational cost than the existing first-order pseudo-Helmholtz decomposition operators. Third, we consider using the successive over-relaxation (SOR) method with alternating sweeping orderings to solve the anisotropic Poisson equation. This method is matrix-free and uses an iterative solution, which can save computation and memory costs compared with LU decomposition (Davis and Duff, 1997).

The rest of this paper is structured as follows. First, we conduct a review of the Christoffel equation and pseudo-Helmholtz decomposition, predicated upon an analysis of eigenforms. Subsequently, we introduce a fresh first-order pseudo-Helmholtz decomposition approach that leverages the eigenform analysis and the wavefront's phase direction. To validate the effectiveness of the new method, three numerical examples are presented. We end with some conclusions.

## METHODOLOGY

### Eigenvalues and vectors of the Christoffel equation

The 2D elastic VTI wave equation is (Aki and Richards, 2002; Tsvankin, 2012)

$$\begin{cases} \rho(\mathbf{x}) \frac{\partial^2 u_x(\mathbf{x};t)}{\partial t^2} = c_{11}(\mathbf{x}) \frac{\partial^2 u_x(\mathbf{x};t)}{\partial x^2} + c_{55}(\mathbf{x}) \frac{\partial^2 u_x(\mathbf{x};t)}{\partial z^2} + (c_{13}(\mathbf{x}) + c_{55}(\mathbf{x})) \frac{\partial^2 u_z(\mathbf{x};t)}{\partial x \partial z}, \\ \rho(\mathbf{x}) \frac{\partial^2 u_z(\mathbf{x};t)}{\partial t^2} = c_{55}(\mathbf{x}) \frac{\partial^2 u_z(\mathbf{x};t)}{\partial x^2} + c_{33}(\mathbf{x}) \frac{\partial^2 u_z(\mathbf{x};t)}{\partial z^2} + (c_{13}(\mathbf{x}) + c_{55}(\mathbf{x})) \frac{\partial^2 u_x(\mathbf{x};t)}{\partial x \partial z}, \end{cases} \quad (1)$$

where  $u_x(\mathbf{x};t)$  and  $u_z(\mathbf{x};t)$  denote the horizontal and vertical displacements, respectively;  $\mathbf{x}$  represents the Cartesian coordinate;  $\rho(\mathbf{x})$  is the density; and  $c_{11}(\mathbf{x})$ ,  $c_{13}(\mathbf{x})$ ,  $c_{33}(\mathbf{x})$ , and  $c_{55}(\mathbf{x})$  denote the elements of the stiffness matrix for elastic VTI media. They can be expressed by the Thomsen (1986) parameters as follows:

$$\begin{aligned} c_{11} &= \rho(1 + 2\epsilon)V_p^2, & c_{33} &= \rho V_p^2, & c_{55} &= \rho V_s^2; \\ c_{13} &= \rho \sqrt{[(1 + 2\delta)V_p^2 - V_s^2][V_p^2 - V_s^2]} - \rho V_s^2; \end{aligned} \quad (2)$$

where  $V_p$  and  $V_s$  are the P- and S-wave velocities along the symmetrical axes, respectively.

Based on a local homogeneous assumption, Fourier transforms of equation 1 give the following Christoffel equation:

$$\begin{bmatrix} c_{11}k_x^2 + c_{55}k_z^2 - \rho\omega^2 & (c_{13} + c_{55})k_x k_z \\ (c_{13} + c_{55})k_x k_z & c_{55}k_x^2 + c_{33}k_z^2 - \rho\omega^2 \end{bmatrix} \begin{bmatrix} U_x \\ U_z \end{bmatrix} = 0: \quad (3)$$

If denoting

$$\mathbf{A} = \begin{bmatrix} c_{11}k_x^2 + c_{55}k_z^2 & (c_{13} + c_{55})k_x k_z \\ (c_{13} + c_{55})k_x k_z & c_{55}k_x^2 + c_{33}k_z^2 \end{bmatrix}; \quad (4)$$

then  $\lambda = \rho\omega^2 = \rho k^2 v^2$  is the eigenvalue of  $\mathbf{A}$ , where  $k$  denotes the wavenumber and  $v$  represents the phase velocity. The eigenvalues of  $\mathbf{A}$  are

$$\lambda_{1,2} = \rho \frac{[(1+2\varepsilon)V_P^2 + V_S^2]k_x^2 + [V_P^2 + V_S^2]k_z^2}{2} \pm \rho \frac{[(1+2\varepsilon)V_P^2 - V_S^2]k_x^2 + [V_P^2 - V_S^2]k_z^2}{2} \times \sqrt{1 + \frac{8(\delta - \varepsilon)V_P^2(V_P^2 - V_S^2)k_x^2 k_z^2}{[(1+2\varepsilon)V_P^2 - V_S^2]k_x^2 + (V_P^2 - V_S^2)k_z^2}}; \quad (5)$$

and the associated eigenvectors are

$$\begin{cases} \mathbf{V}_1 = \begin{bmatrix} k_x \\ \frac{\rho \sqrt{[(1+2\delta)V_P^2 - V_S^2][V_P^2 - V_S^2]k_x^2 k_z^2}}{\lambda_1 - \rho(V_S^2 k_x^2 + V_P^2 k_z^2)} \\ -\rho \sqrt{[(1+2\delta)V_P^2 - V_S^2][V_P^2 - V_S^2]k_x^2 k_z^2} \\ \lambda_2 - \rho[(1+2\varepsilon)V_P^2 k_x^2 + V_S^2 k_z^2] \end{bmatrix} \\ \mathbf{V}_2 = \begin{bmatrix} -k_x \\ \frac{-\rho \sqrt{[(1+2\delta)V_P^2 - V_S^2][V_P^2 - V_S^2]k_x^2 k_z^2}}{\lambda_2 - \rho[(1+2\varepsilon)V_P^2 k_x^2 + V_S^2 k_z^2]} \\ -k_x \end{bmatrix} \end{cases}; \quad (6)$$

The eigenvectors  $\mathbf{V}_1$  and  $\mathbf{V}_2$  indicate the polarization directions of the P and S waves, respectively (Dellinger and Etgen, 1990). As  $\mathbf{V}_1$  and  $\mathbf{V}_2$  are perpendicular to each other in anisotropic media, the P and S waves can be separated by projecting the vector wavefield, e.g., displacement and particle velocity, to the eigenvector directions.

### Pseudo-Helmholtz decomposition

The anisotropic elastic wavefield  $\mathbf{U}$  in the wavenumber domain can be expressed as

$$\mathbf{U} = \mathbf{U}_0^P + \mathbf{U}_0^S; \quad (7)$$

where  $\mathbf{U} = (U_x; U_z)$  is the wavefield in the wavenumber domain obtained by applying the Fourier transform to  $\mathbf{u} = (u_x; u_z)$ . The terms  $\mathbf{U}_0^P$  and  $\mathbf{U}_0^S$  are the vector P and S wavefields, respectively. Because the pseudo-Helmholtz decomposition gives an approximation of P and S wavefields,  $\mathbf{U}^P$  and  $\mathbf{U}^S$  denote the approximate P and S wavefields produced by the pseudo-Helmholtz decomposition in the rest of the paper.

By applying the first-order Taylor expansion on equation 5 (details are shown in Appendix A), the eigenvector  $\mathbf{V}_1$  becomes  $\mathbf{D}_1$ , which is

$$\mathbf{D}_1 = \begin{bmatrix} k_x \\ rk_z \end{bmatrix}; \quad (8)$$

with

$$\begin{aligned} r &= \frac{r_2}{r_1 + \frac{r_4 k_z^2}{r_1 k_x^2 + r_3 k_z^2}}; \\ r_1 &= (1+2\varepsilon)V_P^2 - V_S^2; \\ r_2 &= \sqrt{[(1+2\delta)V_P^2 - V_S^2][V_P^2 - V_S^2]}; \\ r_3 &= V_P^2 - V_S^2; \\ r_4 &= 2(\delta - \varepsilon)V_P^2(V_P^2 - V_S^2); \end{aligned} \quad (9)$$

By projecting the anisotropic elastic wavefield  $\mathbf{U}$  onto the direction  $\mathbf{D}_1$ , we obtain

$$\begin{cases} \mathbf{D}_1 \cdot \mathbf{U} = \mathbf{D}_1 \cdot \mathbf{U}^P \\ \mathbf{D}_1 \times \mathbf{U}^P = 0 \end{cases} \quad (10)$$

and

$$\begin{cases} \mathbf{D}_1 \times \mathbf{U} = \mathbf{D}_1 \times \mathbf{U}^S \\ \mathbf{D}_1 \cdot \mathbf{U}^S = 0 \end{cases}; \quad (11)$$

According to equations 10 and 11, the pure P wave and pure S wave can be separated using the formula (the details are shown in Appendix B):

$$\begin{cases} \mathbf{U}^P = \mathbf{D}_1 \left( \mathbf{D}_1 \cdot \frac{\mathbf{U}}{|\mathbf{D}_1|^2} \right) \\ \mathbf{U}^S = -\mathbf{D}_1 \times \left( \mathbf{D}_1 \times \frac{\mathbf{U}}{|\mathbf{D}_1|^2} \right) \end{cases}; \quad (12)$$

Then, adding  $i = \sqrt{-1}$  to equation 12 gives

$$\begin{cases} \mathbf{U}^P = i\mathbf{D}_1 (i\mathbf{D}_1 \cdot \mathbf{W}_1) \\ \mathbf{U}^S = -i\mathbf{D}_1 \times (i\mathbf{D}_1 \times \mathbf{W}_1) \\ \mathbf{W}_1 = -\frac{\mathbf{U}}{|\mathbf{D}_1|^2} \end{cases}; \quad (13)$$

Equation 13 is transformed into the spatial domain as follows:

$$\begin{cases} \mathbf{u}^P = \bar{\nabla}(\bar{\nabla} \cdot \mathbf{w}_1) \\ \mathbf{u}^S = -\bar{\nabla} \times (\bar{\nabla} \times \mathbf{w}_1) \end{cases}; \quad (14)$$

where the operator  $\bar{\nabla}$  is

$$\bar{\nabla} = \begin{bmatrix} \partial_x \\ r(\mathbf{x})\partial_z \end{bmatrix}; \quad (15)$$

with

$$\begin{aligned} r(\mathbf{x}) &= \frac{r_2(\mathbf{x})}{r_1(\mathbf{x}) + \frac{r_4(\mathbf{x})\partial_z^2}{r_1(\mathbf{x})\partial_x^2 + r_3(\mathbf{x})\partial_z^2}}; \\ r_1(\mathbf{x}) &= (1+2\varepsilon(\mathbf{x}))V_P^2(\mathbf{x}) - V_S^2(\mathbf{x}); \\ r_2(\mathbf{x}) &= \sqrt{[(1+2\delta(\mathbf{x}))V_P^2(\mathbf{x}) - V_S^2(\mathbf{x})][V_P^2(\mathbf{x}) - V_S^2(\mathbf{x})]}; \\ r_3(\mathbf{x}) &= V_P^2(\mathbf{x}) - V_S^2(\mathbf{x}); \\ r_4(\mathbf{x}) &= 2(\delta(\mathbf{x}) - \varepsilon(\mathbf{x}))V_P^2(\mathbf{x})(V_P^2(\mathbf{x}) - V_S^2(\mathbf{x})); \end{aligned} \quad (16)$$

where  $\partial_x$  and  $\partial_z$  represent the first-order spatial derivatives along the x- and z-directions, respectively, and  $\mathbf{w}_1$  is the auxiliary wavefield that satisfies

$$[\partial_x^2 + r^2(\mathbf{x})\partial_z^2]\mathbf{w}_1(\mathbf{x}) = \mathbf{u}(\mathbf{x}); \quad (17)$$

Equations 14–17 constitute the first-order pseudo-Helmholtz decomposition formulas. By assuming  $\delta = \varepsilon$ , then  $r_4 = 0$ , the first-order pseudo-Helmholtz decomposition is reduced to the zero-order pseudo-Helmholtz decomposition. A similar 3D zero-order pseudo-Helmholtz decomposition method has been proposed by Zuo et al. (2022). By assuming  $\delta = \varepsilon = 0$ , the first-order pseudo-Helmholtz decomposition is further reduced to the Helmholtz decomposition in isotropic media.



### First-order pseudo-Helmholtz decomposition with wavefront's phase direction

The operator,  $r_1(\mathbf{x}) + ((r_4(\mathbf{x})\partial_z^2) = (r_1(\mathbf{x})\partial_x^2 + r_3(\mathbf{x})\partial_z^2))$ , acts in the denominator in equation 17, which leads to implementation difficulty and extra high costs. Yang et al. (2019) solve the Poisson equation 17 approximately by assuming  $k_x = k_z$ . To more accurately solve the Poisson equation 17, we present a new pseudo-Helmholtz decomposition operator based on the phase direction of the wavefront.

In the wavenumber domain, the wavenumber vector  $\mathbf{k} = (k_x; k_z)$  indicates the phase direction of the corresponding plane wave. The unit vector of the phase direction  $\mathbf{n}$  can be computed by

$$\mathbf{n} = (n_x; n_z) = \frac{\mathbf{k}}{|\mathbf{k}|} \quad (18)$$

Then, the operator  $\mathbf{D}_1$  turns into

$$\mathbf{D} = \begin{bmatrix} k_x \\ r'k_z \end{bmatrix}; \quad (19)$$

with

$$r' = \frac{r_2}{r_1 + \frac{r_4 n_z^2}{r_1 n_x^2 + r_3 n_z^2}}; \quad (20)$$

Replacing the operator  $\mathbf{D}_1$  in equations 10–13 with  $\mathbf{D}$ , then transforming them to the spatial domain, gives

$$\begin{cases} \mathbf{u}^P = \nabla'(\nabla' \cdot \mathbf{w}) \\ \mathbf{u}^S = -\nabla' \times (\nabla' \times \mathbf{w}) \end{cases}; \quad (21)$$

where the new pseudo-Helmholtz decomposition operator  $\nabla'$  is

$$\nabla' = \begin{bmatrix} \partial_x \\ r'(\mathbf{x})\partial_z \end{bmatrix}; \quad (22)$$

$$r'(\mathbf{x}) = \frac{r_2(\mathbf{x})}{r_1(\mathbf{x}) + \frac{r_4(\mathbf{x})n_z^2}{r_1(\mathbf{x})n_x^2 + r_3(\mathbf{x})n_z^2}}; \quad (23)$$

and  $\mathbf{w}$  satisfies the following anisotropic Poisson equation:

$$\frac{\partial^2 \mathbf{w}(\mathbf{x}; z)}{\partial x^2} + (r'(\mathbf{x}))^2 \frac{\partial^2 \mathbf{w}(\mathbf{x}; z)}{\partial z^2} = \mathbf{u}(\mathbf{x}; z); \quad (24)$$

Appendix C gives the corresponding derivation and formulas for 3D anisotropic elastic media.

In the spatial domain, the phase direction vector  $\mathbf{n}$  can be replaced by using the local phase direction:

$$\mathbf{n} = (n_x; n_z) = \frac{\nabla \mathbf{u}}{|\nabla \mathbf{u}|}; \quad (25)$$

This approach to computing the phase direction can also be seen in Xu and Zhou (2014) for tilted transversely isotropic acoustic wavefield modeling. A more accurate way to compute the local phase direction is the optical flow (Horn and Schunck, 1981;

Barron and Thacker, 2005; Xie et al., 2022). Where multiple events cross over each other, the computed wavefront phase direction is an average direction, which is inaccurate for each individual event. However, the wavefront phase direction in this paper is mainly used for the higher-order term in the denominator of equation 23. Therefore, even if the higher-order term contains some errors, it has an insignificant impact on the result at the location of the wave crossing. Moreover, the wavefield decomposition is mainly applied in the ERTM, which uses smooth velocity models, and thus, the wave crossings are reduced greatly.

Equations 21–25 form a new first-order pseudo-Helmholtz wavefield decomposition method. Its main cost is to solve the anisotropic Poisson equation 24. This anisotropic Poisson equation can be solved effectively by using SOR iteration with alternating sweeping orderings (Kincaid and Young, 1972; Zhao, 2005). Here, the second-order derivative is calculated using the sixth-order central finite difference.

Denoting

$$\begin{cases} \mathbf{a}(\mathbf{x}) = 1 \\ \mathbf{b}(\mathbf{x}) = (r'(\mathbf{x}))^2 \end{cases}; \quad (26)$$

the SOR iteration formula for equation 24 is as follows:

$$w_{i,j}^{(k+1)} = \beta \frac{u_{i,j} - \frac{a_{i,j}}{\Delta x^2} \sum_{n=1}^3 c_n (w_{i+n,j}^{(k)} + w_{i-n,j}^{(k+1)}) - \frac{b_{i,j}}{\Delta z^2} \sum_{n=1}^3 c_n (w_{i,j+n}^{(k)} + w_{i,j-n}^{(k+1)})}{c_0 \left( \frac{a_{i,j}}{\Delta x^2} + \frac{b_{i,j}}{\Delta z^2} \right)} + (1-\beta)w_{i,j}^{(k)}; \quad (27)$$

where  $u_{i,j}$  is the input wavefield,  $w_{i,j}^{(k)}$  represents the value of the  $k$ th iteration at position  $(i,j)$ ,  $c_n$  represents the finite-difference coefficients, and  $\beta$  is the relaxation factor. The SOR convergence criterion is  $\beta \in (0; 2)$ . Here,  $\beta$  is generally evaluated by trial and error according to numerical effectiveness. In this paper, experimental examples use  $\beta = 1.9$ . To accelerate the convergence, SOR iteration with alternating sweeping orderings sweeps the entire region in the following four orders:

- (i)  $i = 1:I; j = 1:J$ ; (ii)  $i = I:1; j = 1:J$ ;
- (iii)  $i = I:1; j = J:1$ ; (iv)  $i = 1:I; j = J:1$ ; (28)

SOR starts with the sweeping ordering of (i) in the first iteration and then changes to subsequent sweeping orderings in the next three iterations. After every four iterations, SOR restarts the sweeping orderings. The solution obtained from the previous sweeping ordering is taken as the initial value of the next sweeping ordering. The anisotropic Poisson equation 24 is then solved. There is no need to build a large sparse matrix, which can save the computation costs effectively. More details related to SOR iteration and alternating sweeping orderings can be found in Kincaid and Young (1972) and Zhao (2005).

### EXAMPLES

In this section, three numerical experiments are presented to show the effectiveness of the proposed first-order pseudo-Helmholtz decomposition for VTI wavefield separation. The anisotropic Poisson equation 24 is solved by using SOR iteration with alternating sweeping orderings.

### VTI layered model

In the first example, the density of the layered model is  $\rho = 1000 \text{ kg/m}^3$ , and other parameters are shown in Figure 1. The model is discretized using a  $1000 \times 300$  grid with a grid spacing of 10 m. A P-wave source is excited at (distance = 5 km, depth = 0.5 km) using a 15 Hz Ricker wavelet.

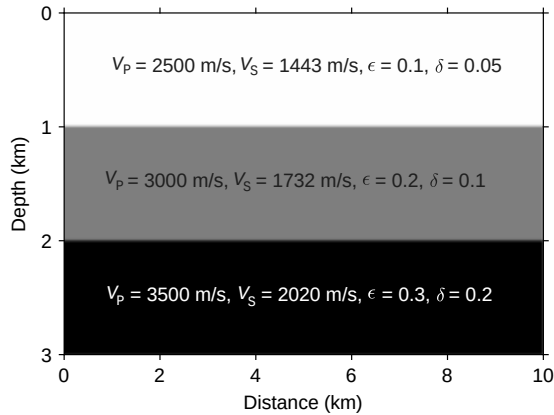


Figure 1. The VTI layered model with its parameters.

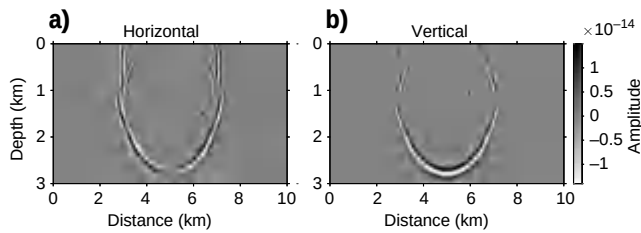


Figure 2. (a) The horizontal and (b) vertical components of the particle velocity wavefields in the VTI layered model at a propagation time of 0.85 s.

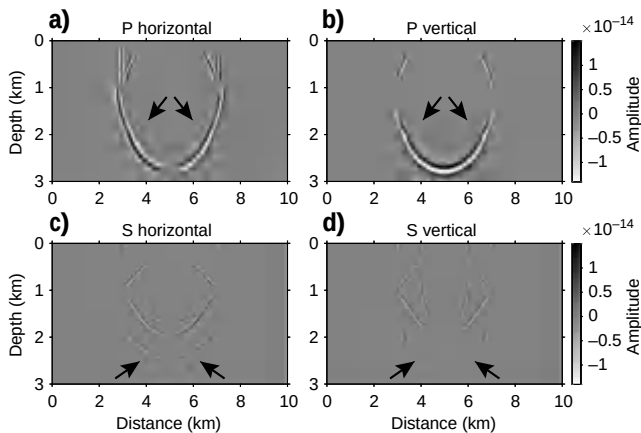


Figure 3. The horizontal and vertical components of the P/S waves in the VTI layered model separated by using the zero-order pseudo-Helmholtz decomposition operator. (a and b) The horizontal and vertical components of the P waves, respectively. (c and d) The counterparts of (a and b) for the S waves, respectively. The black arrows indicate the wave leakages.

The particle velocity wavefields are shown in Figure 2. Figures 3 and 4 depict the P/S waves obtained using the zero-order pseudo-Helmholtz decomposition method presented by Yang et al. (2019) and the first-order pseudo-Helmholtz decomposition method based on the wavefront phase proposed in this paper, respectively. From Figure 3, it can be observed that the P waves obtained using the zero-order pseudo-Helmholtz decomposition method contain residual S waves, and similarly, the S waves also contain residual P waves (as indicated by the black arrows). In contrast, Figure 4 shows that the proposed first-order method has almost no residual wavefield at the same location. Therefore, the proposed method is effective for nonelliptical anisotropic layered models.

### Hess model

In the second example, the Hess model is applied to show the effectiveness of the new pseudo-Helmholtz decomposition method. The model parameters of the Hess model are shown in Figure 5. The

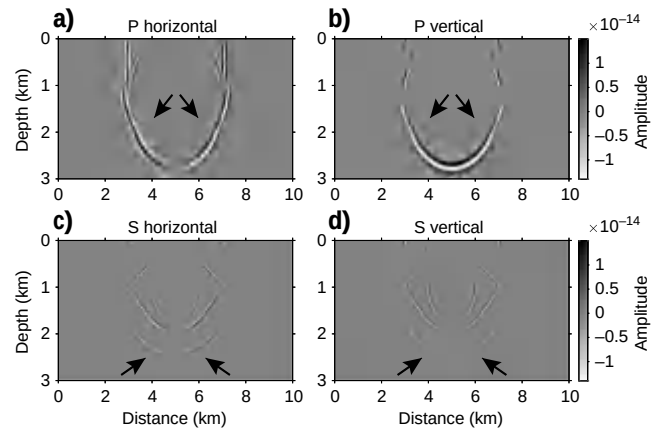


Figure 4. The horizontal and vertical components of the P/S waves in the VTI layered model separated by using the new first-order pseudo-Helmholtz decomposition operator. (a and b) The horizontal and vertical components of the P waves, respectively. (c and d) The counterparts of (a and b) for the S waves, respectively. The black arrows correspond to those in Figure 3.

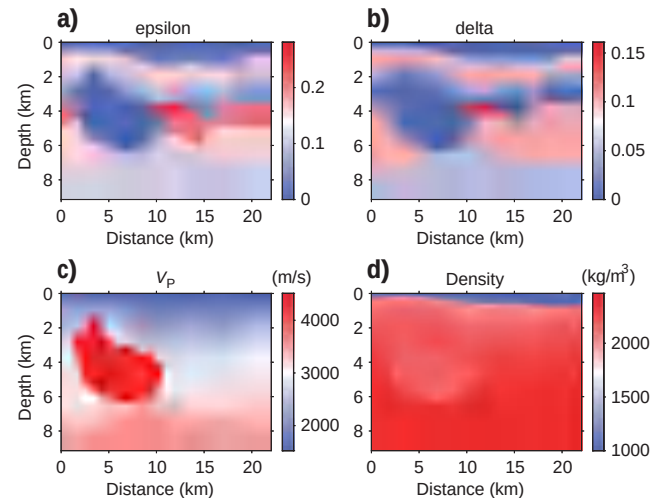


Figure 5. (a–d) The parameters of the Hess model.

S-wave velocity is the P-wave velocity divided by  $\sqrt{3}$ . A P-wave source with a 5 Hz Ricker wavelet is positioned in the center of the surface. The horizontal and vertical components of the VTI wavefield are shown in Figure 6.

Figures 7 and 8 show the horizontal and vertical components of the separated P/S waves obtained using the zero-order pseudo-Helmholtz decomposition method and the new first-order pseudo-Helmholtz decomposition method, respectively. As shown in Figures 7a, 7b, 8a, and 8b, both methods separate the P wave effectively. However, the wiggle display in Figure 9 indicates that the new first-order pseudo-Helmholtz decomposition produces more accurate amplitudes than the zero-order pseudo-Helmholtz decomposition.

The decomposed S-wave results are shown in Figures 7c, 7d, 8c, and 8d. As can be seen, the zero-order pseudo-Helmholtz decomposition method produces discernible P-wave residuals in the S wave, as indicated by the arrows. In contrast, the energy leakage is reduced significantly in Figure 8c and 8d, thanks to the new first-order pseudo-Helmholtz decomposition method.

### Marmousi model

In addition to the Hess model, another general model, Marmousi, is provided here to demonstrate the effectiveness of the method described in this paper. The size and parameters of the Marmousi model are shown in Figure 10. In this model, the S-wave velocity is set as  $V_S = V_P/\sqrt{3}$ . The grid size of the discrete model is 10 m, and the

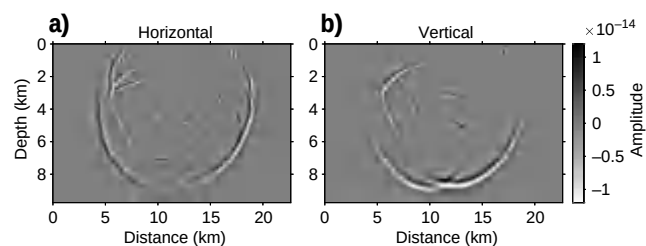


Figure 6. (a) The horizontal and (b) vertical components of the VTI wavefields from the Hess model at a propagation time of 3.6 s.

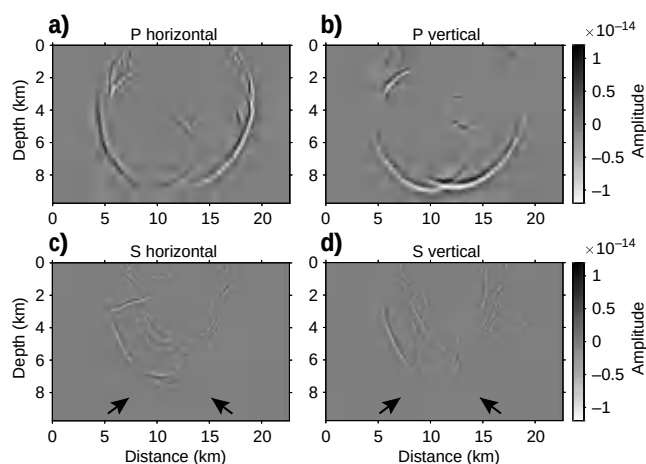


Figure 7. (a) The horizontal and (b) vertical components of the separated P wavefield. (c) The horizontal and (d) vertical components of the separated S wavefield obtained using the zero-order pseudo-Helmholtz decomposition method. The black arrows point to the leaked P-wave energy.

time interval is 1 ms. A 15 Hz Ricker wavelet is used to excite a P-wave source at the middle of the surface. The previous examples have proven that the new method is better than the zero-order pseudo-Helmholtz decomposition method, which shares the same limitation as observed in the Marmousi model. To avoid repetition, this example only displays the decomposition results of the new method.

Figure 11a and 11b shows the particle velocity wavefields of the horizontal and vertical components, respectively. Figure 11c–11f shows the P/S waves of the horizontal and vertical components obtained by using the new method. This method can decompose the P/S waves well. Figure 11g and 11h shows the wavefield residuals by subtracting the decomposed P and S waves from the original wavefields. The error is about two orders of magnitude smaller than

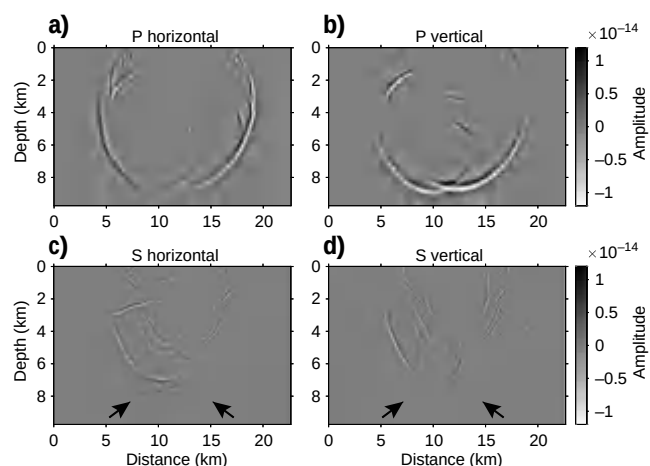


Figure 8. (a) The horizontal and (b) vertical components of the separated P wavefield. (c) The horizontal and (d) vertical components of the separated S wavefield obtained using the new pseudo-Helmholtz decomposition method. The black arrows correspond to those in Figure 7. We see very little leaking P waves at the location indicated by the arrows.

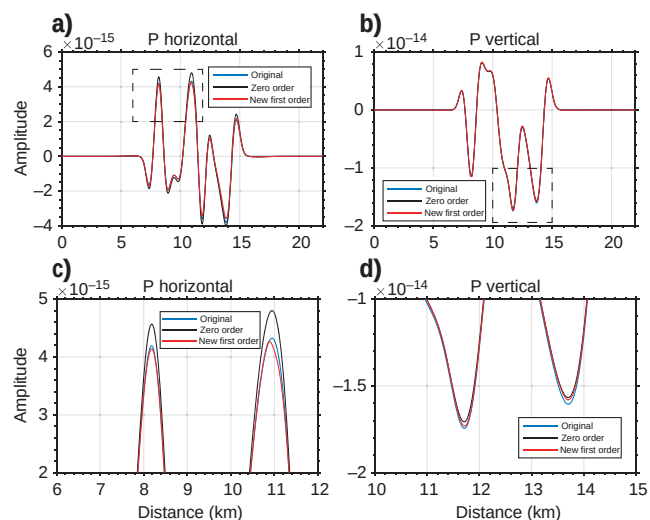


Figure 9. Wiggle display of the (a) horizontal and (b) vertical components of the P waves at a depth of 8.6 km using the zero-order and new pseudo-Helmholtz decomposition methods, respectively. (c) and (d) Enlarged views of the dashed boxes in (a) and (b), respectively.

the original wavefield. Therefore, the new method not only decomposes the anisotropic wavefield effectively but also reconstructs it with high accuracy.

In summary, three examples demonstrate that the new first-order pseudo-Helmholtz decomposition method can achieve a clean P-/S-wave decomposition for elastic VTI wavefields and is also suitable for complex VTI models.

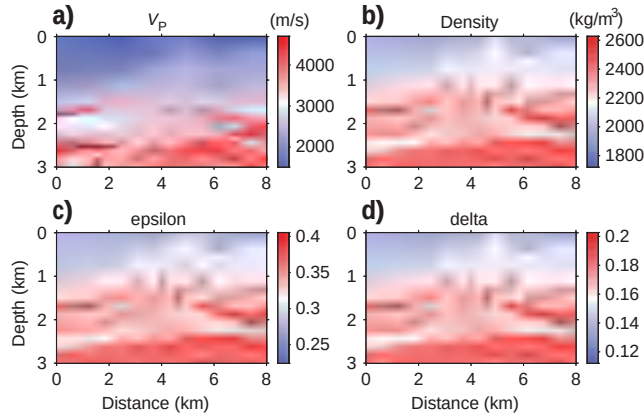


Figure 10. (a–d) The parameters of the Marmousi model.

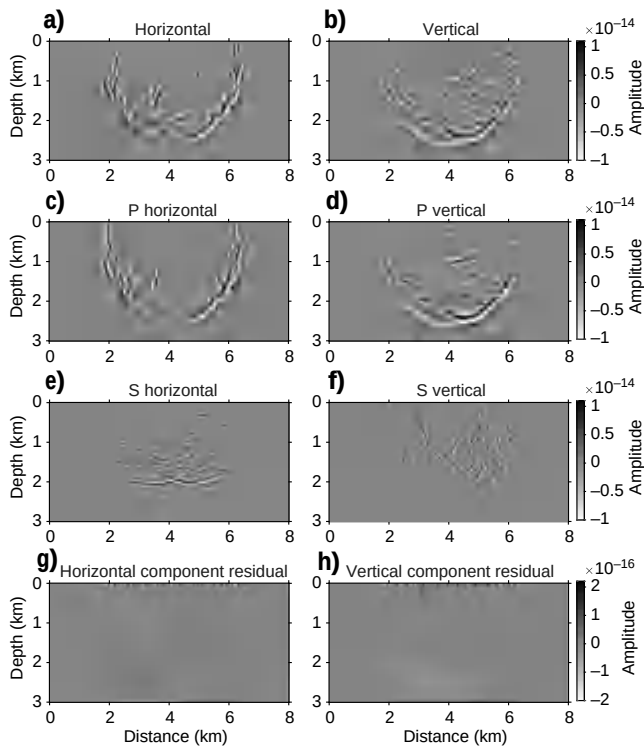


Figure 11. The P-/S-wave separation for the Marmousi model. (a) The horizontal and (b) vertical components of the particle velocity wavefields at a propagation time of 1.1 s. (c and d) The horizontal and vertical components of the P waves, respectively. (e and f) The counterparts of (c and d) for the S waves, respectively. (g and h) The horizontal and vertical components of the wavefield residuals obtained by subtracting the input wavefield from the separated P and S waves, respectively. The residual wavefields are two orders of magnitude smaller than the original wavefields.

## DISCUSSION

### Precision analysis of wavefield decomposition

The three previous examples have demonstrated that the new first-order pseudo-Helmholtz decomposition method is effective and efficient. Here, we carry out a quantitative precision analysis by varying the anisotropic parameter difference, i.e.,  $\epsilon - \delta$ , and the  $V_p=V_s$  ratio for a set of homogeneous models. The method of Zhang and McMechan (2010), which is accurate for homogeneous models, is used to compute the reference results.

The homogeneous models are discretized into a  $600 \times 600$  grid with a spacing of 10 m. A vertical force source of a 15 Hz Ricker wavelet is excited in the center of the model. The wavefield snapshot at 0.6 s was used to analyze the wavefield decomposition accuracy.

Figure 12a shows how the relative errors of P/S waves change with  $\epsilon - \delta$ . The model parameters are  $V_p=V_s = \sqrt{3}$ ,  $V_p = 3000$  m/s,  $V_s = 1732$  m/s,  $\rho = 1000$  kg/m<sup>3</sup>,  $\delta = 0.1$ ,  $\epsilon \in [0.1; 0.4]$ , and  $\epsilon - \delta \in [0; 0.3]$ . The accuracy of this method decreases as the value of  $\epsilon - \delta$  increases. The error is less than 0.5%, when  $\epsilon - \delta = 0.05$ , which is a commonly encountered weakly anisotropic medium in practice. Even for a very strong anisotropic medium,  $\epsilon - \delta = 0.3$ , the error is less than 6%.

Figure 12b shows how the relative errors of P/S waves change with the ratio of  $V_p=V_s$ . The model parameters are  $V_p = 3000$  m/s,  $\rho = 1000$  kg/m<sup>3</sup>,  $\epsilon = 0.3$ ,  $\delta = 0.1$ ,  $V_s \in [1500; 2500]$ , and  $V_p=V_s \in [1.2; 2]$ . As shown in Figure 12b, the accuracy decreases first and then increases as the ratio of  $V_p=V_s$  increases. Note that the test models, i.e.,  $\epsilon = 0.3$ ,  $\delta = 0.1$ , are strongly anisotropic. The errors are much smaller for the commonly encountered weakly anisotropic media. Furthermore, the anisotropy parameter difference, i.e.,  $\epsilon - \delta$ , has a greater effect on the decomposition accuracy than the  $V_p=V_s$  ratio.

### Strongly anisotropic media

The proposed first-order pseudo-Helmholtz decomposition method is derived by taking the first-order Taylor expansion on the eigenvalue of the Christoffel equation around  $\epsilon - \delta$ . The high-order terms are discarded, resulting in errors when  $\epsilon \neq \delta$ . The larger the  $\epsilon - \delta$ , the greater the error. Previous examples and quantitative analyses demonstrate that the new method is quite accurate for a commonly encountered weakly anisotropic medium, e.g.,  $\epsilon - \delta = 0.05$ , and sufficiently accurate for a moderately strong anisotropic medium,

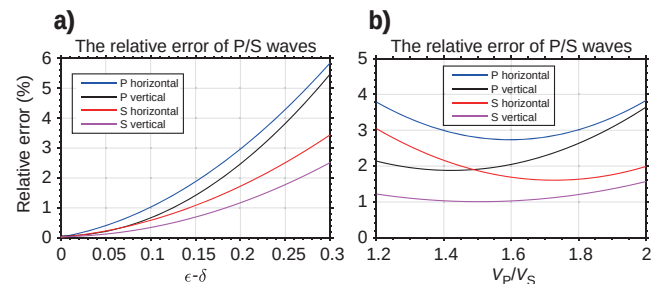


Figure 12. The relative error of the P/S waves obtained by the new method. The method of Zhang and McMechan (2010), which is accurate for homogeneous models, is used to compute the reference results. (a) The relative errors as a function of the difference in anisotropic parameters, i.e.,  $\epsilon - \delta$ . (b) The relative errors as a function of the  $V_p=V_s$  ratio.



e.g., the first-layered model, which has  $\varepsilon = 0.3$  and  $\delta = 0.2$ . To further understand the limits of the new method, we modified the anisotropic parameters of the layered model of the first example into  $\varepsilon = 0.25, 0.3$ , and  $0.4$  and  $\delta = 0.05, 0.1$ , and  $0.15$ , which is strongly anisotropic, i.e.,  $|\varepsilon - \delta| \geq 0.2$  (Thomsen, 1986). Figure 13 shows the decomposed results. As expected, there are some leaks in the P and S waves, but they are insignificant. The residuals plotted in Figure 13g and 13h are two orders of magnitude smaller than the original wavefields. Figure 14 shows one trace of the separated P/S waves and original wavefields at a distance of 7 km. As can be seen, although there are some amplitude differences and leakages in certain locations, overall, this method has good adaptability to strongly anisotropic media. Thus, this example further demonstrates that the new method is robust and should be sufficient for imaging and inversion.

### Effects of noise in P/S-wave decomposition

To illustrate the effectiveness of the new first-order pseudo-Helmholtz decomposition in resisting noise, Gaussian noise is added to the input wavefields of the Marmousi example. The noise-contaminated wavefields have a signal-to-noise ratio of 1.6 for the horizontal component and 1 for the vertical component, as shown in Figure 15a and 15b. The separated P and S waves are shown in Figure 15c–15f. Compared with the noise-free results in Figure 11, we conclude that the new method is quite effective in resisting noise.

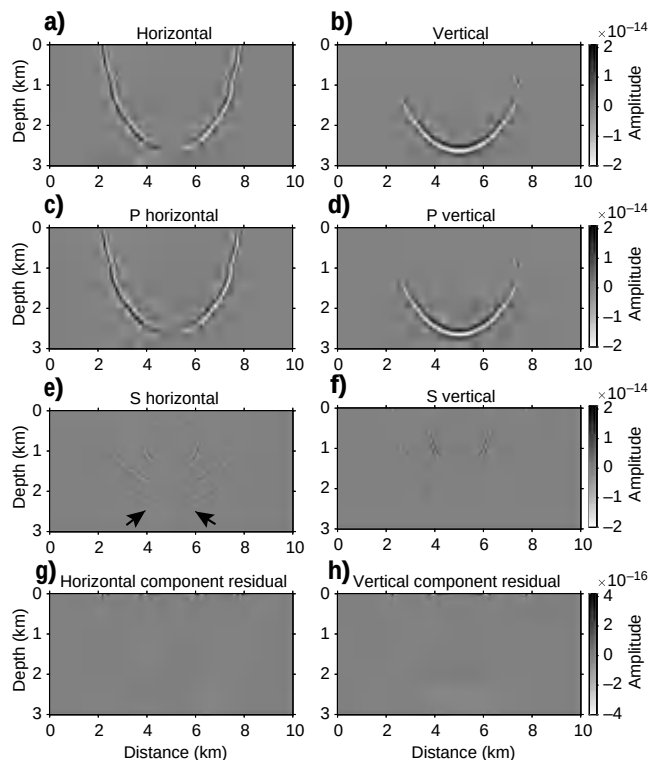


Figure 13. (a) The horizontal and (b) vertical components of particle velocity wavefields in the strongly anisotropic layered model at a propagation time of 1 s. (c and d) The horizontal and vertical components of the P waves, respectively. (e and f) The counterparts of (c and d) for the S waves, respectively. The black arrows indicate the noticeable P-wave leakage. (g and h) The horizontal and vertical components of the wavefield residuals obtained by subtracting the input wavefield from the separated P and S waves, respectively. The residual wavefields are two orders of magnitude smaller than the original wavefields.

### Computational efficiency analysis

The main computational cost of the proposed method lies in solving the Poisson equation 24. There are two Poisson equations for 2D wavefields and three Poisson equations for 3D wavefields. The computational complexity of SOR in equation 27 is  $\alpha \cdot nt \cdot nx \cdot nz$ . Here,  $nx$  and  $nz$  are the dimensions of the wavefield and  $nt$  is the number of iterations. Based on our tests, 20 iterations are sufficient for the simple models, such as the homogeneous models and layered models, and 60 iterations are sufficient for the complex models, e.g., the Marmousi model. The scalar  $\alpha$  depends on the finite-difference order, and it is 28 for the six-order finite difference. The proposed method has a computational cost similar to that of the zero-order pseudo-Helmholtz decomposition method by Yang et al. (2019). However, their first-order method solves six Poisson equations for the 2D wavefields. The low-rank method proposed by Cheng and Fomel (2014) includes a one-time forward Fourier transform and  $r$  times inverse Fourier transforms, resulting in a computational complexity of  $c \cdot (r + 1) \cdot nx \cdot nz \cdot \log(nx \cdot nz)$ . Here, the value of  $c$  depends

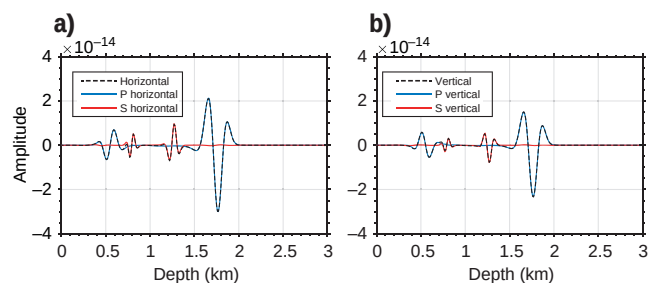


Figure 14. Wiggle display of the (a) horizontal and (b) vertical components of the P and S waves at a distance of 7 km, respectively.

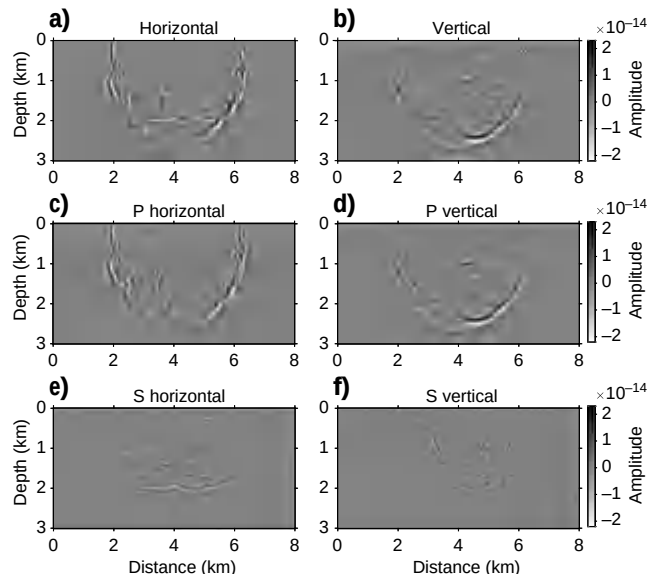


Figure 15. The P/S-wave separation for the Gaussian noise-contaminated wavefields from the Marmousi model. (a) The horizontal and (b) vertical components of the particle velocity wavefields at a propagation time of 1.1 s. (c and d) The horizontal and vertical components of the P waves, respectively. (e and f) The counterparts of (c and d) for the S waves, respectively.



on the specific implementation and hardware; typically, this is eight (Golub and Van Loan, 2013) and  $r$  denotes the reduced rank. Cheng and Fomel (2014) choose  $r = 6$  for the Hess VTI model. The low-rank method also involves the cost of matrix decomposition, which is one to two orders of magnitude higher than Fourier transforms (refer to Tables 1 and 2 in Cheng and Fomel, 2014). To mitigate this cost, they propose precomputing the matrices. Therefore, the proposed pseudo-Helmholtz method achieves a similar level of computational efficiency as the low-rank method when the matrix decomposition is not taken into account.

## CONCLUSION

In this paper, we propose a new pseudo-Helmholtz decomposition method based on the wavefront's phase direction for elastic VTI wavefields. It overcomes the difficulty of implementing the first-order pseudo-Helmholtz decomposition and its associated anisotropic Poisson equation. SOR iteration with alternating sweeping orderings is used to solve the Poisson equation iteratively. It is more efficient than the LU decomposition methods. Compared with the first-order Helmholtz decomposition method, the new pseudo-Helmholtz decomposition method requires much less computational cost, and more importantly, it is easier to implement the new method in the space domain. Compared with the zero-order pseudo-Helmholtz decomposition method, the new pseudo-Helmholtz decomposition method can obtain more accurate P-/S-wave decomposition at a similar computational cost. Although the first-order Taylor approximation is applied in the new pseudo-Helmholtz decomposition method, accuracy analysis and numerical experiments demonstrate that the accuracy is sufficient for normal elastic VTI models.

## ACKNOWLEDGMENTS

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## DATA AND MATERIALS AVAILABILITY

Data associated with this research are available and can be obtained by contacting the corresponding author. None of the authors have a conflict of interest to disclose.

## APPENDIX A

### DERIVATION OF THE EIGENVALUES AND VECTORS OF THE CHRISTOFFEL EQUATION

Based on the Christoffel equation 3, we denote

$$\mathbf{A} = \begin{bmatrix} c_{11}k_x^2 + c_{55}k_z^2 & (c_{13} + c_{55})k_xk_z \\ (c_{13} + c_{55})k_xk_z & c_{55}k_x^2 + c_{33}k_z^2 \end{bmatrix} \quad (\text{A-1})$$

and

$$\mathbf{V} = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}; \quad (\text{A-2})$$

Then,  $\lambda = \rho\omega^2 = \rho k^2 v^2$  ( $v$  is the phase velocity) and  $\mathbf{V}$  are the eigenvalue and eigenvector of the matrix  $\mathbf{A}$ , respectively. According to the eigen analysis theory, we form the following determinant:

$$|\mathbf{A} - \lambda \mathbf{E}| = \begin{vmatrix} c_{11}k_x^2 + c_{55}k_z^2 - \lambda & (c_{13} + c_{55})k_xk_z \\ (c_{13} + c_{55})k_xk_z & c_{55}k_x^2 + c_{33}k_z^2 - \lambda \end{vmatrix} = 0; \quad (\text{A-3})$$

From equation A-3, we obtain a quadratic equation for the variable  $\lambda$ :

$$a\lambda^2 + b\lambda + c = 0; \quad (\text{A-4})$$

where

$$\begin{cases} a = 1 \\ b = -[(c_{11}k_x^2 + c_{55}k_z^2) + (c_{55}k_x^2 + c_{33}k_z^2)] \\ c = (c_{11}k_x^2 + c_{55}k_z^2) \cdot (c_{55}k_x^2 + c_{33}k_z^2) - (c_{13} + c_{55})^2 k_x^2 k_z^2 \end{cases}; \quad (\text{A-5})$$

Then,  $\lambda$  in equation A-4 can be solved by

$$\begin{aligned} \lambda_{1,2} &= \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \\ &= \frac{(c_{11} + c_{55})k_x^2 + (c_{33} + c_{55})k_z^2}{2} \\ &\quad \pm \frac{[(c_{11} - c_{55})k_x^2 + (c_{33} - c_{55})k_z^2]}{2} \\ &\quad \times \sqrt{1 + \frac{4[(c_{11} - c_{55}) \cdot (c_{55} - c_{33}) + (c_{13} + c_{55})^2]k_x^2 k_z^2}{[(c_{11} - c_{55})k_x^2 + (c_{33} - c_{55})k_z^2]^2}}. \end{aligned} \quad (\text{A-6})$$

Note  $c_{11}$ ,  $c_{13}$ ,  $c_{33}$ , and  $c_{55}$  can be replaced with the Thomsen parameters given in equation 2. Therefore,

$$\begin{aligned} \lambda_{1,2} &= \rho \frac{[(1 + 2\varepsilon)V_p^2 + V_s^2]k_x^2 + [V_p^2 + V_s^2]k_z^2}{2} \\ &\quad \pm \rho \frac{[(1 + 2\varepsilon)V_p^2 - V_s^2]k_x^2 + [V_p^2 - V_s^2]k_z^2}{2} \\ &\quad \times \sqrt{1 + \frac{8(\delta - \varepsilon)V_p^2(V_p^2 - V_s^2)k_x^2 k_z^2}{[(1 + 2\varepsilon)V_p^2 - V_s^2]k_x^2 + (V_p^2 - V_s^2)k_z^2]^2}}. \end{aligned} \quad (\text{A-7})$$

Let  $\mathbf{V}_1 = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$ . Then, we obtain

$$\begin{cases} (c_{11}k_x^2 + c_{55}k_z^2)x_1 + (c_{13} + c_{55})k_xk_zx_2 = \lambda x_1 \\ (c_{13} + c_{55})k_xk_zx_1 + (c_{55}k_x^2 + c_{33}k_z^2)x_2 = \lambda x_2 \end{cases}. \quad (\text{A-8})$$

Assuming  $x_1 = k_x$ , the second equation in equation A-8 gives

$$x_2 = \frac{(c_{13} + c_{55})k_x^2 k_z}{\lambda_1 - (c_{55}k_x^2 + c_{33}k_z^2)}; \quad (\text{A-9})$$

Therefore, the eigenvector associated with  $\lambda_1$  can be written as

$$\mathbf{V}_1 = \begin{bmatrix} k_x \\ \frac{(C_{13} + C_{55})k_x^2 k_z}{\lambda_1 - (C_{55}k_x^2 + C_{33}k_z^2)} \end{bmatrix} = \begin{bmatrix} k_x \\ \frac{\rho \sqrt{[(1+2\delta)V_p^2 - V_s^2][V_p^2 - V_s^2]} k_x^2 k_z}{\lambda_1 - \rho(V_s^2 k_x^2 + V_p^2 k_z^2)} \end{bmatrix} \quad (\text{A-10})$$

Similarly, assuming  $x_2 = -k_x$ , the first equation in equation A-8 gives

$$x_1 = \frac{-(C_{13} + C_{55})k_x^2 k_z}{\lambda_2 - (C_{11}k_x^2 + C_{55}k_z^2)} \quad (\text{A-11})$$

Therefore, the eigenvector corresponding to  $\lambda_2$  can be written as

$$\mathbf{V}_2 = \begin{bmatrix} \frac{-(C_{13} + C_{55})k_x^2 k_z}{\lambda_2 - (C_{11}k_x^2 + C_{55}k_z^2)} \\ -k_x \end{bmatrix} = \begin{bmatrix} \frac{-\rho \sqrt{[(1+2\delta)V_p^2 - V_s^2][V_p^2 - V_s^2]} k_x^2 k_z}{\lambda_2 - \rho((1+2\epsilon)V_p^2 k_x^2 + V_s^2 k_z^2)} \\ -k_x \end{bmatrix} \quad (\text{A-12})$$

For the nonelliptic anisotropy problem ( $\epsilon \neq \delta$ ), when  $\epsilon - \delta \rightarrow 0$ , the eigenvalues can be obtained by the first-order Taylor expansion of the radical term of equation A-7:

$$\begin{cases} \lambda_1 = \rho V_p^2 [(1+2\epsilon)k_x^2 + k_z^2] + \rho \frac{2(\delta-\epsilon)V_p^2(V_p^2 - V_s^2)k_x^2 k_z^2}{[(1+2\epsilon)V_p^2 - V_s^2]k_x^2 + (V_p^2 - V_s^2)k_z^2} \\ \lambda_2 = \rho V_s^2 [k_x^2 + k_z^2] - \rho \frac{2(\delta-\epsilon)V_p^2(V_p^2 - V_s^2)k_x^2 k_z^2}{[(1+2\epsilon)V_p^2 - V_s^2]k_x^2 + (V_p^2 - V_s^2)k_z^2} \end{cases} \quad (\text{A-13})$$

Then, the eigenvectors of  $\mathbf{A}$  can be obtained by substituting equation A-13 into equation A-10 and equation A-12:

$$\begin{cases} \mathbf{V}_1 = \begin{bmatrix} k_x \\ \frac{\sqrt{[(1+2\delta)V_p^2 - V_s^2][V_p^2 - V_s^2]}}{[(1+2\epsilon)V_p^2 - V_s^2] + \frac{2(\delta-\epsilon)V_p^2(V_p^2 - V_s^2)k_x^2 k_z^2}{[(1+2\epsilon)V_p^2 - V_s^2]k_x^2 + (V_p^2 - V_s^2)k_z^2}} k_z \end{bmatrix} \\ \mathbf{V}_2 = \begin{bmatrix} \frac{\sqrt{[(1+2\delta)V_p^2 - V_s^2][V_p^2 - V_s^2]}}{[(1+2\epsilon)V_p^2 - V_s^2] + \frac{2(\delta-\epsilon)V_p^2(V_p^2 - V_s^2)k_x^2 k_z^2}{[(1+2\epsilon)V_p^2 - V_s^2]k_x^2 + (V_p^2 - V_s^2)k_z^2}} k_z \\ -k_x \end{bmatrix} \end{cases} \quad (\text{A-14})$$

Physically,  $\lambda_1$  and  $\lambda_2$  represent the phase velocities of the P and S waves, respectively. In addition,  $\mathbf{V}_1$  and  $\mathbf{V}_2$  denote the polarization directions of the P and S waves, respectively. Based on equation A-14, the eigenvectors of the matrix  $\mathbf{A}$  can also be expressed as follows:

$$\begin{cases} \mathbf{V}_1 = \begin{bmatrix} k_x \\ \frac{\sqrt{[(1+2\delta)V_p^2 - V_s^2][V_p^2 - V_s^2]}}{[(1+2\epsilon)V_p^2 - V_s^2] + \frac{2(\delta-\epsilon)V_p^2(V_p^2 - V_s^2)k_x^2 k_z^2}{[(1+2\epsilon)V_p^2 - V_s^2]k_x^2 + (V_p^2 - V_s^2)k_z^2}} k_z \end{bmatrix} = \begin{bmatrix} k_x \\ rk_z \end{bmatrix} \\ \mathbf{V}_2 = \begin{bmatrix} \frac{\sqrt{[(1+2\delta)V_p^2 - V_s^2][V_p^2 - V_s^2]}}{[(1+2\epsilon)V_p^2 - V_s^2] + \frac{2(\delta-\epsilon)V_p^2(V_p^2 - V_s^2)k_x^2 k_z^2}{[(1+2\epsilon)V_p^2 - V_s^2]k_x^2 + (V_p^2 - V_s^2)k_z^2}} k_z \\ -k_x \end{bmatrix} = \begin{bmatrix} rk_z \\ -k_x \end{bmatrix} \end{cases} \quad (\text{A-15})$$

where

$$r = \frac{r_2}{r_1 + \frac{r_4 k_z^2}{r_1 k_x^2 + r_3 k_z^2}}; \quad (\text{A-16})$$

where  $r_1$ ,  $r_2$ ,  $r_3$ , and  $r_4$  are the functions given in equation 9.

Because the elliptic anisotropy problem ( $\epsilon = \delta$ ) is a special case of the non-elliptic anisotropy problem, its eigenvalues and eigenvectors of  $\mathbf{A}$  can be obtained in equations A-13 and A-15:

$$\begin{cases} \lambda_1 = \rho V_p^2 [(1+2\epsilon)k_x^2 + k_z^2] \\ \lambda_2 = \rho V_s^2 [k_x^2 + k_z^2] \end{cases} \quad (\text{A-17})$$

and

$$\begin{cases} \mathbf{V}_1 = \begin{bmatrix} k_x \\ \frac{r_2}{r_1} k_z \end{bmatrix} \\ \mathbf{V}_2 = \begin{bmatrix} \frac{r_2}{r_1} k_z \\ -k_x \end{bmatrix} \end{cases} \quad (\text{A-18})$$

## APPENDIX B

### DERIVATION OF THE FIRST-ORDER PSEUDO-HELMHOLTZ DECOMPOSITION

According to Helmholtz's theorem, the vector anisotropic elastic wavefield  $\mathbf{u}$  can be resolved into the sum of a curl-free vector field and a divergence-free vector field:

$$\mathbf{u} = \mathbf{u}_0^P + \mathbf{u}_0^S; \quad (\text{B-1})$$

where  $\mathbf{u}_0^P$  and  $\mathbf{u}_0^S$  are the P and S wavefields, respectively. Applying the Fourier transform to  $\mathbf{u} = (u_x; u_z)$  gives  $\mathbf{U} = (U_x; U_z)$  in the wavenumber domain. The terms  $\mathbf{U}_0^P$  and  $\mathbf{U}_0^S$  are the vector P and S wavefields in the wavenumber domain, respectively, satisfying

$$\begin{cases} \mathbf{V}_1 \cdot \mathbf{U} = \mathbf{V}_1 \cdot \mathbf{U}_0^P \\ \mathbf{V}_1 \times \mathbf{U}_0^P = 0 \end{cases} \quad (\text{B-2})$$

and

$$\begin{cases} \mathbf{V}_1 \times \mathbf{U} = \mathbf{V}_1 \times \mathbf{U}_0^S \\ \mathbf{V}_1 \cdot \mathbf{U}_0^S = 0 \end{cases} \quad (\text{B-3})$$

By applying the first-order Taylor expansion in equation 5, the eigenvector  $\mathbf{V}_1$  becomes  $\mathbf{D}_1$ . Then, equations B-2 and B-3 become

$$\begin{cases} \mathbf{D}_1 \cdot \mathbf{U} = \mathbf{D}_1 \cdot \mathbf{U}^P \\ \mathbf{D}_1 \times \mathbf{U}^P = 0 \end{cases} \quad (\text{B-4})$$

and

$$\begin{cases} \mathbf{D}_1 \times \mathbf{U} = \mathbf{D}_1 \times \mathbf{U}^S \\ \mathbf{D}_1 \cdot \mathbf{U}^S = 0 \end{cases} \quad (\text{B-5})$$

Here,

$$\begin{cases} \mathbf{D}_1 = \begin{bmatrix} k_x \\ rk_z \end{bmatrix} \\ r = \frac{r_2}{r_1 + \frac{r_4 k_z^2}{r_1 k_x^2 + r_3 k_z^2}} \end{cases} \quad (\text{B-6})$$

Based on equation B-4, we can obtain

$$\begin{cases} k_x U_x + rk_z U_z = k_x U_x^p + rk_z U_z^p \\ rk_z U_x^p - k_x U_z^p = 0 \end{cases} \quad (\text{B-7})$$

Hence

$$\begin{cases} U_x^p = (k_x^2 U_x + rk_x k_z U_z) / (k_x^2 + r^2 k_z^2) \\ U_z^p = (rk_x k_z U_x + r^2 k_z^2 U_z) / (k_x^2 + r^2 k_z^2) \end{cases} \quad (\text{B-8})$$

Moreover, from equation B-5, we obtain

$$\begin{cases} rk_z U_x - k_x U_z = rk_z U_x^s - k_x U_z^s \\ k_x U_x^s + rk_z U_z^s = 0 \end{cases} \quad (\text{B-9})$$

Thus, we have

$$\begin{cases} U_x^s = (r^2 k_z^2 U_x - rk_x k_z U_z) / (k_x^2 + r^2 k_z^2) \\ U_z^s = (k_x^2 U_z - rk_x k_z U_x) / (k_x^2 + r^2 k_z^2) \end{cases} \quad (\text{B-10})$$

Formula B-1 can also be written as

$$\begin{cases} U_x = U_x^p + U_x^s \\ U_z = U_z^p + U_z^s \end{cases} \quad (\text{B-11})$$

Combining this formula with equations B-8, B-10, and B-11, we have

$$\begin{cases} U_x = (k_x^2 U_x + r^2 k_z^2 U_x) / (k_x^2 + r^2 k_z^2) \\ U_z = (k_x^2 U_z + r^2 k_z^2 U_z) / (k_x^2 + r^2 k_z^2) \end{cases} \quad (\text{B-12})$$

Formulas B-8, B-10, and B-12 can also be expressed as follows:

$$\begin{cases} \mathbf{U}^p = \mathbf{D}_1 \left( \mathbf{D}_1 \cdot \frac{\mathbf{U}}{|\mathbf{D}_1|^2} \right) \\ \mathbf{U}^s = -\mathbf{D}_1 \times \left( \mathbf{D}_1 \times \frac{\mathbf{U}}{|\mathbf{D}_1|^2} \right) \\ [k_x^2 + r^2 k_z^2] \frac{\mathbf{U}}{|\mathbf{D}_1|^2} = \mathbf{U} \end{cases} \quad (\text{B-13})$$

After adding  $i = \sqrt{-1}$  to equation B-13, we obtain

$$\begin{cases} \mathbf{U}^p = i\mathbf{D}_1 (i\mathbf{D}_1 \cdot \mathbf{W}) \\ \mathbf{U}^s = -i\mathbf{D}_1 \times (i\mathbf{D}_1 \times \mathbf{W}) \\ \mathbf{W} = -\frac{\mathbf{U}}{|\mathbf{D}_1|^2} \\ -[k_x^2 + r^2 k_z^2] \mathbf{W} = \mathbf{U} \end{cases} \quad (\text{B-14})$$

## APPENDIX C

### NEW FIRST-ORDER PSEUDO-HELMHOLTZ DECOMPOSITION FOR 3D WAVEFIELDS

For 3D VTI media, the matrix  $\mathbf{A}$  in equation A-1 turns into

$$\mathbf{A} = \begin{bmatrix} c_{11}k_x^2 + c_{66}k_y^2 + c_{44}k_z^2 & (c_{11} - c_{66})k_x k_y & (c_{13} + c_{44})k_x k_z \\ (c_{11} - c_{66})k_x k_y & c_{66}k_x^2 + c_{11}k_y^2 + c_{44}k_z^2 & (c_{13} + c_{44})k_y k_z \\ (c_{13} + c_{44})k_x k_z & (c_{13} + c_{44})k_y k_z & c_{44}k_x^2 + c_{44}k_y^2 + c_{33}k_z^2 \end{bmatrix} \quad (\text{C-1})$$

Then, the eigenvalues of matrix  $\mathbf{A}$  can be obtained as follows:

$$\begin{aligned} \lambda_{1,3} &= \rho \frac{[(1 + 2\varepsilon)V_p^2 + V_s^2](k_x^2 + k_y^2) + [V_p^2 + V_s^2]k_z^2}{2} \\ &\pm \rho \frac{[(1 + 2\varepsilon)V_p^2 - V_s^2](k_x^2 + k_y^2) + [V_p^2 - V_s^2]k_z^2}{2} \\ &\times \sqrt{1 + \frac{8(\delta - \varepsilon)V_p^2(V_p^2 - V_s^2)(k_x^2 + k_y^2)k_z^2}{[(1 + 2\varepsilon)V_p^2 - V_s^2](k_x^2 + k_y^2) + (V_p^2 - V_s^2)k_z^2}} \\ \lambda_2 &= \rho V_s^2 [(1 + 2\gamma)(k_x^2 + k_y^2) + k_z^2] \end{aligned} \quad (\text{C-2})$$

For the non-elliptic anisotropy problem ( $\varepsilon \neq \delta$ ), the eigenvalues can be obtained by the first-order Taylor expansion of the square-root term of equation C-2:

$$\begin{cases} \lambda_1 = \rho V_p^2 [(1 + 2\varepsilon)(k_x^2 + k_y^2) + k_z^2] + \rho \frac{2(\delta - \varepsilon)V_p^2(V_p^2 - V_s^2)(k_x^2 + k_y^2)k_z^2}{((1 + 2\varepsilon)V_p^2 - V_s^2)(k_x^2 + k_y^2) + (V_p^2 - V_s^2)k_z^2} \\ \lambda_2 = \rho V_s^2 [(1 + 2\gamma)(k_x^2 + k_y^2) + k_z^2] \\ \lambda_3 = \rho V_s^2 [k_x^2 + k_y^2 + k_z^2] - \rho \frac{2(\delta - \varepsilon)V_p^2(V_p^2 - V_s^2)(k_x^2 + k_y^2)k_z^2}{((1 + 2\varepsilon)V_p^2 - V_s^2)(k_x^2 + k_y^2) + (V_p^2 - V_s^2)k_z^2} \end{cases} \quad (\text{C-3})$$

where  $\lambda_1$ ,  $\lambda_2$ , and  $\lambda_3$  represent the phase velocities of the P, SH, and SV waves, respectively.

The Christoffel equation for 3D VTI media is

$$\begin{cases} [c_{11}k_x^2 + c_{66}k_y^2 + c_{44}k_z^2]x_1 + [(c_{11} - c_{66})k_x k_y]x_2 + [(c_{13} + c_{44})k_x k_z]x_3 = \lambda x_1 \\ [(c_{11} - c_{66})k_x k_y]x_1 + [c_{66}k_x^2 + c_{11}k_y^2 + c_{44}k_z^2]x_2 + [(c_{13} + c_{44})k_y k_z]x_3 = \lambda x_2 \\ [(c_{13} + c_{44})k_x k_z]x_1 + [(c_{13} + c_{44})k_y k_z]x_2 + [c_{44}k_x^2 + c_{44}k_y^2 + c_{33}k_z^2]x_3 = \lambda x_3 \end{cases} \quad (\text{C-4})$$

Similar to the 2D case, the eigenvectors for 3D problems can also be obtained by the Christoffel equation C-4 using the first-order Taylor expansion method. Let the eigenvectors correspond to  $\lambda_1$ ,  $\lambda_2$ , and  $\lambda_3$  be  $\mathbf{V}_1$ ,  $\mathbf{V}_2$ , and  $\mathbf{V}_3$ , respectively. Then,

$$\begin{cases} \mathbf{V}_1 = \begin{bmatrix} k_x \\ k_y \\ rk_z \end{bmatrix} \\ \mathbf{V}_2 = \begin{bmatrix} -k_y \\ k_x \\ 0 \end{bmatrix} \\ \mathbf{V}_3 = \begin{bmatrix} -rk_x k_z \\ -rk_y k_z \\ k_x^2 + k_y^2 \end{bmatrix} \end{cases} \quad (\text{C-5})$$

with

$$r = \frac{r_2}{r_1 + \frac{r_4 k_z^2}{r_1(k_x^2 + k_y^2) + r_3 k_z^2}}; \quad (\text{C-6})$$

Physically,  $\mathbf{V}_1$ ,  $\mathbf{V}_2$ , and  $\mathbf{V}_3$  are the polarization directions of the P, SH, and SV waves, respectively. Thus, we define the operator  $\mathbf{D}_1$  as follows:

$$\mathbf{D}_1 = \begin{bmatrix} k_x \\ k_y \\ rk_z \end{bmatrix}; \quad (\text{C-7})$$

In the wavenumber domain, the wavenumber vector  $\mathbf{k} = (k_x; k_y; k_z)$  indicates the phase direction of the corresponding plane wave. Let the unit vector of the phase direction be  $\mathbf{n}$ . Then, it can be expressed by

$$\mathbf{n} = (n_x; n_y; n_z) = \frac{\mathbf{k}}{|\mathbf{k}|}; \quad (\text{C-8})$$

Then, the operator  $\mathbf{D}_1$  turns to

$$\mathbf{D} = \begin{bmatrix} k_x \\ k_y \\ r'k_z \end{bmatrix}; \quad (\text{C-9})$$

where

$$r' = \frac{r_2}{r_1 + \frac{r_4 n_z^2}{r_1(n_x^2 + n_y^2) + r_3 n_z^2}}; \quad (\text{C-10})$$

Similar to replacing the operator  $\mathbf{D}_1$  in equations 10–13 with  $\mathbf{D}$ , and then transforming them to the spatial domain, we have

$$\begin{cases} \mathbf{u}^P = \nabla'(\nabla' \cdot \mathbf{w}) \\ \mathbf{u}^S = -\nabla' \times (\nabla' \times \mathbf{w}) \end{cases}; \quad (\text{C-11})$$

where the new pseudo-Helmholtz decomposition operator  $\nabla'$  is

$$\nabla' = \begin{bmatrix} \partial_x \\ \partial_y \\ r'(\mathbf{x})\partial_z \end{bmatrix}; \quad (\text{C-12})$$

where

$$r'(\mathbf{x}) = \frac{r_2(\mathbf{x})}{r_1(\mathbf{x}) + \frac{r_4(\mathbf{x})n_z^2}{r_1(\mathbf{x})(n_x^2 + n_y^2) + r_3(\mathbf{x})n_z^2}}; \quad (\text{C-13})$$

and  $\mathbf{w}$  satisfies the following anisotropic Poisson equation:

$$\left( \frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2} + (r'(\mathbf{x}))^2 \frac{\partial}{\partial z^2} \right) \mathbf{w} = \mathbf{u}; \quad (\text{C-14})$$

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Biographies and photographs of the authors are not available.

# Least-squares reverse time migration with a multiplicative Cauchy constraint

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## ABSTRACT

One of reverse time migration's main limitations is that an unscaled adjoint operator is prone to produce images with low resolution, inaccurate amplitudes, and even artifacts. Least-squares reverse time migration (LSRTM) has been introduced to mitigate this inadequacy via the use of an approximation to an inverse operator. LSRTM suffers from its own limitations, most importantly from poor condition, which often manifests itself as image artifacts. One approach to ameliorate this issue is to constrain the optimization problem by introducing a penalty term to the cost function. Penalizing estimated parameters for sparsity is one such constraint that has been shown to be effective. A drawback of this technique is that it introduces a trade-off between data fitting and image sparsity. Furthermore, if using the Cauchy constraint, an additional trade-off is introduced due to the requirement to estimate a hyperparameter. We introduce an alternative

approach that mitigates these trade-offs by combining a multiplicative cost function with an effective means for determining the Cauchy hyperparameter. We also introduce a new formulation of the multiplicative cost function that avoids over-penalization by the constraint via the introduction of a relaxation term. Finally, we seek to improve the computational efficiency by introducing a new approach for computing the step length. As such, our method introduces three novel aspects to constrained LSRTM: (1) a relaxed multiplicative cost function, (2) semiautomatic estimation of the Cauchy hyperparameter, and (3) efficient computation of the step length. We discuss the theory and implementation, followed by application to three synthetic data sets and a real ultrasonic data set. Given the presence of large salt bodies, elasticity, and noise, along with the directivity of piezoelectric ultrasonic transducers, these data sets provide a challenging test of the approach outlined. Results demonstrate that our method is robust in handling the challenges imposed by these scenarios.

## INTRODUCTION

Reverse time migration (RTM) (e.g., Baysal et al., 1983; Lailly, 1983; McMechan, 1983; Whitmore, 1983) has been used widely in geophysical exploration for imaging complex geologic structures (e.g., Zhang et al., 2011; Elita Li et al., 2018; Zhao et al., 2021). The technique has been extended for other nondestructive imaging purposes, for instance, assessing material properties, interior defects, and heterogeneities related to objects and structures (e.g., Asadollahi and Khazanovich, 2019; Liu et al., 2019) as well as

imaging through biological tissues (e.g., Roy et al., 2016). The data recorded for imaging can be of varying nature, including but not limited to seismic, ultrasonic, and electromagnetic (e.g., Zhou et al., 2005) waves.

RTM linearizes the wave equation used with respect to the model parameters, e.g., acoustic reflectivity, and applies the adjoint operator of the linearized wave equation to produce migration images. Equation 14 of Xu et al. (2011) demonstrates that the Hessian — the second derivative of the data-misfit norm with respect to the model parameters — is an identity matrix, with the proviso that

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the acquisition geometry fully covers the surface of the model and that the high-frequency asymptotic approximation is satisfied. In this scenario, the adjoint operator is a good approximation for the inverse of the linearized wave equation. Seismic imaging via migration can be carried out without explicit inversion through the minimization of an objective function. However, in practice, seismic acquisition is unable to achieve the idealized conditions described previously. As a result, the Hessian matrix contains nonzero off-diagonal elements (Trad, 2020), and conventional adjoint migration methods can only deliver approximate solutions to the imaging problem. The image quality is subsequently compromised in terms of amplitude fidelity, noise attenuation, and resolution — particularly if the shotpoints are sparse or large gaps in coverage exist.

Formulating migration as a least-squares problem is a means to improve image quality. Migration under the least-squares fitting framework is referred to as least-squares migration (LSM) and has been introduced and discussed by, e.g., Nemeth et al. (1999), Kühn and Sacchi (2003), and Kaplan et al. (2010). Least-squares RTM (LSRTM) (e.g., Dai et al., 2012; Yao and Wu, 2015; Zhang et al., 2015; Liu and Peter, 2018; Yang and Zhang, 2018; Yang et al., 2018, 2019a, 2019b; Zhang et al., 2019; Liu and Zhang, 2020) is a recent development in LSM technology that can be formulated in either the data or image domain. Recently published work demonstrates that LSRTM can achieve higher resolution and more balanced amplitudes while producing fewer artifacts than conventional RTM based on adjoint operators. The data-fitting principle and workflow behind LSRTM are remarkably similar to those of full-waveform inversion (FWI) (Tarantola, 1984), which is a modern approach to seismic velocity model building. Zhang et al. (2014) and Tang and McMechan (2017) bridge the gap between RTM/LSRTM and FWI by modifying RTM for the recovery of models of velocity and impedance. Conversely, Kalinicheva et al. (2020) and Zhang et al. (2020) obtain high-quality migration images through the use of FWI.

Similar to other geophysical inverse problems, LSRTM is ill-conditioned. This is principally because of low- and high-frequency components of the data having reduced amplitudes, receiver arrays being of limited offset, and limited source coverage. These factors cause the Hessian matrix to contain small eigenvalues (Trad, 2020). The presence of small eigenvalues generally manifests as a series of small side-lobes surrounding the true reflectors in the migration image, as described in Figure 1 of Yao and Jakubowicz (2016). In addition, the small eigenvalues can lead to the creation of artificial events in the migration image. These artifacts may not be suppressed but instead amplified with increasing numbers of LSRTM iterations (Trad, 2020). These problems can be mitigated by incorporating sparsity constraints, which assume that the reflectivity consists of a sequence of sparse spikes (Sacchi et al., 1994; Velis, 2007).

Several examples of the use of sparsity-promoting constraints during LSRTM follow. Lin and Huang (2015) apply total variation (TV) of the migration image as a constraint to suppress the creation of artifacts. They also promote the sparsity of the gradient of the image in an effort to boost the piecewise smoothness of the migration image. To solve this constrained system, they choose to apply the split-Bregman method (Goldstein and Osher, 2009). Because the aim of migration is to recover a model representing the reflectivity of the earth, which is typically sparse but not piecewise smooth, a TV constraint is, to some degree, not an ideal choice for constrained LSRTM. Wu et al. (2016) apply the L1-norm of the migration image as a constraint to promote the sparsity of the reflectivity model. They solve their

L1-norm-constrained problem using the spectral projected gradient for L1-norm (SPGL1) optimization method (van den Berg and Friedlander, 2008). Although effective, the examples published indicate slow convergence.

An alternative to an L1-norm constraint is the Cauchy constraint, an approach comparable with L0-norm penalization and that works to promote the sparsity of the inverted model. A desirable feature of the Cauchy constraint is that it is differentiable at the origin. As such, when used to constrain a least-squares problem, gradient methods can be adopted for simple and efficient optimization. As a result, the Cauchy constraint has been successfully applied in seismic data denoising (Yuan et al., 2018) and inversion (Sacchi, 1997; Wang and Wang, 2016). Cauchy-constrained problems are usually formulated as an additive cost function that contains a regularization, or trade-off, parameter. In such a case, an optimal regularization parameter must be determined. Unfortunately, this parameter often needs to be obtained through trial and error. Fortunately, this issue can be circumvented through the use of a multiplicative cost function (van den Berg et al., 1999, 2003; da Silva and Yao, 2018), which eliminates the need to estimate a regularization parameter.

We propose a Cauchy-constrained approach to data-domain LSRTM using a modified multiplicative cost function, which involves three novel aspects: first, a relaxation term in the multiplicative functional for avoiding over-penalization of the recovered model; second, a spatially varying hyperparameter in the Cauchy term for complex reflectivity models that contain strong and weak reflectors; and third, an intelligent nonquadratic line-search method for Cauchy-constrained LSRTM, which avoids repeated solution of the wave equation when computing the step length. Examples using three synthetic data sets and a real ultrasonic data set demonstrate the effectiveness and efficiency of our proposed approach to LSRTM.

## METHOD

### Least-squares RTM

LSRTM is typically carried out by minimizing the L2-norm functional:

$$F(m) = \frac{1}{2} \|u_s(\mathbf{x}_r) - d_0(\mathbf{x}_r)\|_2^2, \quad (1)$$

where  $u_s(\mathbf{x}_r)$  denotes the simulated scattering wavefield at receiver location  $\mathbf{x}_r$  (produced by solving equation A-4 for the stacked reflectivity model  $m$ ),  $u_s(\mathbf{x}_r)$  is some function of the reflectivity model, and  $d_0(\mathbf{x}_r)$  represents the observed data. As stated in equation A-7, the gradient of the functional can be expressed in integral form as

$$\frac{\partial F(m)}{\partial m(\mathbf{x})} = - \iiint i\omega(G_s(\mathbf{x}|\mathbf{x}_s, \omega)s(\mathbf{x}_s, \omega))^* G_r^*(\mathbf{x}|\mathbf{x}_r, \omega) (u_s(\mathbf{x}_r, \mathbf{x}_s, \omega) - d_0(\mathbf{x}_r, \mathbf{x}_s, \omega)) d\omega d\mathbf{x}_r d\mathbf{x}_s, \quad (2)$$

where  $*$  denotes the complex conjugation. Equation 2 shows that the gradient of the objective function in equation 1 is produced by taking the zero-lag crosscorrelation between the source wavefield and the back-propagated residual wavefield (Yao and Wu, 2015). It is worth noting that the forward-modeling formula in equation 2 is based on the Kirchhoff approximation (Yao et al., 2018b; Lu and Liu, 2020). One advantage of the Kirchhoff approximation is that it

produces zero-phase migration images, a property desirable in seismic interpretation.

As discussed in the previous studies (e.g., Dai et al., 2012; Zhang et al., 2015; Yao and Jakubowicz, 2016), LSRTM can improve the resolution of the recovered reflectivity model. The resolution achievable is, nonetheless, limited by the bandwidth of the observed data  $d_0$ . The existence of small eigenvalues in the Hessian matrix (Trad, 2020) has two undesirable effects on images estimated using LSRTM: (1) generation of a series of sidelobes around true reflectors (also known as “ringing” within the geophysical community) and (2) generation of several other artifacts that arise from boosting noise contained in the observed data.

### LSRTM with a multiplicative Cauchy constraint

To further improve the resolution of LSRTM and suppress any sidelobes and artifacts in the reflectivity model, one can apply sparsity-promoting regularization during LSRTM. In this paper, we explore the Cauchy constraint for this purpose. The constrained functional is defined as

$$J(m) = F(m) + \beta R(m), \quad (3)$$

where  $\beta$  denotes the regularization parameter and is a positive scalar, and  $R(m)$  represents the Cauchy constraint, defined by Wang (2016) as

$$R(m) = \frac{1}{2} \sum_{k=1}^N \ln \left( 1 + \frac{m_k^2}{\lambda_k^2} \right), \quad (4)$$

where  $\lambda_k$  is a hyperparameter that controls the sparseness of the model  $m$ , where  $k$  represents the index of the model element, and  $N$  denotes the total number of model elements. In general, the hyperparameter  $\lambda_k$  is determined by experimental means. We propose to determine  $\lambda_k$  by examining the gradient of  $R(m)$ , where  $m$  is the reflectivity model recovered after a handful of iterations, e.g., five iterations, of unconstrained LSRTM. The rationale behind the strategy presented here is that the optimal  $\lambda_k$  should generate low gradient values at true interfaces but high gradient values at artifacts and sidelobes. Because the maximum gradient of the Cauchy term  $\ln(1 + m^2/\lambda^2)$  occurs when  $m$  equals  $\lambda$ , it follows that the value  $\lambda$  should roughly match the magnitude of the sidelobes and artifacts but be less than the magnitude of the reflectors. As a result, the constraint penalizes sidelobes and artifacts while boosting the resolution of the reflectivity model. Because the magnitude of reflectors varies in space, we propose to use a spatially varying  $\lambda_k$  rather than a constant value. Using a constant value is the conventional approach. A general guide to determining the spatially varying hyperparameter is that its value should approximate the magnitude of the noise but be less than the magnitude of most reflectors, with the value increased for weak reflectors. This strategy will be explored further in the “Examples” and “Discussion” sections.

It is widely recognized that the determination of the regularization parameter  $\beta$  is a nontrivial task (Bakushinskii, 1984; van den Berg et al., 1999). There are two broad categories of strategy for determining the regularization parameter: a priori strategies and a posteriori strategies (Xiao et al., 2003). In general, a posteriori strategies, such as the generalized cross validation principle and the L-curve principle,

are more practical than a priori strategies but can sometimes fail (Yagola et al., 2002). As a result, the determination of  $\beta$  can involve a considerable number of experimental tests. To circumvent this drawback, van den Berg et al. (1999, 2003) propose a multiplicative cost function:

$$J_n(m) = F(m)C_n(m), \quad (5)$$

where the constraint term is defined as

$$C_n(m) = \frac{R(m)}{R(m_n)}, \quad (6)$$

where  $m_n$  denotes the estimated  $m$  at the current iteration  $n$  and  $R(m_n)$  is used as a normalizing constant during each iteration of the inversion process.

The multiplicative cost function in equation 5 is equivalent to the additive cost function:

$$J_n(m) = \frac{1}{2} (F(m) + \beta R(m)), \quad (7)$$

where  $\beta = F(m)/R(m_n)$ , as demonstrated by van den Berg et al. (1999, 2003). Compared to equation 3, the regularization parameter  $\beta$  in equation 7 is determined automatically. During early iterations of the inversion process, the regularization parameter  $\beta$  will be large because the data-misfit term  $F(m)$  will itself be large. As  $F(m)$  decreases with successive iterations, the regularization term  $\beta R(m)$  will decrease also. This gradual “cooling” of the regularization parameter  $\beta$  is a desirable property (van den Berg et al., 1999). Furthermore, the regularization parameter  $\beta$ , which is determined implicitly in equation 7, can compensate (to some degree) for non-optimal selection of the hyperparameter  $\lambda$ . Consequently,  $\lambda$  only needs to be close to its optimum value.

As described in our analysis of the forward problem for LSRTM (Appendix A), the forward-modeling operator for LSRTM, equation A-4, is different from the full wave equation, equation A-1, because only first-order scattering is considered during LSRTM. Consequently,

$$\|u_s(m_{\text{inv}}) - d_0\|_2^2 > 0, \quad (8)$$

where  $u_s(m_{\text{inv}})$  represents the data predicted by the reflectivity model  $m_{\text{inv}}$  inverted by minimizing  $F(m)$ . The discrepancies between  $u_s(m_{\text{inv}})$  and  $d_0$  become larger with increasing model complexity and increasing noise in  $d_0$ . Consequently, the data-misfit term will tend to remain large after  $F(m)$  has been minimized for a complex model. This large residual will force the regularization term  $\beta R(m)$  to over-penalize the reflectivity model  $m$ , thereby introducing undesired biases into the estimate. Therefore, we propose adding a relaxation term  $\epsilon$  to the multiplicative functional, given by

$$J_n(m) = (F(m) - \epsilon)C_n(m). \quad (9)$$

The relaxation term  $\epsilon$  should be smaller than  $F(m_{\text{inv}})$  but positive, thereby imposing sufficient sparsity onto the model while avoiding  $F(m) - \epsilon$  becoming negative.

The gradient of the multiplicative functional in equation 9 is

$$\begin{aligned}\frac{\partial J_n}{\partial m} &= C_n(m) \frac{\partial F(m)}{\partial m} + \frac{F(m) - \varepsilon}{R_n(m)} \frac{\partial R(m)}{\partial m} \\ &= \frac{\partial F(m)}{\partial m} + \frac{F(m) - \varepsilon}{R_n(m)} \frac{\partial R(m)}{\partial m}.\end{aligned}\quad (10)$$

In the relaxed multiplicative functional (equation 9), the data-misfit term  $F(m)$  is quadratic because the forward-modeling equation (equation A-4) is linear. However, the Cauchy term  $R(m)$  is nonquadratic. As a result, equation 9 is nonquadratic. We use a preconditioned nonlinear conjugate-gradient (PNCG) method based on the Polak-Ribière formula to minimize the relaxed functional (equation 9). Our implementation of PNCG is adapted from page 53 of Shewchuk (1994). To improve convergence, we use the energy contained within the stacked source wavefields  $u_0$  as a preconditioner  $M$ , which is a diagonal positive-definite matrix, the major-diagonal elements of which are defined as

$$M_{kk} = \sum_{i=1}^{N_{\text{shot}}} \sum_t u_0^2(\mathbf{x}_k | \mathbf{x}_{si}, t). \quad (11)$$

The preconditioner  $M$  approximates the Hessian matrix by acting as an illumination-compensation operator (Kaelin and Guitton, 2006). As such, the introduction of  $M$  can improve convergence of the optimization problem. This form of preconditioner happens to have been widely applied in FWI (e.g., Pratt, 1999; Virieux and Operto, 2009; Warner et al., 2013).

### Step-length calculation

At each iteration, we must perform a line search to find a minimizer  $\alpha_{\text{opt}}$ , the optimal step length, for

$$\alpha_{\text{opt}} = \arg \min_{\alpha} J_n(m + \alpha \delta m), \quad (12)$$

where  $\delta m$  denotes a small perturbation to the current model  $m$  along the conjugate update direction.

Because the Cauchy-constrained multiplicative functional is nonquadratic, common line-search methods (without intelligent treatment) can involve multiple rounds of forward modeling and backpropagation. When minimizing equation 1, each iteration usually requires two forward-modeling solves and a single back-propagation solve.

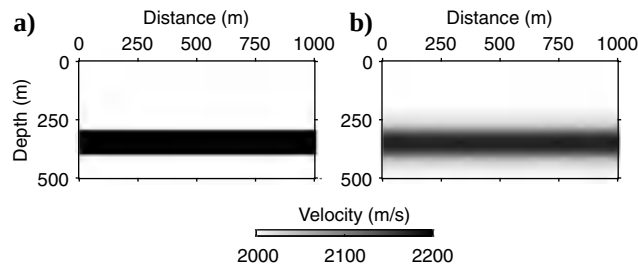


Figure 1. The velocity profile of the three-layer model. (a) The true velocity profile for generating the observed data. (b) The smoothed velocity profile for migration.

Comparatively, the computational cost of Cauchy-constrained LSRTM is increased by several times due to the requirement to repeatedly solve a linearized wave equation (equation A-4). This feature precludes Cauchy-constrained LSRTM from becoming practical for most applications. To tackle this problem, we propose an alternative approach: first, we find a step length  $\alpha_d$  that minimizes the data misfit  $F(m)$ , and second, we formulate a parabola as a function of  $\alpha$  that fits the data misfit almost exactly along the direction indicated by the perturbation  $\delta m$ . This parabola is expressed as

$$\phi(\alpha) = a(\alpha - \alpha_d)^2 + c, \quad (13)$$

where  $a = (\phi(1) - \phi(0))/(1 - 2\alpha_d)$ ,  $c = \phi(0) - a\alpha_d^2$ ,  $\phi(1)$  is the data misfit with the step length  $\alpha = 1$ , and  $\phi(0)$  is the data misfit with the step length  $\alpha = 0$ . When determining the initial step length  $\alpha_d$ , one choice is the method described in Appendix A of Yao et al. (2019). This method requires only a single forward-modeling solve to determine  $\alpha_d$ .

Equation 12 now becomes

$$\alpha_{\text{opt}} = \arg \min_{\alpha} (\phi(\alpha) - \varepsilon) C_n(m + \alpha \delta m), \quad (14)$$

which can be solved efficiently using any line-search method, and we use a bisection method (Nocedal and Wright, 2006). In our tests, it takes less than 10 iterations to find a minimizer with a relative error of less than  $10^{-7}$ . Compared with the minimization problem of equation 12, minimization of the problem in equation 14 does not introduce any additional wave equation solves; consequently, the computational cost of Cauchy-constrained LSTRM becomes much more tractable. As such, a single iteration when minimizing the functional in equation 9 requires only two forward-modeling solves and one back-propagation solve, therefore costing almost the same as unconstrained LSRTM, i.e., when minimizing the functional in equation 1. If our proposed line-search method is not used and the line search should require 10 iterations, solving the Cauchy-constrained multiplicative functional of equation 5 will involve approximately seven times more computational burden than solving the unconstrained functional of equation 1. The proposed line-search strategy has the potential to be extended to other geophysical problems that involve the computation of gradients and step lengths via repeated solution of partial differential equations, such as FWI.

## EXAMPLES

We migrate three synthetic data sets along with a real ultrasonic data set to demonstrate the effectiveness of the proposed Cauchy-constrained LSRTM.

### A three-layer model

The velocity field for a synthetic three-layer model is shown in Figure 1a. From this, we generated a data set containing three shot records. The data set was generated by solving equation A-1 with a constant density of  $1000 \text{ kg/m}^3$ . The source wavelet used was a 30 Hz Ricker wavelet. The three sources were located at horizontal distances of 200, 500, and 800 m, and at a depth of 5 m. The receiver array was positioned at the same depth as the sources but spread across the entire model. An example shot record is shown in Figure 2a.

We have carried out migration using all three shot records. The RTM image is shown in Figure 3a. Several shortcomings in the imaging are noticeable: first, one can observe the presence of strong arc-shaped artifacts above each reflector, and second, the amplitudes of the reflectors are not uniform laterally nor between themselves. These are two common features of RTM images, especially when the shotpoints are sparse or there are gaps in the acquisition coverage. Formulating seismic migration as an inverse problem is a well-known remedy for mitigating these issues. With this in mind, we choose to carry out unconstrained LSRTM (equation 1) starting from the RTM image. The reflectivity model obtained after 100 iterations is shown in Figure 3b. Compared with the RTM image, Figure 3a, the LSRTM image contains two uniform reflectors and fewer artifacts. Moreover, as expected (Yao and Jakubowicz, 2016), LSRTM also has improved the resolution of the migration image. However, a side effect is that the inversion process has generated weak sidelobes/oscillations around the true reflectors. In addition, due to the limited aperture of the receiver array, some weak arc-shaped artifacts remain in the image.

To further improve the resolution and suppress the residual artifacts, we have next carried out Cauchy-constrained LSRTM using a multiplicative cost function. The hyperparameter  $\lambda$  has been determined by following the approach presented in the previous section. From examination of the gradient of the Cauchy term based on the unconstrained LSRTM image obtained after five iterations, this approach returns a value of  $\lambda = 1 \times 10^{-6}$ . Figure 4 shows the gradient of the Cauchy term for  $\lambda = 1 \times 10^{-6}$ . We can see that the magnitude of the gradient is large in the regions that contain artifacts but small at the reflectors. In this example, as the data residual (the blue

curve in Figure 5) is small after unconstrained LSRTM, we set the relaxation term  $\varepsilon$  to zero during subsequent Cauchy-constrained LSRTM. Figure 5 also indicates that Cauchy-constrained and unconstrained LSRTM produce a similar data fit.

The reflectivity model produced by Cauchy-constrained LSRTM is shown in Figure 3c. Compared with the unconstrained LSRTM image (Figure 3b), the Cauchy constraint effectively suppresses any artifacts. In comparison, the additive functional (equation 3) requires that  $\beta$  is determined by trial and error. After conducting several tests, we have found that  $\beta = 2 \times 10^{-4}$  gives a reflectivity model (Figure 3d) similar to the one shown in Figure 3c. These tests demonstrate that the Cauchy-constrained approach to LSRTM introduced here is effective in suppressing noise and dramatically simplifies the application of a sparsity-promoting constraint by eliminating the need for intensive user interaction when selecting an appropriate trade-off between data and constraint misfits.

It is worth noting that the reflectors contained within the migration images of Figure 3 have zero phase. This is an important property for seismic interpretation and occurs because the forward-modeling formula (equation A-5) is based on the Kirchhoff approximation (Yao et al., 2018b; Lu and Liu, 2020). By way of comparison, the forward-modeling formula based on the Born approximation produces antisymmetric images of reflectors (Yao et al., 2018b; Lu and Liu, 2020). In addition, the recovered reflectivity with both formulas has a magnitude different than the actual reflectivity but it can be calibrated, for example, using well-log data.

The images depicted in Figure 3c and 3d can be compared with the image in Figure 3e, which was originally presented in Figure 2d of Wu et al. (2016). The latter has been obtained by using the L1-norm of the model as a sparsity-promoting constraint and recasting migration as a basis pursuit denoise (BPDN) problem, which was then solved using SPGL1 (van den Berg and Friedlander, 2008). Both constraints are shown to improve resolution and to

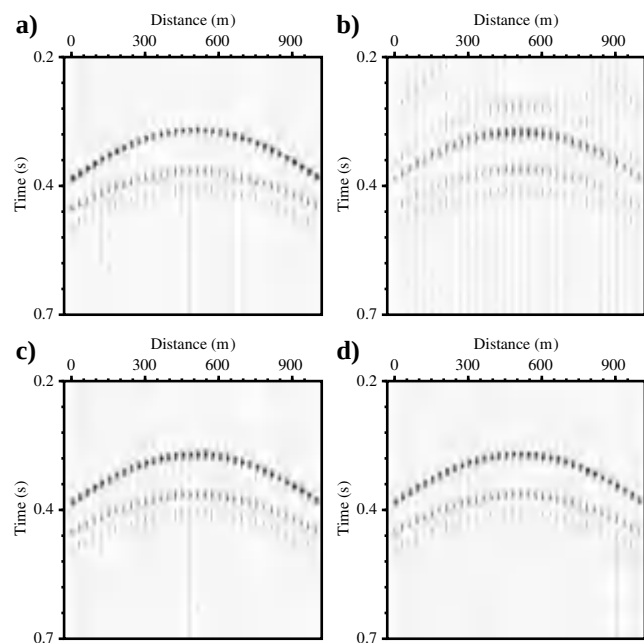


Figure 2. One shot profile from the three-layer model. The source wavelet is a 30 Hz Ricker wavelet. The source is located at a distance of 500 m and a depth of 5 m. (a) The observed data. (b) The predicted data from the RTM result, which is shown in Figure 3a. (c) The predicted data from the unconstrained LSRTM result, which is shown in Figure 3b. (d) The predicted data from the Cauchy-constrained LSRTM result, which is shown in Figure 3c. The direct arrivals have been muted. All of the plots are displayed on the same scale.

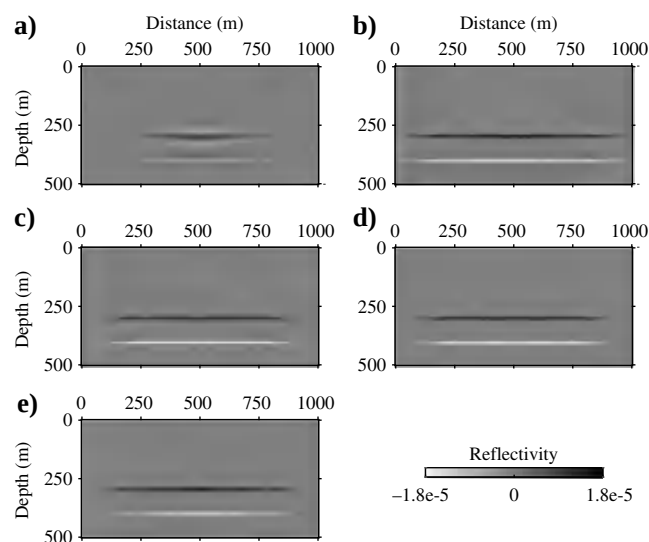


Figure 3. The migration results by using (a) RTM, (b) unconstrained LSRTM, and Cauchy-constrained LSRTM with (c) a multiplicative cost function and with (d) an additive cost function, which has a fixed regularization parameter of  $2 \times 10^{-4}$ . (e) The BPDN result presented in Figure 2d of Wu et al. (2016). Note that the magnitude of the recovered reflectivity does not represent the actual reflectivity, but it can be calibrated, for example, using well-log data.



suppress artifacts. However, the Cauchy constraint yields an image that is smoother laterally, which occurs because the Cauchy constraint is continuous (equation 4). Comparison between Figure 4b of Wu et al. (2016) and Figure 5 indicates that the convergence of Cauchy-constrained LSRTM using conjugate-gradient methods is better than that of SPGL1. See Wu et al. (2021) for a more detailed comparison between the performance of the Cauchy and L1 constraints, where it is demonstrated that the Cauchy-constrained LSRTM converges faster than L1-norm-constrained LSRTM.

### The SEG/EAGE overthrust model

In this example, a 2D slice was extracted from the 3D SEG/EAGE overthrust model, shown in Figure 6a. The migration velocity model was obtained by smoothing the selected slice, as depicted in Figure 6b. A reflectivity model was generated as a reference,

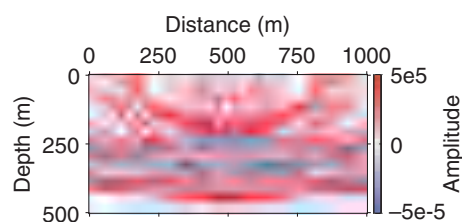


Figure 4. The gradient of the Cauchy term for the reflectivity model at the fifth iteration of unconstrained LSRTM.

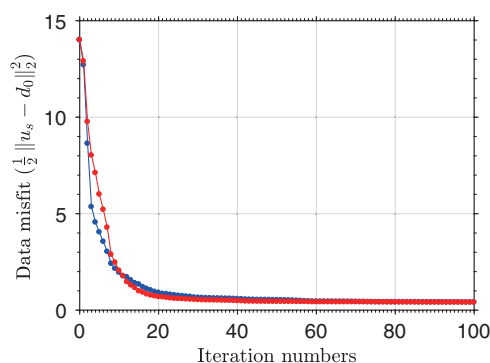


Figure 5. The data-misfit functional against the iteration numbers. The blue curve indicates the functional value of unconstrained LSRTM, whereas the red curve is for Cauchy-constrained LSRTM.

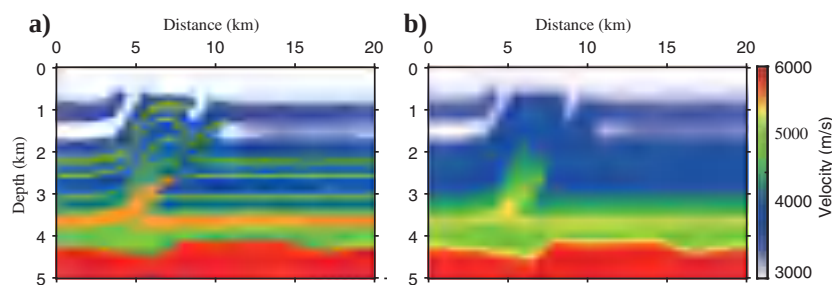


Figure 6. The velocity profile of one slice of the 3D overthrust model. (a) The true velocity profile for generating the observed data. (b) The migration velocity profile, which is a smoothed version of (a) by using Seismic Unix command “smooth2.”

shown in Figure 7a. Note that the model term in equations A-4 and A-5 does not represent the absolute reflectivity. Thus, the reference reflectivity model (Figure 7a) was scaled, as represented in Figure 7b.

In this experiment, we generated an observed data set containing 183 shot records. The source wavelet was a 15 Hz Ricker wavelet. The source location of the first shot record was at a horizontal distance of 0.9 km. The shotpoint interval was 100 m. All sources were located at a depth of 50 m. A split-spread receiver geometry was used with a maximum offset of 5.25 km. An absorbing boundary (Yao et al., 2018a) was applied at each boundary of the model. A single shot record is displayed in Figure 8a. The direct arrivals have been removed because they do not contain any information about the subsurface. The black curve indicates the position of the top mute used.

The RTM image is shown in Figure 9a. Because it is a stack of 183 shot records, the RTM image is relatively clean when compared to the RTM image produced from the three-layer model (Figure 3a). However, Figure 9a still exhibits two noticeable issues: first, the amplitudes are not balanced between reflectors at different depths, even after illumination compensation using the stacked source wavefield energy, and second, the resolution of the image is relatively low.

To temper these two issues, unconstrained LSRTM has been carried out next. The resulting image after 50 iterations is shown in Figure 9b. Comparing this with the corresponding RTM image, we observe, as expected, improvement in the image resolution as well as in the balance of the amplitudes of the image. However, compared with the reference image, Figure 7b, the LSRTM image contains some high-wavenumber migration noise and oscillations around the reflectors, principally because of poor conditioning.

We subsequently applied Cauchy-constrained LSRTM in an effort to reduce these artifacts. It was observed that a typical reflector beneath the top interface is roughly an order of magnitude stronger than those at or close to the top interface, e.g.,  $2 \times 10^{-6}$  versus  $2.5 \times 10^{-7}$ . Therefore, we chose to use a spatially varying hyperparameter  $\lambda$ , increasing the hyperparameter by eight times for the top interface. Doing so served to reduce the magnitude of the gradient of the Cauchy term for small values (Figure 10). The spatially varying hyperparameter is shown in Figure 11a, whereas the gradient of the Cauchy term for the reflectivity model recovered after five iterations of unconstrained LSRTM is shown in Figure 11b. As can be seen, the magnitude of the gradient was weak around the true reflectors but strong around artifacts, as well as relatively weak around the top interface — this prevents the inversion from erroneously suppressing any weak reflectors. Numerical tests indicated that the reflectors close to the top interface would be removed completely if we instead chose a constant hyperparameter of  $5 \times 10^{-8}$ .

It is observed that the residual data misfit for unconstrained LSRTM (the blue curve in Figure 12) is relatively large. The residual decreases to approximately 42% of its initial value when starting from the RTM image. This is because LSRTM uses a linearized wave equation (equation A-4), whereas the observed data are generated via the full nonlinear wave equation (equation A-1); the data generated by these two



equations contain numerous discrepancies, especially at large offsets when using complex models such as the overthrust model. In this case, if we do not relax the Cauchy constraint in the multiplicative cost function, the inversion will over-penalize the reflectivity model.

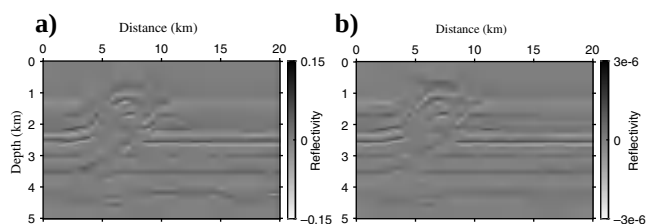


Figure 7. A version of the reflectivity profile of the velocity model, which is shown in Figure 6a. (a) The reflectivity profile calculated by using  $r[z] = (v[z+1] - v[z]) / (v[z+1] + v[z])$ , where  $r$  denotes the reflectivity,  $v$  represents the velocity, and  $z$  is the index of the element in the direction of depth. (b) A scaled version of (a), which has magnitude comparable with the reflectivity images of LSRTM.

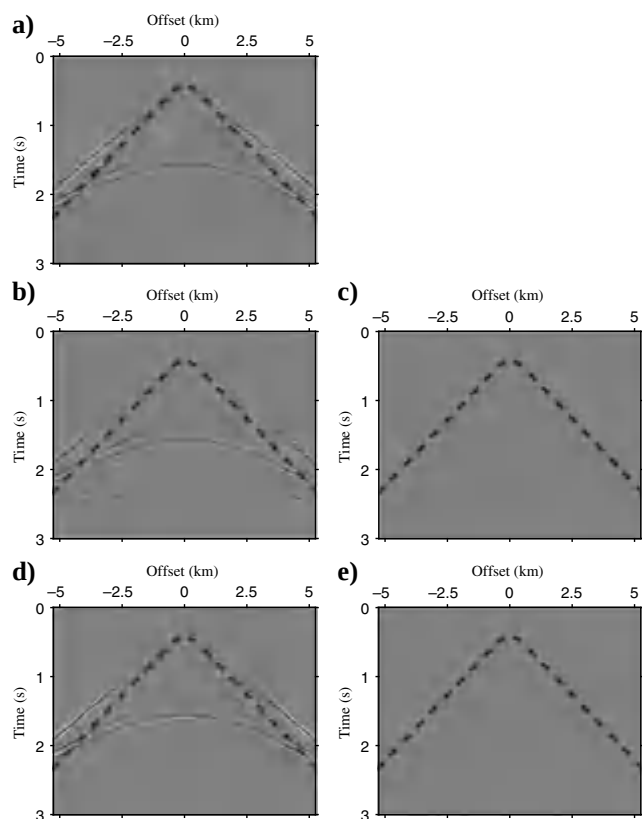


Figure 8. One shot profile. The source wavelet is a 15 Hz Ricker wavelet. The source is located at a distance of 12.9 km and a depth of 50 m. (a) The observed data from the true velocity model, which is shown in Figure 6a. (b) The predicted data from the RTM image, which is shown in Figure 9a. (c) The predicted data from the unconstrained LSRTM image, which is shown in Figure 9b. (d) The residual of (b), which is the difference between (a) and (b). (e) The residual of (d). The dashed black curves indicate the mute position. The data above the curves are not involved in the inversion process. All of the plots are displayed on the same scale.

The relaxation term  $\varepsilon$  should be smaller than the residual data misfit after unconstrained LSRTM has achieved convergence. For this example, this is approximately  $5.94 \times 10^5$ . Our tests show that, for this example, it is reasonable to set  $\varepsilon$  to 70% of the residual data misfit. As shown in Figure 9c, the Cauchy-constrained inversion suppresses the high-wavenumber artifacts and sidelobes, as well as further improving the image resolution. The enlarged sections in Figure 13 and wiggle display in Figure 14 provide more detailed comparisons. More quantitative methods, e.g., structure similarity index measure (Zhou et al., 2004), also could be used to provide an assessment of image quality.

Figure 15 shows the Cauchy-constrained LSRTM image obtained when using different percentages of the residual data misfit for the relaxation term  $\varepsilon$ . As can be seen, weaker relaxation allows for artifacts and sidelobes to be suppressed more effectively, however, it also tends to remove weak reflectors. Consequently, weaker relaxation leaves relatively large residual data misfits, as shown in Figure 12. Thus, care must be taken to choose a relaxation value based on our expectation for the migration. A general guide is that  $\varepsilon$  should be smaller than the residual data misfit after unconstrained LSRTM has achieved convergence. In terms of the additive Cauchy constraint  $\beta$  (equation 3), there may be a long trial and error process involved in finding a suitable value for producing an adequate reflectivity model. In this case, it is found that  $\beta = 1.4$  returns a reflectivity model similar to the one shown in Figure 9c. As shown in Figure 12, the additive and multiplicative functionals allow for convergence toward a desirable solution.

### The SMAART Sigsbee2A model

In this next example, we apply the proposed Cauchy-constrained approach to LSRTM to data generated from the SMAART Sigsbee2A model. The large salt body within the model (Figure 16a) poses a significant challenge to migration algorithms, including

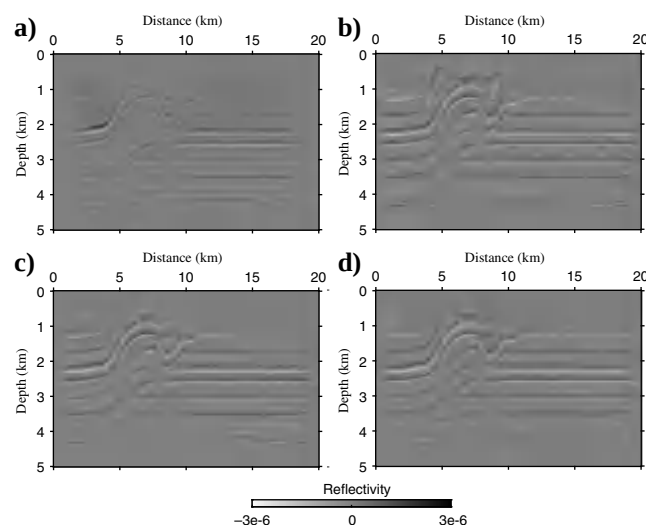


Figure 9. The profiles of migration images. (a) The RTM image. (b) The unconstrained LSRTM image. (c) The LSRTM image with a multiplicative Cauchy constraint, the relaxation term  $\varepsilon$  of which is set to 70% of the functional residual of the unconstrained LSRTM after 50 iterations. (d) The LSRTM image with an additive Cauchy constraint, the fixed regularization parameter of which is set to  $\beta = 1.4$ . All of the inversion includes 50 iterations.

RTM. One of the main reasons for this is that the salt body impedes the propagation of seismic waves, resulting in weak illumination of the subsalt region. The observed data set is generated by solving the full two-way wave equation (equation A-1) with a constant density model. We choose a towed-streamer geometry, using a single

streamer containing 347 receivers spaced by an interval of 75 ft. The minimum offset is 37.5 ft. The data set contains 500 shot records with a shot interval of 150 ft. The time dependency of the source term is given by a Ricker wavelet with a peak frequency of 12 Hz. An absorbing boundary is applied such that the data set does not include surface-related multiple arrivals or ghost arrivals but does contain interbed multiple arrivals. Figure 16b shows a single shot record from the observed data set.

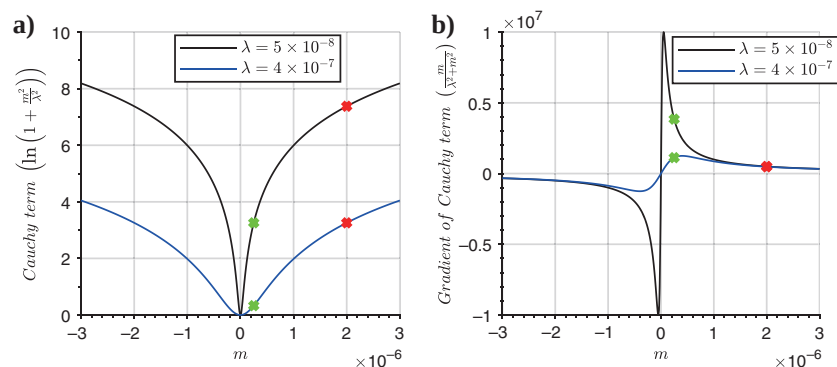


Figure 10. (a) The Cauchy term and (b) its gradient for  $\lambda = 5 \times 10^{-8}$  and  $\lambda = 4 \times 10^{-7}$ . The green and red crosses represent the case of  $m = 2.5 \times 10^{-7}$  and  $m = 2 \times 10^{-6}$ , respectively.

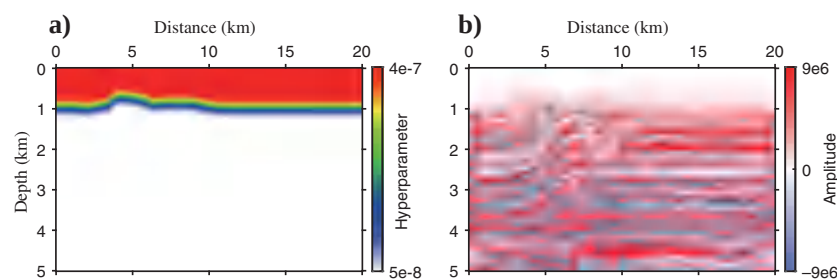


Figure 11. (a) The profile of the hyperparameter  $\lambda$  for the Cauchy-constrained LSRTM. (b) The gradient of the Cauchy term with  $\lambda$  shown in (a) for the reflectivity model at the fifth iteration of the unconstrained LSRTM.

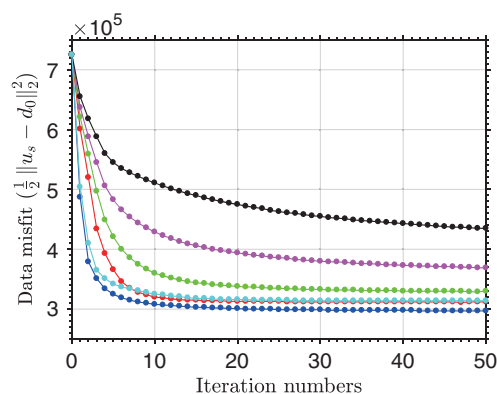


Figure 12. The data-misfit functional against the iteration numbers. The blue curve indicates the functional value of unconstrained LSRTM, whereas the red, green, magenta, and black curves are, respectively, for the multiplicative Cauchy-constrained LSRTM with the relaxation term  $\epsilon$  set to 100%, 70%, 40%, and 0% of the data-misfit functional value of the unconstrained LSRTM. The cyan curve indicates the additive Cauchy-constrained LSRTM with a fixed regularization parameter of 1.4.

Figure 17b shows the RTM image recovered. Comparing this with the reference reflectivity model, Figure 17a, the RTM image is shown to contain clear reflectors through the sedimentary sequence on the left side and is able to delineate the salt body as well as most of the postsalt events. We use the deprimary imaging condition proposed by Fei et al. (2015), which allows for images with good signal-to-noise ratios to be obtained. As can be seen, the reflectors in the subsalt region are weak. In contrast, the surface of the salt body is overly strong. The subsalt reflectors become discontinuous at a horizontal distance of 16 km, as indicated by the blue box in Figure 17b.

Unconstrained LSRTM is subsequently applied to improve the image quality. Figure 17c shows the result obtained after 20 iterations. As expected, LSRTM produces events with more balanced amplitudes by weakening the amplitude of the salt body and boosting amplitudes within the subsalt region. However, unconstrained LSRTM also generates spurious sidelobes around reflectors and introduces arc-shaped artifacts, as indicated by the black arrows in Figure 17c.

Following this, the multiplicative Cauchy constraint is applied to investigate whether these artifacts could be suppressed and the resolution boosted. By following the strategy presented

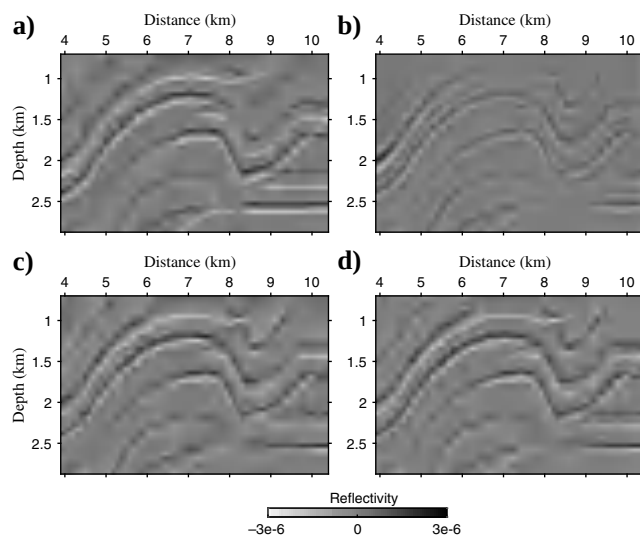


Figure 13. The enlarged view of the reflectivity images, with (a)–(d) corresponding to Figures 7b and 9a–9c, respectively.

previously, a spatially varying hyperparameter is determined, as shown in Figure 18. We use the stacked source wavefield energy (equation 11) to construct an initial trend for the hyperparameter

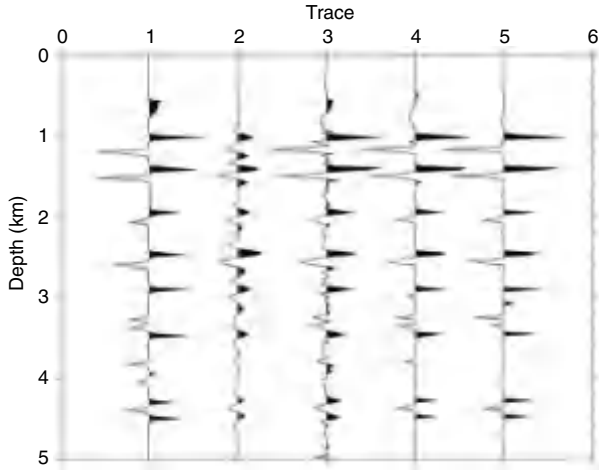


Figure 14. Wiggle display of one trace from the reference reflectivity model and migration images. The trace is located at a distance of 5.75 km. The five traces from left to right are from the reference reflectivity model (Figure 7b), the RTM image, the unconstrained LSRTM image, the multiplicative Cauchy-constrained LSRTM image, and the additive Cauchy-constrained LSRTM image. The migration images are shown in Figure 9.

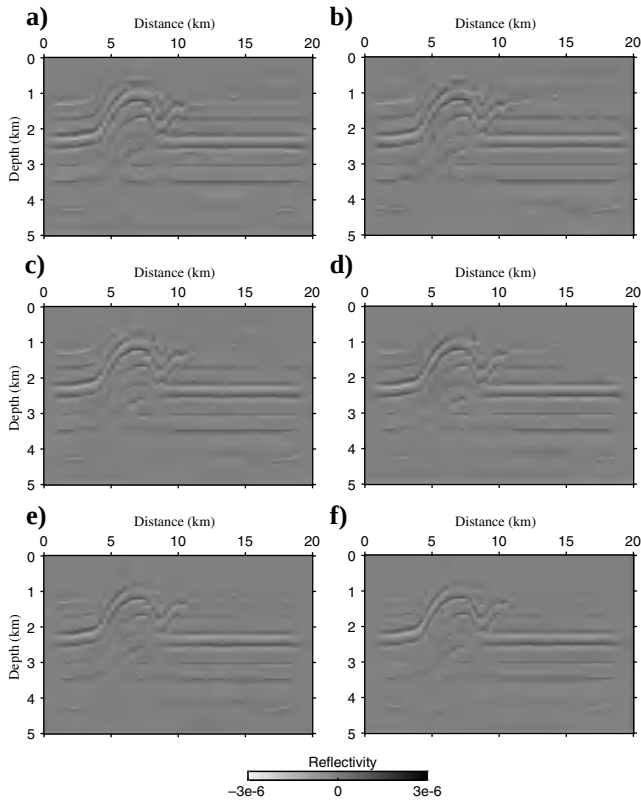


Figure 15. The reflectivity images of Cauchy-constrained LSRTM with the relaxation term  $\epsilon$  set in (a)–(f), respectively, to 100%, 80%, 60%, 40%, 20%, and 0% of the data misfit functional value of the unconstrained LSRTM after 50 iterations.

and then weaken this in the subsalt region so as to avoid over-penalization of weak events. The relaxation term is again set to 70% of the residual data misfit after unconstrained LSRTM. The inversion result is shown in Figure 17d, in which it can be seen that the Cauchy constraint suppresses the artifacts effectively. However, this result is still imperfect: several reflectors below the salt body remain poorly imaged, as indicated by the black arrows in Figure 17d. The main reason for this is that the L2-norm-based inversion is being dominated by strong events produced from the salt-sediment boundary and is unable to enhance sufficiently the weaker events in the data.

The Huber norm of the data misfit can be used to mitigate this problem. Here, we choose to use a pseudo-Huber norm (Hartley and Zisserman, 2003, p. 619), which is a smooth approximation to the Huber norm that is subsequently more suitable for differentiation. The pseudo-Huber norm reads

$$F_H(m) = \delta^2 \sum_i \left( \sqrt{1 + ((u^i - d_0^i)/\delta)^2} - 1 \right), \quad (15)$$

where the superscript  $i$  is the index of the element of the data and  $\delta$  is the threshold for the Huber norm, which is set to half of the maximum residual during each iteration.

The image obtained using unconstrained Huber-norm-based LSRTM is shown in Figure 17e. Compared with the image obtained using unconstrained L2-norm-based LSRTM (Figure 17c), the

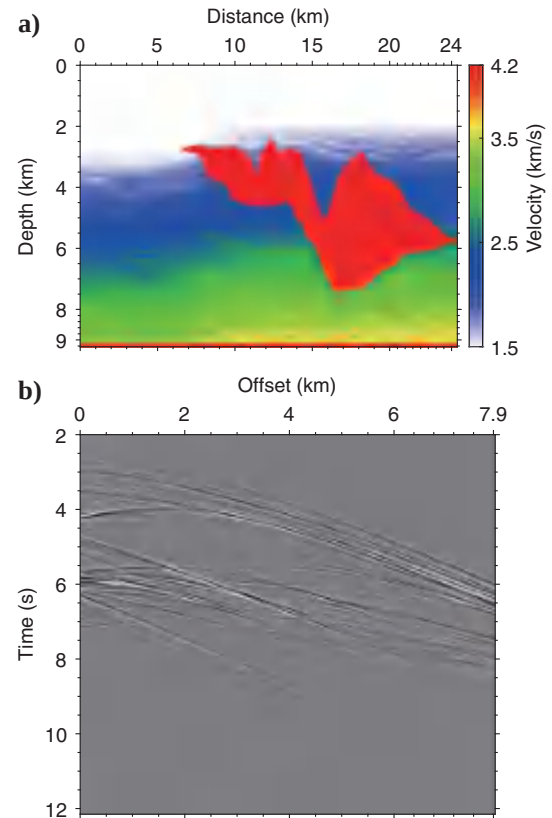


Figure 16. (a) The velocity of Sigsbee2A. (b) One shot profile generated by solving equation A-1 with a constant density. The source is located at a distance of 16.23 km. The direct arrivals are removed.

Huber-norm-based LSRTM image shows improved continuity of reflectors, especially in the subsalt domain. However, one drawback is that artifacts and noise have become more pronounced, as indicated by the black arrows in Figure 17e. In fact, noise boosting is a

potential drawback of LSM approaches in general (Trad, 2020). With this in mind, we apply the multiplicative Cauchy constraint to LSRTM based on the Huber norm to suppress any artifacts and/or noise. The same strategy as for L2-norm-based LSRTM

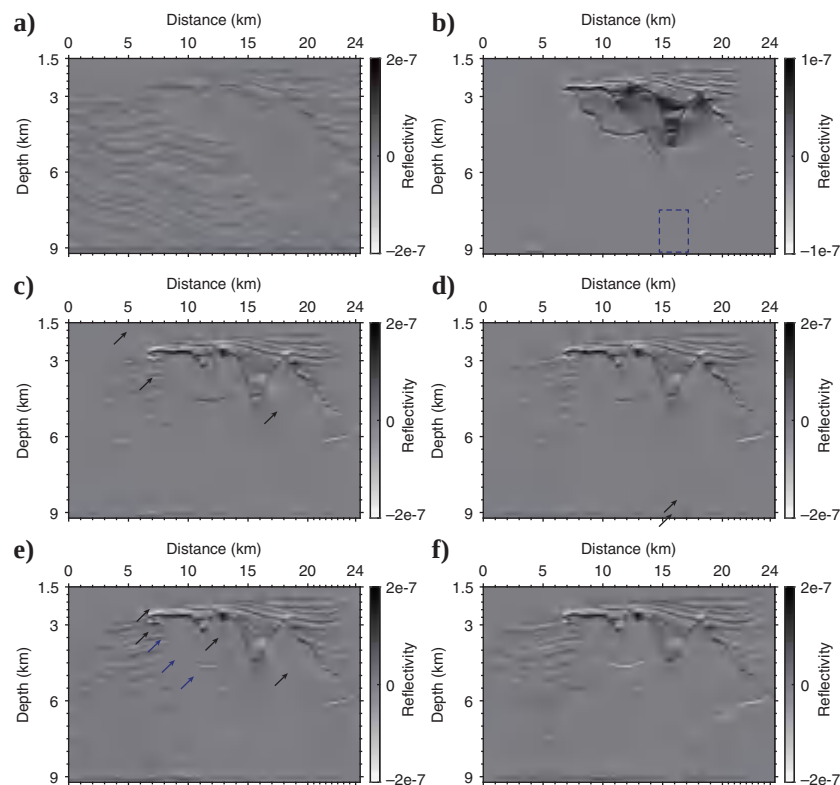


Figure 17. The profiles of the reference reflectivity model and migration images. (a) The reference reflectivity model, which is scaled to a comparable magnitude of LSRTM images. (b) The RTM image. (c) The L2-norm-based LSRTM image without constraint. (d) The L2-norm-based LSRTM image with a multiplicative Cauchy constraint. (e) Huber-norm-based LSRTM image without constraint. (f) Huber-norm-based LSRTM image with a multiplicative Cauchy constraint.

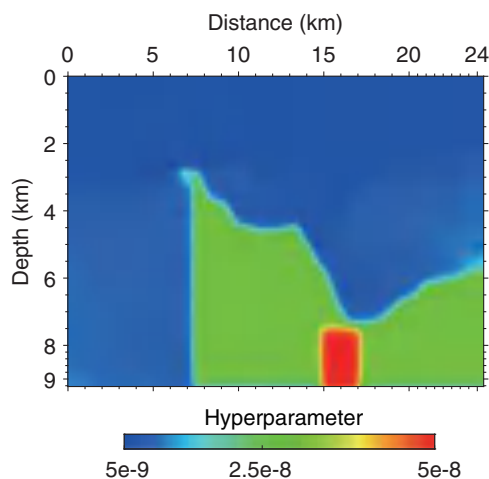


Figure 18. The profile of the hyperparameter  $\lambda$  for the Cauchy-constrained LSRTM.

is used when choosing the relaxation and hyperparameter terms. Figure 17f shows the migration image obtained from this approach. As can be seen, the artifacts and noise (the black arrows in Figure 17e) are attenuated greatly. This is principally because the data are insensitive to these artifacts, which means that their removal does not noticeably change the predicted data. In contrast, the artifacts indicated by the blue arrows in Figure 17e are only removed partially. There are two reasons for this: first, these artifacts are likely related to interbed multiples, which are present in the observed data. Artifacts of this nature become attenuated by the multiplicative constraint but are then regenerated during subsequent iterations. Second, the magnitude of these artifacts is close to that of the true reflectors. This requires the hyperparameter for these regions to be elevated, otherwise the Cauchy constraint will suppress the artifacts and the true reflectors. As a result of this trade-off, any artifacts emanating from interbed multiples will still generate some data residuals while the constraint also will impinge on the true reflectors, resulting in some degree of imperfection in the imaged reflectors. One potential solution is to remove the interbed multiples from the data prior to imaging; however, this is outside the scope of this paper.

In general, Huber-norm-based and L2-norm-based LSRTM (when using a multiplicative sparsity promoting constraint) significantly improve the quality of the migration image, especially when compared with conventional RTM. Further evidence for this is contained within the wiggle display of Figure 19. The data misfit for each of the inversion examples discussed here is reduced

to a similar level, as indicated by the data-misfit curves in Figure 20. This suggests that the chosen parameters did not over-penalize the model.

## A physical model

Finally, we provide an example of the proposed Cauchy-constrained LSRTM inverting a real ultrasonic data set acquired using a physical laboratory-based model. This data set contains a 2D transect of 41 shot records acquired using a shotpoint interval of 8 mm and a trace interval of 2 mm. The minimum offset for each shotpoint is 20 mm. A one-sided receiver array is used, and the first 20 shot records contain 96 traces per shotpoint. Each subsequent shot record then contains four traces fewer than the last. The source location for the first shot record is at a horizontal distance of 5 mm. Piezoelectric ultrasonic transducers are used for sources as well as receivers. A P-wave mode is used for source generation and data recording. As such, P-wave energy dominates the observed data and any S-wave energy recorded arises from mode conversions. Figure 21a shows a single shot record from the data set. As can be seen, the record con-



tains two direct arrivals, multiple arrivals, S-wave energy, boundary reflections, and other dipping noise — all of which serve to hamper the migration process. To lessen the effects of these undesirable

energies, a preprocessing sequence is applied to the data. This sequence relies predominantly on f-k filtering to remove unwanted events. Furthermore, each record is scaled by a factor of  $t^{0.5}$ , where  $t$  represents the two-way traveltimes to compensate for the discrepancy between 2D and 3D wave propagation. Figure 21b shows the example shot record of Figure 21a after preprocessing.

Because the primary events are sparse, we generate a source wavelet by stacking a single reference event in the data, applying a half-derivative operator to correct the phase for 2D propagation. The estimated source wavelet is shown in Figure 22a. Figure 22b shows the wavelet's power spectrum, which exhibits a peak frequency of approximately 220 kHz.

We then took three steps in building the migration velocity model. First, we built a simple 1.5D model using traveltimes tomography. Second, we built a more comprehensive 2D model by combining a migration image generated using the 1.5D velocity model with the traveltimes misfit between the synthetic and the observed data. The final velocity model is shown in Figure 23. As can be seen, the model included a syncline-like structure and a fault-like structure. Finally, before migrating the data, we smoothed the velocity model using a Gaussian filter with a standard deviation of 13.

During the migration step, we first migrate the preprocessed data set using conventional RTM, the image from which is shown in

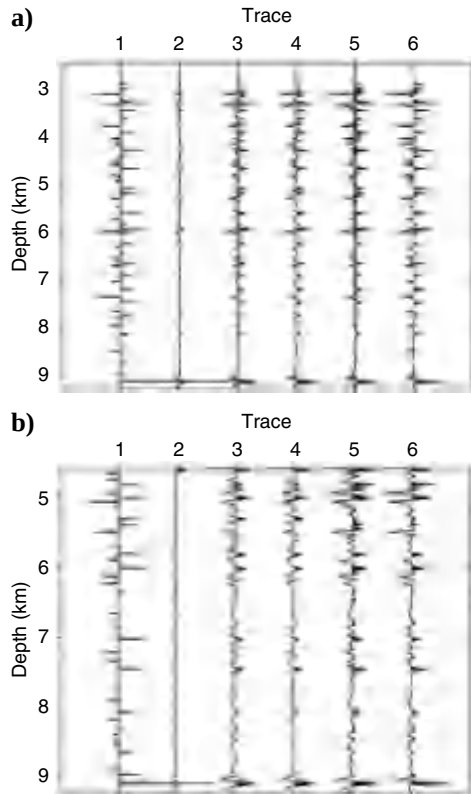


Figure 19. Wiggle display of two traces from the reference reflectivity model and the migration images shown in Figure 17. The traces are located at the distance of (a) 3.43 km and (b) 12.57 km. The six traces from left to right are from the reference reflectivity model, the RTM image, the unconstrained L2-norm-based LSRTM image, the multiplicative Cauchy-constrained L2-norm-based LSRTM image, the unconstrained Huber-norm-based LSRTM image, and the multiplicative Cauchy-constrained Huber-norm-based LSRTM image.

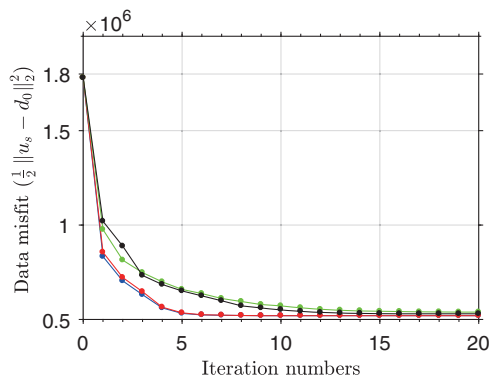


Figure 20. The data-misfit functional against the iteration numbers. The blue and red curves indicate the data misfit of unconstrained L2-norm-based LSRTM and the multiplicative Cauchy-constrained L2-norm-based LSRTM, respectively. The green and black curves are the counterparts of the red and black curves for the Huber-norm-based LSRTM.

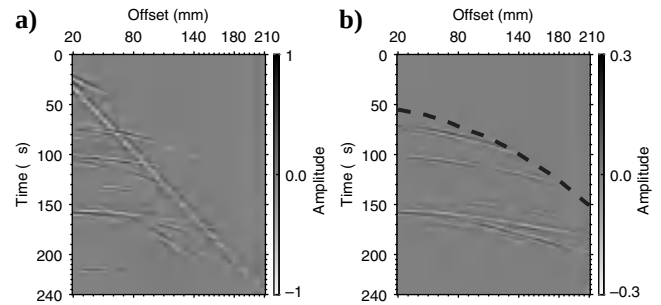


Figure 21. The 20th shot of the ultrasonic data set: (a) the raw data and (b) the preprocessed data. The preprocess removes the direct arrivals, other coherence noise, including S-wave energy, and the multiples. The dashed curve indicates the top mute, the data above which are not used in the migration.

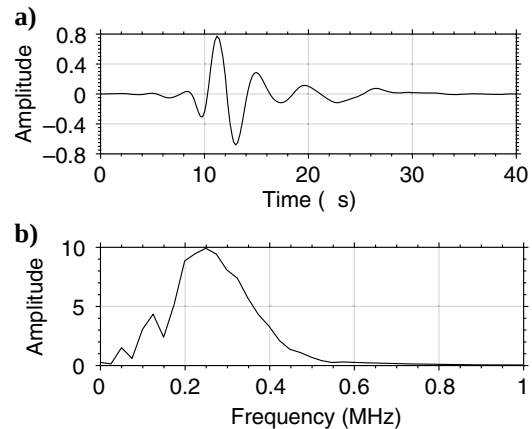


Figure 22. (a) The wavelet for inversion extracted by stacking one reference event from records. (b) The frequency spectrum of the extracted wavelet.



Figure 24a. Then, we migrate the preprocessed data set using unconstrained LSRTM. The image after 30 iterations is shown in Figure 24b. When comparing Figure 24a and 24b, it is evident that LSRTM produces an image with higher resolution than conventional RTM. This also is demonstrated by the wiggle display in Figure 24e. Due to poor conditioning of the unconstrained LSRTM system, however, the inversion process generates noticeable artificial sidelobes and high-angle reverberations, both of which degrade the image quality.

To suppress these artifacts, we then carried out LSRTM with a multiplicative Cauchy constraint. Using the magnitude of the reflectors and artifacts, we estimated a hyperparameter value of  $2.5 \times 10^{-5}$ , which is close to the amplitude of the artifacts. It was observed that the horizontal event beneath the syncline is relatively weak; therefore, the hyperparameter was relaxed for this region. The final spatially

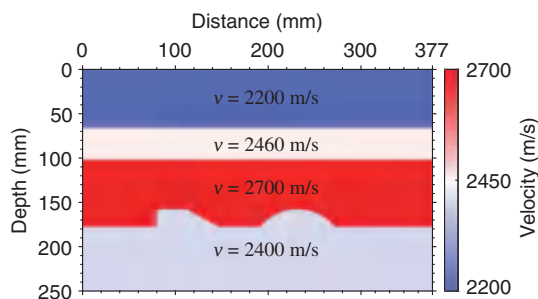


Figure 23. The final velocity model, which is built based on the traveltime tomography velocity model, the migration image, and the traveltime misfit between the synthetic data and recorded data.

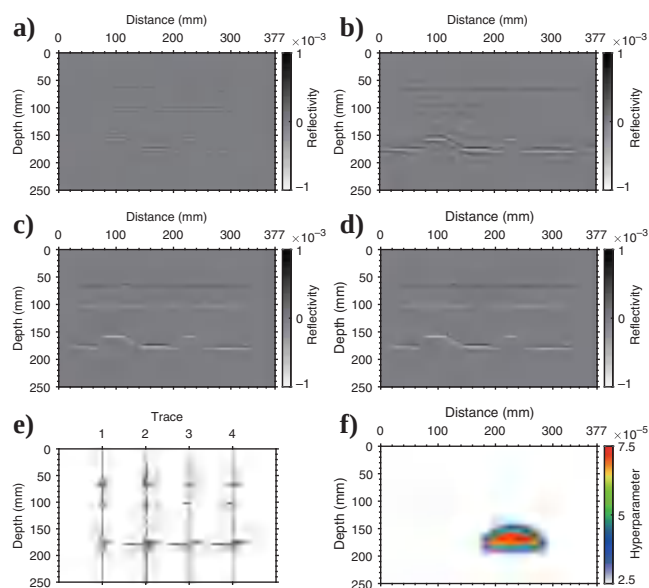


Figure 24. Migration images. (a) The RTM images with the preprocessed data set. (b) The unconstrained LSRTM image with 30 iterations. The image from Cauchy-constrained LSRTM with the relaxation term  $\epsilon$  set to (c) 60% and (d) 70% of the data-misfit functional value of the unconstrained LSRTM after 30 iterations. (e) The wiggle display of a trace from the four migration images. The trace is located at a distance of 159 mm. The trace numbers 1–4 indicate the images in (a)–(d), respectively. (f) The hyperparameter used in Cauchy-constrained LSRTM.

variable hyperparameter is shown in Figure 24f. Figure 24c and 24d depicts the Cauchy-constrained LSRTM images with the relaxation term  $\epsilon$  set to 60% and 70%, respectively, of the data misfit after 30 iterations of unconstrained LSRTM. As can be seen, these two images exhibited much-reduced noise levels compared with the unconstrained LSRTM image (Figure 24b). If instead we chose to use the additive functional of equation 3, an appropriate regularization parameter  $\beta$  must be found by trial and error. In contrast, when using the multiplicative functional, our only requirement was that we choose a relaxation term  $\epsilon$  that is less than the data misfit after unconstrained LSRTM. The wiggle display of Figure 24e, which contains a single trace from the four migration images, demonstrated the significant improvement imparted by the multiplicative Cauchy constraint. Wu et al. (2021) compared the Cauchy and L1-norm constraints for the same data set.

Data-misfit curves for unconstrained and constrained LSRTM are shown in Figure 25. These curves show that unconstrained LSRTM produces a reduced data misfit relative to constrained LSRTM, achieved by generating artifacts in the model that produce arrivals matching events in the observed data. However, unconstrained and constrained LSRTM leave relatively large residuals after each inversion has converged. Beyond the reasons discussed in the second example, there are two further reasons for this. First, ultrasonic waves propagating through an elastic model produce a different amplitude-variation-with-offset behavior than the acoustic wave equation used during the inversion (Chapter 5 of Aki and Richards, 2002). Second, the piezoelectric transducers used during the acquisition possess strong directivity. The energy is much stronger along the direction of the transducer points than it is in other orientations. (Budensiek et al., 2009). However, the response of the sources and receivers in the experiment is isotropic.

## DISCUSSION

### Regularization parameters $\lambda$ and $\epsilon$

The multiplicative Cauchy-constrained functional, i.e., equation 9, includes two regularization parameters  $\lambda_k$  and  $\epsilon$ . As analyzed and demonstrated in the previous sections, we determine the Cauchy hyperparameter  $\lambda_k$  first, followed by a heuristic approach to estimate the relaxation parameter  $\epsilon$ . The procedure to determine them both can be summarized as follows:

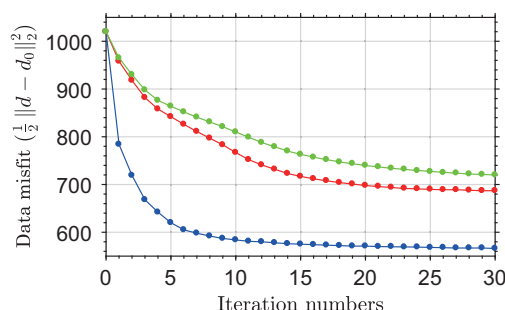


Figure 25. The data misfit against iteration numbers. The blue curve represents the data misfit of unconstrained LSRTM. The red and green curves denote the data misfit of Cauchy-constrained LSRTM with the relaxation term  $\epsilon$  set to 60% and 70% the data-misfit functional value of the unconstrained LSRTM after 30 iterations.

- 1) Compute the reflectivity model  $m_k$  using a few, e.g., five, iterations of unconstrained LSRTM.
- 2) Set  $\lambda_k$  close to the magnitude of the sidelobes and artifacts but less than the magnitude of most reflectors in the reflectivity model  $m_k$ .
- 3) Tune  $\lambda_k$  based on the gradient of  $\ln(1 + m_k^2/\lambda_k^2)$ : increase  $\lambda_k$  in areas where reflectors are considerably weaker than most of reflectors, even where these reflectors are close in magnitude to sidelobes and artifacts. An optimal  $\lambda_k$  generates a low gradient value near to reflectors but a high gradient value in regions bearing artifacts.
- 4) Set  $\varepsilon$  to a value smaller than the residual data misfit after unconstrained LSRTM has converged. In general, 70% of the residual data misfit is an acceptable estimate.

### Fine stratigraphy

A subset of the Sigsbee2A model that contains thin layers is used to demonstrate how conventional RTM, unconstrained LSRTM, and our proposed Cauchy-constrained LSRTM behave

in geologic settings that include fine stratigraphy. Three data sets generated using Ricker wavelets with peak frequencies of 10, 15, and 20 Hz have been constructed for this test. The migration results are shown in Figure 26. As expected, and as can be seen, data lacking high-frequency content are unable to resolve fine layers in the subsurface. For instance, the RTM image obtained from the data generated using the 10 Hz wavelet (Figure 26d) is missing certain thin layers. This is because, for this particular spectral content, events that have reflected from adjacent layers have interfered in a manner that does not allow for energy from those layers to be separated. LSRTM is able to improve the resolution by deconvolving the wavelet. However, LSRTM also tends to generate sidelobes and migration artifacts; we have shown that these can be suppressed using the Cauchy constraint. However, if reflections from two interfaces in close proximity to one another are canceled completely or suppressed significantly via interference due to opposing signs of reflectivity, then none of the three migration methods discussed can recover these interfaces. For instance, this phenomenon can be observed at the tip of a wedge layer highlighted by the black arrows in Figure 26.

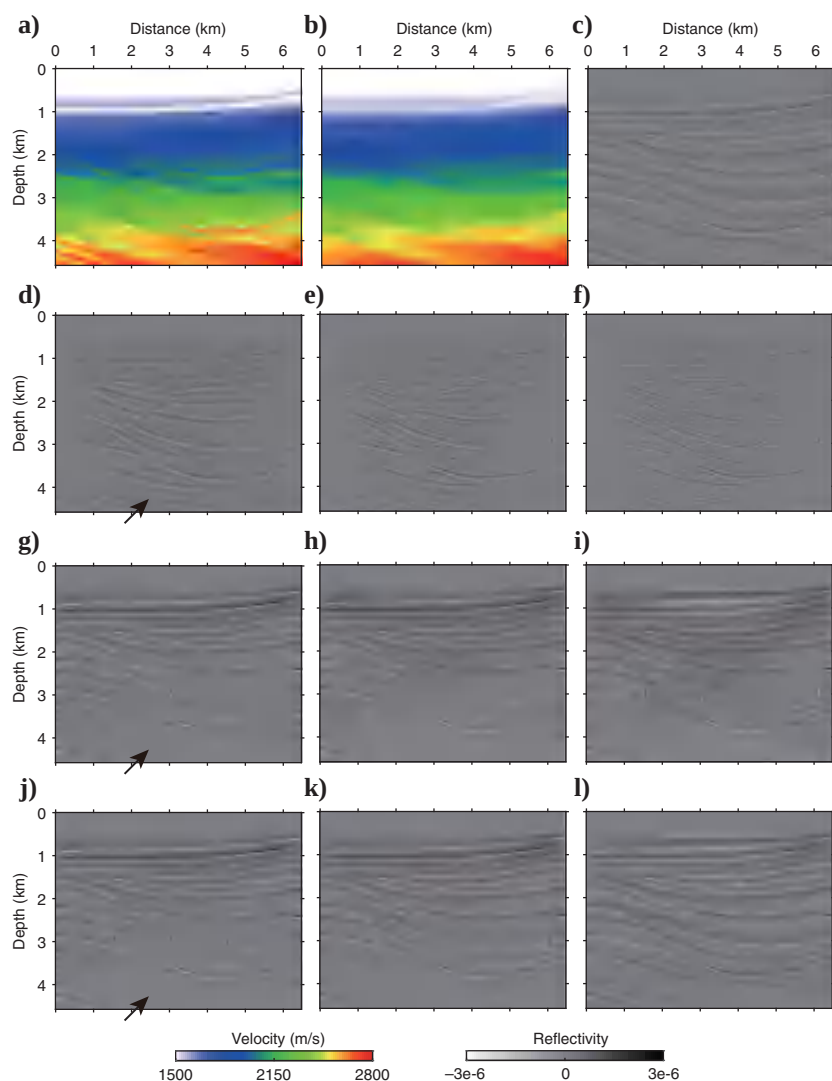


Figure 26. Migration imaging a section of the Sigsbee2A model with three RTM methods. (a) The true velocity model. (b) The migration velocity model, which is a smoothed version of (a) by using Seismic Unix command smooth2, (c) a scaled version of the normal incident reflectivity of (a), (d–f) conventional RTM image, (g–i) unconstrained LSRTM images with 50 iterations, and (j–l) Cauchy-constrained LSRTM images with 50 iterations. Plots in (d), (g), and (j), respectively, (e), (h), and (k), respectively, and (f), (i), and (l), respectively, show the images of data generated using 10, 15, and 20 Hz Ricker wavelets. Each data set comprises 56 shots. The receivers are spread on the top of the model uniformly. The black arrows indicate the tip of a wedge layer.

## Inaccurate migration velocities

We have repeated the migration of the subset data set generated using a 15 Hz Ricker wavelet, this time using an inaccurate migration velocity model that was produced by scaling the accurate migration velocity by a factor of 0.975. As a result, each reflector is imaged at a shallower position than its true depth. The deeper the reflector, the larger the depth error. In addition, the amplitude of each event becomes weaker due to an incoherent stack response. In this case, unconstrained LSRTM still improves image resolution relative to conventional RTM, however, the migration artifacts produced (Figure 27c) are stronger than when using the accurate velocity model (Figure 26h). These artifacts, as well as some of the sidelobe energy, are suppressed effectively by the Cauchy constraint; this also is evident in the physical model test. The main reason behind the degradation in image quality when using an imperfect migration velocity is that data from different offsets becomes focused at slightly different depths, leading to incoherent stacking. This is demonstrated in Figure 27, in which the migration images in Figure 27b, 27d, and 27f that are produced using short-offset data focus better than the migration images in Figure 27a, 27c, and 27e that are produced using full-offset data. This test implies that all three RTM algorithms explored here are

sensitive to the accuracy of the migration velocity model, especially in the case of long-offset data. Luo and Hale (2014) and Yang et al. (2019a) explore the topic of LSM in the presence of velocity error. Yang et al. (2019a) suggest stacking subsurface common-image-point gathers to within half a wavelength in width when producing the final image. This suggestion is congruent with our test, in which migration using short-offset data provides better focusing than when using full-offset data. By way of contrast, the sensitivity of long-offset data to migration velocity errors provides the basis for reflection waveform inversion, a technique for providing background velocity updates from reflected events (e.g., Yao et al., 2020).

## Coherent noise

The data sets used in the overthrust model and physical model tests include coherent noise, such as interbed multiples and S waves. This coherent noise gives rise to migration artifacts, for example, in Figure 9, which contains high-wavenumber artifacts around the reverse faults. These artifacts become stronger in the unconstrained LSRTM results, as shown in Figures 9b, 17c, and 24b. In turn, the artifacts are largely suppressed by the Cauchy constraint. If a shot record does not include any coherent noise, unconstrained and Cauchy-constrained LSRTM will produce adequate results. This is demonstrated by the results contained in Figure 28, in which the observed data are generated using Born modeling (equation A-4) instead of the full wave equation (equation A-1). Consequently, the modeling kernel in each of the LSRTM methods can predict precisely the observed data. In this case, the automatically computed regularization parameter  $\beta$  is small. Therefore, the Cauchy constraint plays a minor role in the inversion so as to avoid over-penalization. The results contained in Figure 28 serve to further demonstrate the robustness of the proposed Cauchy-constrained approach to LSRTM.

## Alternative optimization methods

Many optimization methods are suitable for sparsity promotion. However, in the case of the Cauchy constraint, the number of choices reduces considerably. The L0-norm is generally used as the standard measure of sparseness. However, it is NP (nondeterministic polynomial-time) hard to solve an optimization problem using the L0-norm (Natarajan, 1995). For this reason, the L1-norm is commonly used as an approximation to the L0-norm, as its mathematical properties yield more practical optimization algorithms. Thus, L1-norm-constrained LSRTM can be expressed as an L1-norm penalty problem:

$$\arg \min_m \frac{1}{2} \|u_s(\mathbf{x}_r) - d_0(\mathbf{x}_r)\|_2^2 + \beta \|m\|_1. \quad (16)$$

The iterative soft-threshold method is an efficient approach for solving the L1-norm penalty problem (Daubechies et al., 2004). The L1-norm penalty problem also can be converted into a constraint problem, i.e., a Lasso problem or, equivalently, a BPDN problem, which then can be solved using the SPGL1 minimization method (van den Berg and Friedlander, 2008). Wu et al. (2021) demonstrate that Cauchy-constrained LSRTM converges faster and to a solution closer to the true one than L1-norm-constrained LSRTM. This phenomenon also has been observed with FWI (Guitton, 2012). Alternatively, one might split the two optimization terms into two subproblems, minimizing each in an alternating fashion. In this case,

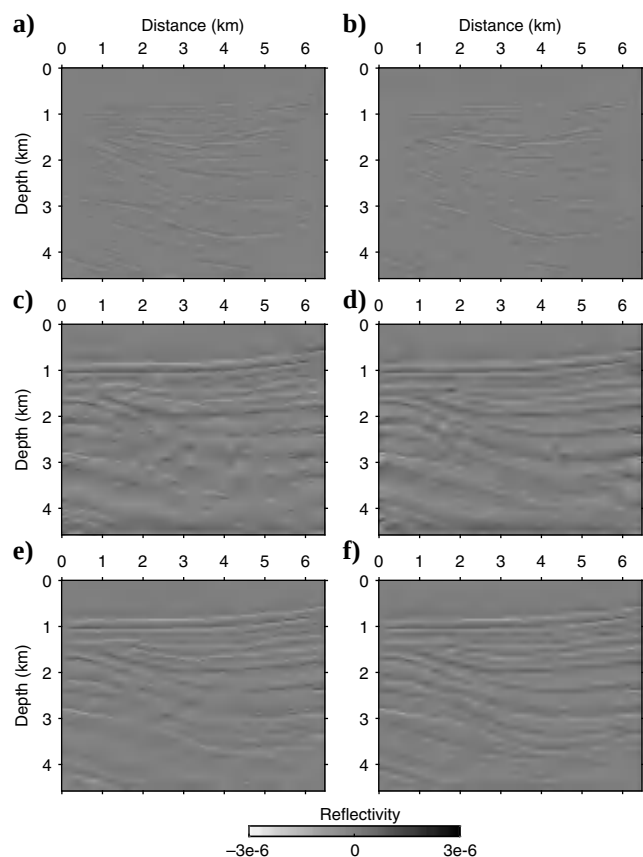


Figure 27. Migration with inaccurate velocity. The data set is generated using a Ricker wavelet with a 15 Hz peak frequency. Migration results depicted in (a), (c), and (e) use data with a maximum offset of 5.715 km, whereas half of its offset is used for obtaining the migration results in (b), (d), and (f). The migration velocity is produced scaling the migration velocity shown in (b) with a factor of 0.975. (a and b) Conventional RTM, (c and d) unconstrained LSRTM, and (e and f) Cauchy-constrained LSRTM.

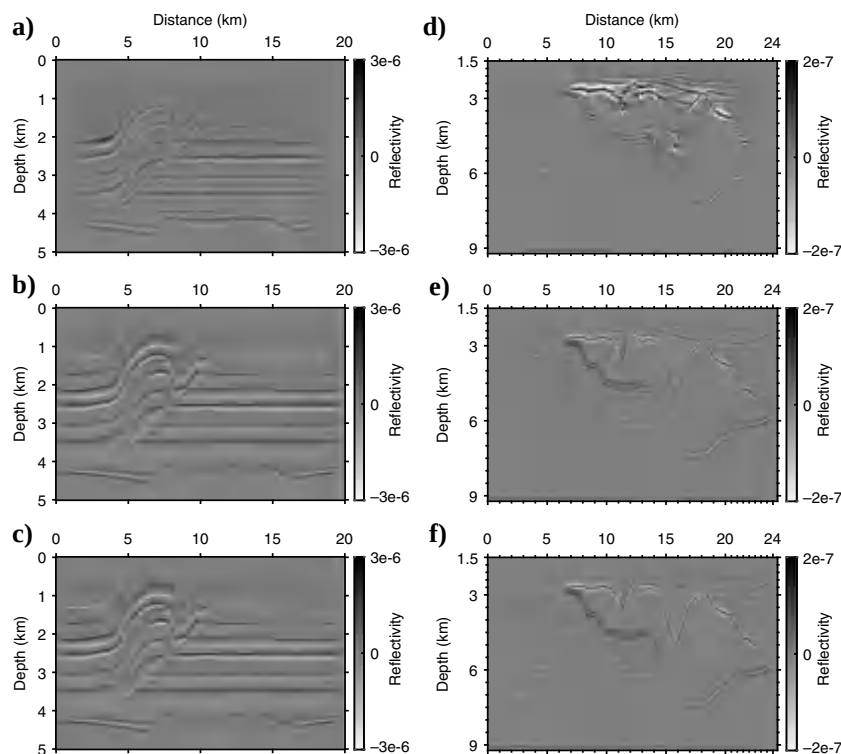


Figure 28. Migration images of the record generated with Born modeling. (a and d) Conventional RTM image, (b and e) unconstrained LSRTM image, and (c and f) Cauchy-constrained LSRTM image. The parameters for migration are the same as those for the two models in the example section. The background velocity of Sigsbee2A for Born modeling is generated by smoothing the true velocity model with a cosine-square window, the half-width of which is 80 cells.

the regularization essentially becomes a postprocessing step. Kalita et al. (2019) demonstrate this strategy as effective for salt flooding during FWI.

## CONCLUSION

Compared to RTM, LSRTM introduces an improved approximation to the inverse of the Hessian matrix that helps to remove the blurring effects of the source wavelet and compensate for uneven illumination; it can thereby produce amplitude-balanced high-resolution migration images. However, due to the typically large condition number of the Hessian matrix, as well as noise inherent to field data, LSRTM also can produce a series of sidelobes around true reflectors along with artificial events in the migration image. To mitigate these problems, we propose the use of the Cauchy constraint as part of a multiplicative cost function. Doing so avoids the requirement to determine a regularization parameter. We introduce a relaxation term to the multiplicative cost function that assists in avoiding over-penalization for complex models. The value of the relaxation term should be smaller than the residual data misfit after unconstrained LSRTM. Numerical experiments show that it is reasonable to use approximately 70% of the residual data-misfit functional value. A spatially varying hyperparameter in the Cauchy constraint is recommended. The value of the hyperparameter should approximate the magnitude of the artifacts but be less than the magnitude of the reflectors; the hyperparameter also can be tuned to prevent the inversion from removing weak reflectors. The

multiplicative functional is nonquadratic due to the Cauchy term being nonquadratic. We use a PNCG method to minimize the functional. A parabola, which is a function of step length but not the reflectivity model, is computed to fit the data-misfit functional prior to the line search. As a result, this new line-search method determines a step length with a trivial cost. Thus, the overall computational cost is comparable to unconstrained LSRTM. Numerical examples demonstrate that our proposed Cauchy-constrained LSRTM can improve the image resolution as well as suppress migration artifacts. Furthermore, the ultrasonic example demonstrates the robustness and effectiveness of our method when used with real-world data.

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## DATA AND MATERIALS AVAILABILITY

Data associated with this research are available and can be obtained by contacting the corresponding author.

## APPENDIX A

### FORWARD MODELING AND GRADIENT CALCULATION FOR LSRTM

As of today, the use of seismic imaging in exploration geophysics relies on acoustic wave equations. In this paper, we elect to use the isotropic acoustic wave equation to demonstrate our proposed Cauchy-constrained approach to LSRTM. The isotropic acoustic wave equation reads

$$\left( \frac{1}{\rho(\mathbf{x})v^2(\mathbf{x})} \frac{\partial^2}{\partial t^2} - \nabla \cdot \frac{1}{\rho(\mathbf{x})} \nabla \right) u(\mathbf{x}, t) = s(t)\delta(\mathbf{x} - \mathbf{x}_s), \quad (\text{A-1})$$

where  $u(\mathbf{x}, t)$  represents the pressure wavefield,  $v(\mathbf{x})$  indicates the wave speed,  $\rho(\mathbf{x})$  denotes the density,  $s(t)$  is the source wavelet at position  $\mathbf{x}_s$ ,  $\delta$  is the Dirac delta function,  $\mathbf{x}$  is a vector containing spatial coordinates, and  $t$  represents the time. A unique solution to equation A-1 is determined by the initial conditions, in our case being

$$\begin{cases} u(\mathbf{x}, t=0) = 0 \\ \frac{\partial}{\partial t} u(\mathbf{x}, t=0) = 0 \end{cases}, \quad (\text{A-2})$$



which ensure that the energy contained in the wavefield  $u(\mathbf{x}, t)$  originates from the injected source, and a boundary condition, given by

$$u(\mathbf{x} \in \partial\Omega, t) = 0, \quad (\text{A-3})$$

where  $\partial\Omega$  denotes the domain boundary. In seismic imaging, absorbing boundaries are typically imposed to fulfill the boundary condition of equation A-3 (Yao et al., 2018a).

The two-way wave equation (equation A-1) does not contain the reflectivity model, which is a requirement for the forward-modeling process in LSRTM. To solve this problem, the forward-modeling equation for LSRTM is usually derived by linearizing the wave equation, using either the Born scattering or Kirchhoff approximations (Yao et al., 2018b). In this paper, we choose to use the Kirchhoff approximation, which can be expressed as

$$\begin{cases} \left( \frac{1}{\rho v_0} \frac{\partial^2}{\partial t^2} - \nabla \cdot \frac{1}{\rho} \nabla \right) u_0(\mathbf{x}, t) = \frac{\partial s(t)}{\partial t} \delta(\mathbf{x} - \mathbf{x}_s) \\ \left( \frac{1}{\rho v_0} \frac{\partial^2}{\partial t^2} - \nabla \cdot \frac{1}{\rho} \nabla \right) u_s(\mathbf{x}, t) = m(\mathbf{x}) u_0(\mathbf{x}, t) \end{cases}, \quad (\text{A-4})$$

where  $u_0$  denotes the source wavefield,  $u_s$  is the scattering wavefield,  $v_0$  is the migration velocity, which is typically smooth, and  $m$  represents the reflectivity model. It follows that the energy recorded at receiver positions can be expressed in the integral form as

$$u_s(\mathbf{x}_r, \mathbf{x}_s, \omega) = i\omega \int G_r(\mathbf{x}_r|\mathbf{x}, \omega) m(\mathbf{x}) G_s(\mathbf{x}|\mathbf{x}_s, \omega) s(\omega) d\mathbf{x}, \quad (\text{A-5})$$

where  $G_s$  is the Green's function between the source location  $\mathbf{x}_s$  and the model position  $\mathbf{x}$  and  $G_r$  is the Green's function between the model position  $\mathbf{x}$  and the receiver location  $\mathbf{x}_r$ . One noticeable merit of the forward-modeling approach based on equations A-4 and A-5 is that any migration image generated will have zero phase, which is convenient for seismic interpretation. However, a migration image based on the Born approximation will contain a 90° phase shift, resulting in an antisymmetric image. It is worth noting that the reflectivity model  $m$  has a different magnitude than the actual reflectivity but it can be calibrated, for example, using well-log data. Readers are referred to Yao et al. (2018b) and Lu and Liu (2020) for more details.

The L2-norm functional, i.e., equation 1, can be expressed in integral form as

$$F(m) = \frac{1}{2} \iiint (u_s(\mathbf{x}_r, \mathbf{x}_s, \omega) - d_0(\mathbf{x}_r, \mathbf{x}_s, \omega))^* (u_s(\mathbf{x}_r, \mathbf{x}_s, \omega) - d_0(\mathbf{x}_r, \mathbf{x}_s, \omega)) d\omega d\mathbf{x}_r d\mathbf{x}_s. \quad (\text{A-6})$$

Substituting equation A-5 into equation A-6 and taking the first-order derivative of  $F(m)$  with respect to  $m(\mathbf{x})$  yields

$$\begin{aligned} \frac{\partial F(m)}{\partial m(\mathbf{x})} &= \iiint \left( \frac{\partial u_s(\mathbf{x}_r, \mathbf{x}_s, \omega)}{\partial m(\mathbf{x})} \right)^* (u_s(\mathbf{x}_r, \mathbf{x}_s, \omega) - d_0(\mathbf{x}_r, \mathbf{x}_s, \omega)) d\omega d\mathbf{x}_r d\mathbf{x}_s \\ &= - \iiint i\omega (G_s(\mathbf{x}|\mathbf{x}_s, \omega) s(\mathbf{x}_s, \omega))^* G_r^*(\mathbf{x}|\mathbf{x}_r, \omega) (u_s(\mathbf{x}_r, \mathbf{x}_s, \omega) - d_0(\mathbf{x}_r, \mathbf{x}_s, \omega)) d\omega d\mathbf{x}_r d\mathbf{x}_s. \end{aligned} \quad (\text{A-7})$$

Equations A-1 and A-4 can be solved numerically via finite-difference methods. Repeatedly solving the wave equation is the dominant source of computational cost when performing LSRTM.

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Biographies and photographs of the authors are not available.

中国地球物理学会科学技术奖

# 证书



为表彰中国地球物理学会科学技术奖获得者，特颁发此证书。

获奖项目：海洋地震高精度全波形反演技术研发与规模化应用

奖项名称：科技进步奖

获奖等级：二等奖

获奖者：姚刚

证书号：DKJB-2025-07-001



证书号第7432006号



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# 发明专利证书

发明名称: 一种低噪音的最小二乘逆时偏移方法

专利权人: 中国石油大学(北京)

地址: 102249 北京市昌平区府学路18号

发明人: 吴迪;姚刚;吴博

专利号: ZL 2022 1 0201779.8

授权公告号: CN 114690242 B

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证书号第8328413号



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# 发明专利证书

发明名称：基于自伴随VTI方程的全波形反演方法、装置、介质及设备

专利权人：中国石油大学（北京）

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# 发明专利证书

发明名称：基于亥姆霍兹分解的弹性波场分离方法、装置和介质

专利权人：中国石油大学（北京）

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专利公告信息

# 发明专利证书

发明名称: 各向异性介质中纵横波的伪亥姆霍兹分解方法、装置和介质

专利权人: 中国石油大学(北京)

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证书号：软著登字第9243399号

软件名称：基于不依赖子波的卷积型Wasserstein-2距离目标函数全波形反演软件  
[简称：CW2-FWI]  
V1.0

著作权人：中国石油大学（北京）

开发完成日期：2021年12月23日

首次发表日期：未发表

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证书号： 软著登字第7772396号

软件名称： 基于稳定Q补偿粘滞声波全波形反演软件  
[简称：Q补偿VA-FWI]  
V1.0

著作权人： 中国石油大学（北京）

开发完成日期： 2021年03月27日

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软件名称： 3D各向同性声波高分辨FWI软件  
[简称： FWI\_AC\_IS03D]  
V1.0

著作权人： 中国石油大学（北京）

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[简称： FWI\_EL\_IS02D]  
V1.0

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V1.0

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软件名称： 2DVTI各向异性qP波高分辨FWI软件  
[简称： FWI\_AC\_VTI2D]  
V1.0

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软件名称： 3DVTI各向异性qP波高分辨FWI软件  
[简称： FWI\_AC\_VTI3D]  
V1.0

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2025年04月11日

合同编号: 33550000-21-FW0399-0005

合同编号:

# 科研对外协作合同

项目名称: 最优传输反射波全波形反演理论和方法

委托方 (甲方): 中国石油化工股份有限公司石油勘探开发研究院

受托方 (乙方): 中国石油大学 (北京)

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根据《中华人民共和国民法典》等有关法律规定, 甲乙双方在自愿平等、诚实信用的原则下, 就《最优传输反射波全波形反演理论和方法》项目有关事宜协商一致, 签订本合同, 双方共同履行, 严格恪守。

## 第一条 名词及术语解释

本合同所涉及的相关技术术语、技术名词按如下进行解释:

### 1. 基础资料

包括但不限于从甲方收集到的所有资料(纸质和电子文件)及项目研究过程中形成的原始资料。

### 2. 成果

包括但不限于中间成果和最终成果。

## 第二条 合同标的、主要技术服务内容(以批复后设计书为准)

- 1) 针对全波形反演中周波跳跃的问题, 本课题将采用数据域的方法, 研究凸性更好的目标函数来抑制周波跳跃, 研究内容包括: ①最优传输距离的目标函数; ②基于该目标函数的全波形反演方法。
- 2) 针对实际数据偏移距有限, 透射波穿透深度有限的问题, 本课题将利用反射波, 开展波形反演的研究, 内容包括: ①开发针对反射数据的波形反演算法, 包括优化目标函数, 提取梯度中的层析分量, 引入地质约束; ②探索针对反射波反演的数据预处理。

3) 针对复杂地表和构造地区, 观测数据的信噪比极低问题, 本课题将利用初至波, 开展波形反演的研究, 内容包括: ①开发针对初至波的波形反演算法; ②研发起伏地表模型的高效波场模拟算法; ③探索新的地震数据观测系统。

## 2. 研究内容

### 1) 基于最优传输距离目标函数的全波形反演

#### (1) 服务于最优传输距离目标函数的地震数据预处理方法

使用最优传输距离目标函数的前提是信号非负, 同时, 两个信号的“质量”相等, 而地震数据并不满足这两个条件, 故需要在反演之前对地震数据进行预处理。现有文献报道的预处理方法包括基于 W2 目标函数的正负分离方法, 线性变换法和正负交替指数函数法。正负分离方法导致目标函数对模拟数据不可导, 因此不适用于基于伴随法的全波形反演。线性变换法能保留原始的相位信息, 计算简单, 在一些合成数据算例中被证实有效, 且反演效果优于传统 L2 目标函数, 但理论分析表明经过线性变换后最优传输距离目标函数的凸性明显降低, 反演存在陷入局部极值的可能。正负交替指数函数法分别对地震数据作用和, 分别突出地震数据中的正值和负值, 反演中先利用正值构建目标函数进行模型更新, 再利用负值构建目标函数函数进行模型更新, 由此形成一个完整的模型更新过程。然而, 该方法有可能在两次模型更新中产生相反的更新方向, 且反演的计算量翻倍。现有文献报道的基于 W1 目标函数的全波形反演方法不要求数据非负, 但实际上计算的目标函数是, 这要求模拟和观测数据必须有一定的重叠部分, 否则寻优的结果可能是数据之间的自传输, 没有实现数据匹配。因此, 无论是 W1 还是 W2, 研究一种合适的地震数据预处理方法至关重要。

#### (2) 最优传输算子和伴随源的快速计算方法

仅考虑数据在一个维度上的差异，使用 W2 目标函数具有计算效率方面的优势，此时的最优传输算子可使用数据的积分和反函数解析地表示，免去了寻找最优传输算子的过程，但当模型的准确度低，地震数据不仅在时间方向有误差，在偏移距方向也会发生偏移，显然二维最优传输距离目标函数更适用。高维的 W2 目标函数需要求解复杂的 Monge-Ampère 方程，计算量大，现有文献报道的高维最优传输距离目标函数均是基于 W1 的，并将其转换为其他近似形式进行计算，该计算过程也是迭代进行的，具体的数学算法包括 SDMM (Simultaneous Descent Method of Multipliers) 和 PDHG (primal-dual hybrid gradient)。这些方法仅在数据道数和采样点数较少的情况下具有较高的计算效率，而当道数和采样点数较多时涉及大型矩阵和向量运算，计算成本显著增加。因此，需要研究一种高效的高维最优传输距离目标函数计算方法。将最优传输距离目标函数应用于全波形反演还需要推导相应的伴随源表达式，还需要保证伴随源的快速计算。

### (3) 不依赖于震源子波的最优传输距离反演方法

震源子波对全波形反演的影响很大，虽然理论上全波形反演能同时反演模型参数和震源子波，但多参数反演存在很强的不稳定性，故需要在全波形反演之前估计子波，然而准确提取子波是十分困难的。现有的基于最优传输距离目标函数的全波形反演方法尚未考虑子波不准确的情况，限制了该方法的实用性。因此，有必要在最优传输距离目标函数的框架下研究消除子波影响的全波形反演方法。

#### 2) 反射波波形反演

##### (1) 针对反射波的波形反演系统

反射波波形反演的主要目的是更新背景速度模型。而由反射波产生的梯度中包含了偏移和层析分量，并且偏移分量强于层析分量。偏移分量的作用是构



建模型的界面，而层析分量的作用是修正背景速度模型。因此，构建的反射波波形反演系统需要能有效分离梯度中的这两种分量。另外，因为反演系统的模拟算子不能完全描述地震数据的振幅特性，所以预测的数据和观测数据，特别是大偏移距上，振幅存在较大差异。因此，反射波波形反演系统需要很好地消除振幅上的差异，强调走时差异。

## (2) 利用约束条件消减反射波波形反演的零空间

由于地震观测系统的观测孔径有限，记录到的反射数据只在有限的角度内收集地下界面和背景速度的信息，因此，导致反射波波形反演系统是一个欠定性很明显的系统，反演系统中必须引入额外的信息来约束反演，使其反演结果稳定。

## (3) 针对反射波波形反演的数据预处理

实际观测到的地震数据包含了多种类型的信号和噪声，而反射波波形反演是针对反射波数据。因此，除了反射数据，其它类型的地震信号和噪声都不能为反演提供任何有用的信息，应该在反演的数据预处理中消除。另外，常规深度偏移，包括 Kirchhoff 深度偏移和逆时偏移，都有一套明确的处理流程，这些处理流程是否适合反射波波形反演是一个有意义的研究点。

## 3) 初至波波形反演

### (1) 针对初至波的波形反演系统

初至波的波形反演主要利用初至波的走时信息来反演近地表的速度模型。由于噪声、模拟内核的不准确性以及初始模型的不精确性，初至波波形反演需要一个鲁棒的反演系统来克服这三个因素对反演系统的影响。

### (2) 针对起伏地表模型的地震波场的高效模拟

初至波波形反演的模拟算子需要高效、准确地描述地震波的传播，特别是

走时信息。在陆地数据的应用中，波场模拟算子也需要准确地描述起伏地表。

(3) 针对中、深层速度建模演的观测系统设计

在复杂地表和构造地区，实际观测到的数据信噪比低，其中反射波同相轴不明显，因此基于反射波的速度建模方法，包括射线析成像和反射波波形反演，不能够正确建立速度模型。在这种情况下，时间偏移的效果往往比深度偏移效果好。然而，现有观测系统的初至波穿透的深度不足以实现对中、深层速度的建模。因此，需要设计新的观测系统在不明显地增加采集成本的情况下，实现对深层信息的采集。

第三条 技术方法和路线

(1) 高效最优传输距离目标函数预处理和计算方法

基于对数据旅行时信息凸性更好的最优传输距离目标函数研发稳健的全波形反演方法，具体实现思路如图 1 所示，包括：采用适当的地震数据预处理方法满足目标函数对模拟数据（近似）可导以及数据非负的要求；采用 Sinkhorn 距离近似代替最优传输距离，并引入计算效率较高的熵正则化目标函数，在保持目标函数良好凸性的前提下提高计算效率；使用卷积型最优传输距离目标函数消除子波估计不准对全波形反演的影响，增强实用性，并采用 GPU 并行计算提高效率。

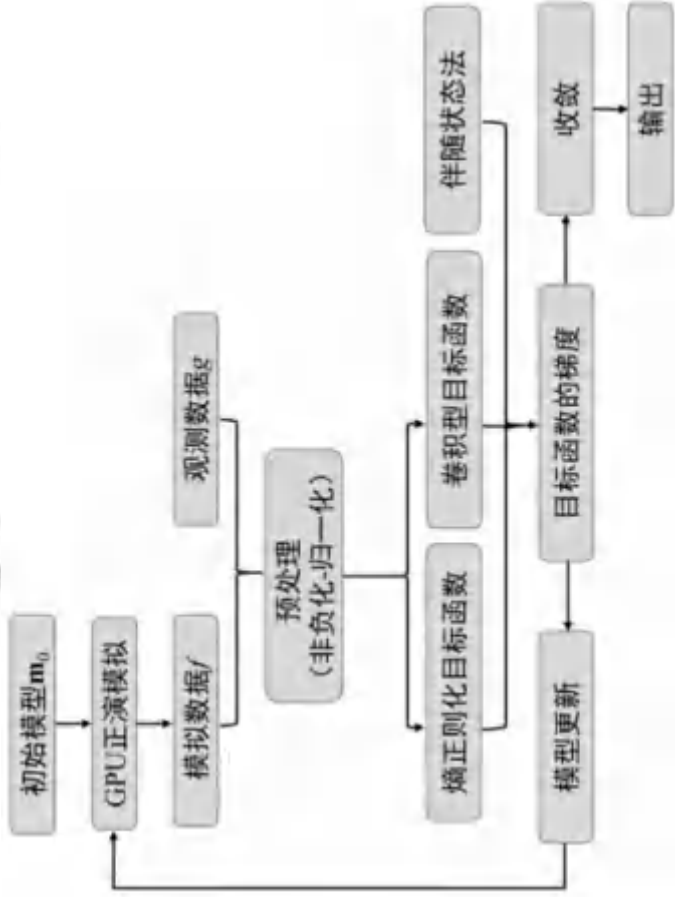


图 1 基于最优传输距离目标函数的全波形反演技术流程

## (2) 反射波波形反演

在该研究方向, 波动方程将被参数化成高频的反射轴模型和低频的背景速度模型, 引入缩放因子来增强反射波和透射波的分离效果, 利用“中间数据”(“intermediate data”)和“动态规整”(“dynamic wrapping”)来消除预测数据和观测数据的振幅不一致性, 利用各向异性扩散方程来实现“岩石物性沿层变化缓慢”的地质规律, 从而约束反演系统, 分析和改进常规处理流程来实现数据预处理。其具体技术流程如图 2 所示。

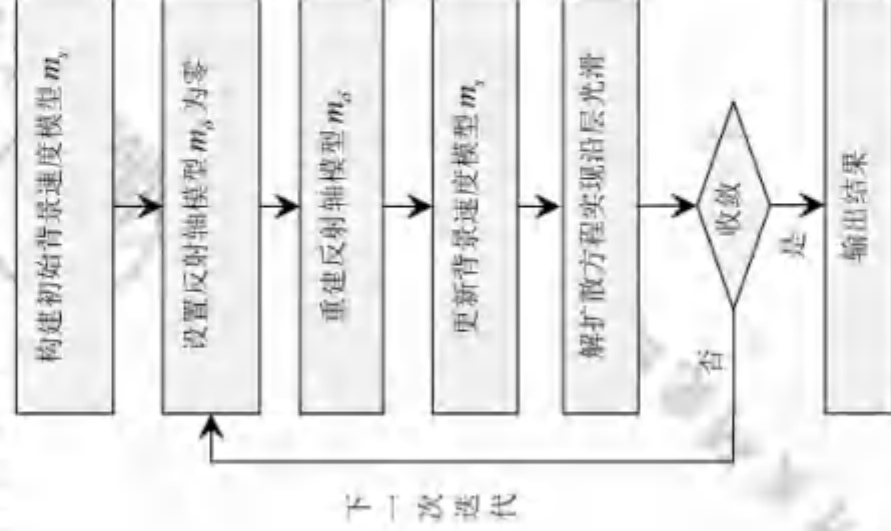


图2 反射波波形反演技术流程

## (3) 初至波波形反演

利用“浸入边界”(immersed boundary)法来实现起伏地表的初至波走时信息的精确模拟, 构建针对地表垂直分量数据的波形反演系统, 利用“中间数据”来消除振幅的不一致性和周期跳跃的问题, 设计和论证在常规采集的观测系统中添加大偏移距炮点来实现初至波对深层信息的采集。其具体技术流程如图 3 所示。

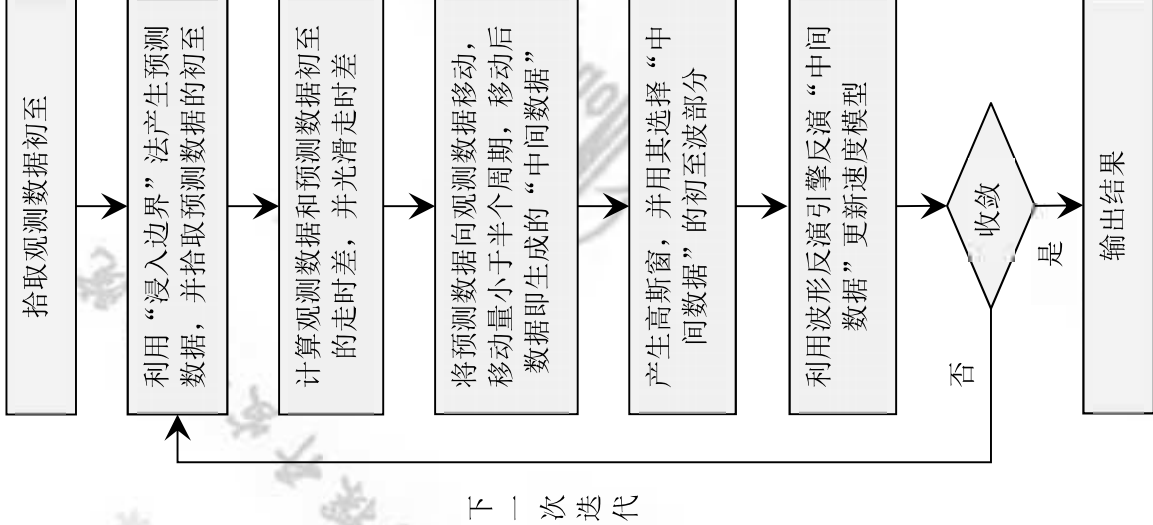


图3 初至波波形反演技术流程

#### 第四条 提交的主要成果

1. OT-FWI、反射波和初至波波形反演算法和二维程序;
2. 完成 2 套理论数据测试，速度反演效果优于常规全波形反演技术;
3. 完成 1 套实际数据测试，初步形成浅、中、深层一体化速度反演流程;
4. 项目成果报告。

#### 第五条 技术及经济考核指标

1. 最优传输目标函数相比常规目标函数收敛性提升 30%。



第六条 合同期限及进度计划

| 年度   | 起止时间<br>(-月-月)  | 研究内容                         | 提交成果与考核指标                                                     | 备注 |
|------|-----------------|------------------------------|---------------------------------------------------------------|----|
| 2021 | 合同签订日期<br>至 8 月 | 1) 适用于最优传输距离目标函数的地震数据预处理方法研究 | 1) 实现一种合适的地震数据预处理方法保证目标函数凸性                                   |    |
|      |                 | 2) 研究并分析改进的观测系统的方法，改进初至波反演效果 | 2) 实现初至波波形反演对中、深层速度模型反演效果的改善                                  |    |
|      |                 | 3) 一维 W2 目标函数的全波形反演方法        | 3) 编制基于一维 W2 目标函数的全波形反演程序，验证其反演效果                             |    |
|      |                 | 反射波波形反演算法研究                  | 编制稳健的反射波波形反演程序，验证其反演效果                                        |    |
| 2021 | 9 月             |                              |                                                               |    |
| 2021 | 10 月            | 基于地层构造约束的反射波形反演方法研究          | 在反射波波形反演中加入地层构造约束，改善反演效果                                      |    |
| 2021 | 11 月            | 畸正则化目标函数的快速计算方法              | 利用畸正则化实现最优传输距离目标函数的快速计算                                       |    |
| 2021 | 12 月            | 起伏地表地震波场数值模拟方法               | 利用浸入式边界条件实现自由地表条件下的波场模拟，消除网格阶梯状造成的虚假绕射                        |    |
| 2022 | 1 月             | 起伏地表条件下的初至波波形反演方法            | 编制起伏地表条件下初至波波形反演程序，验证其正确性                                     |    |
| 2022 | 2 月             | 基于畸正则化最优传输距离目标函数的全波形反演方法     | 编制基于畸正则化最优传输距离目标函数的全波形反演程序，验证其正确性                             |    |
| 2022 | 3 月             | 消除子波影响的畸正则化目标函数及全波形反演        | 消除子波影响反演程序运行稳定，具有较好的反演效果                                      |    |
| 2022 | 4 月             | 基于最优传输距离目标函数全波形反演合成和实际数据测试   | 利用典型的合成数据和实际数据测试全波形反演程序，取得明显优于传统 L2 目标函数全波形反演的效果，并形成详细的技术总结报告 |    |
| 2022 | 5 月             | 初至波波形反演、反射波波形反演方法的合成和实际数据测试  | 利用典型的合成数据和实际数据测试反演程序，取得明显优于传统反演方法的效果，并形成详细的技术总结报告             |    |

第七条 合同价款及支付方式

1. 本合同价款共计：【玖拾】万元（大写，含税）。本合同价款包括但不限于乙方完成本合同工作所需的全部费用，乙方不得以任何理由向甲方主张其他费用。

2. 若甲、乙双方无特别约定，合同价款按以下方式支付：

甲方在合同生效后一个月内, 付给乙方合同价款的 40%; 甲方在乙方成果通过最终验收, 完成归档后一个月内, 向乙方支付合同价款的 60%。

3. 甲方每次付款前都必须收到乙方开出的具有税务和财务专用章的正规【增值税】发票, 甲方签发的银行转帐票据日期为甲方付款日期。甲方付款前, 乙方未向甲方提供等额、合法的发票的, 甲方有权拒绝付款, 且视为违约。如乙方向甲方提供的发票不符合本合同约定或法律规定, 因此给甲方造成的一切损失由乙方承担 (包括但不限于损害赔偿、消除影响等)。

4. 乙方保证账户信息准确真实, 乙方的信息发生变化的, 应至少于甲方付款前书面通知甲方, 否则由此导致的错付、无法支付等所有法律后果均由乙方自行承担。

## 第八条 合同的履行期限

本合同履行期限自: 合同签订日起至 2022 年 5 月 30 日。

## 第九条 检查与验收

1. 乙方对工作进度和质量负责自检, 并接受甲方的检查和监督。
2. 甲方按照合同和设计书规定的进度要求, 对乙方工作进度、质量、阶段研究成果进行阶段检查。项目完成后, 乙方提出申请, 甲方组织专家进行最终成果验收。最终验收结果以甲方出具的书面报告为准。
3. 阶段成果检查和最终项目成果验收工作, 由甲方主持, 外部单位评审费用由乙方承担。检查、验收地点由甲方确定。

## 第十条 成果资料归档要求

1. 按照中国石化石油勘探开发研究院地质资料中心成果归档的相关规定执行。

2. 研究成果验收后【3】个月内完成归档。

## 第十一条 权利的归属

1. 专利申请权: 归甲方
2. 所有基础资料和成果所有权以及包括著作权在内的全部知识产权(包括但不限于申请专利的权利、专利权、著作权、著作邻接权、商标权等)均归甲方所有。

## 第十二条 保密条款

1. 乙方保证采取所有必要的方法对甲方提供的一切资料和乙方作业所取得的一切资料进行保密, 未经甲方事先书面许可不得以任何理由、任何方式提供给第三方。
2. 乙方保证从甲方收集的资料及本项研究中形成的资料数据只用于完成本合同规定的任务。
3. 项目取得的研究成果和资料数据, 未经甲方允许不得擅自发表、出版或者其他进行任何形式的使用或者透露给任何第三方。
4. 保密期限: 乙方对本项目的基础资料和成果负有永久性保密义务。

## 第十三条 双方权利与义务

1. 甲方有权对乙方使用、管理合同款项的情况进行监督和检查。
2. 甲方有权对乙方执行本合同的过程进行审查、批准, 有权对乙方执行合同的进度、质量、成果进行检查、监督、验收和提出修改意见。
3. 甲方有权要求乙方对提交的不合格成果和资料进行返工, 且甲方支付的合同费用以及乙方的履行期限不变。
4. 甲方负责答复乙方在合同执行过程中的有关问题。

5. 甲方负责按合同规定及时向乙方支付合同价款。
6. 如果乙方工作未能按合同、设计规定的要求按质按量完成，甲方有权减少或不支付余下的费用，有权要求返还已付合同价款并赔偿相应损失。
7. 在乙方未履行合同的的情况下，甲方有权终止合同并不支付任何费用；若甲方已向乙方支付了部分合同价款的，则甲方有权通过法律手段要求乙方无条件返还全部合同价款，并赔偿相应损失。
8. 未经甲方事先书面许可，乙方不得将其承担任务转包第三方完成。
9. 原则上乙方应在每月 25 日前向甲方呈报工作进度、完成工作量、取得的初步认识和工作中的新发现、存在问题及解决问题的措施、下一步工作安排等。
10. 乙方应严格按甲方批准的设计书开展工作，如研究过程中发现须要变更设计，必须及时上报甲方并经甲方书面批复后方可实施。
11. 乙方要配合甲方派出的检查人员工作，如实向甲方检查人员反映情况。

#### 第十四条 违约条款

1. 甲、乙双方任何一方未履行本合同条款，并造成对方经济损失的，受损方有权向对方索赔。
2. 因甲方原因而导致合同不能继续履行，乙方应将甲方交付中间成果。
3. 乙方承诺具有签署及履行本合同的合法资质和能力，履行本合同下的所有义务皆不存在任何法律上的限制或障碍。在本合同签署或履行过程中，如乙方违反本款约定导致本合同无法履行或终止的，应向甲方支付本合同标的金额的 30% 的违约金并赔偿给甲方造成的一切直接损失。



4. 乙方保证对其提交的全部工作成果拥有完全的处置权，其上无权利限制，且不侵害第三方的合法权益；甲方在使用本合同项下资料或其任何一部分材料时不受任何第三方提出的侵犯合法权益的追索，否则，因此造成甲方受到有权机关的处罚或受到第三方的投诉、诉讼、索赔等对甲方不利的后果，应由乙方负责承担全部法律责任和经济赔偿，并赔偿甲方因此遭受的全部损失。

5. 乙方交付的各项工作成果未能通过甲方验收的，应按照甲方的要求在（30）日内进行整改，因此构成逾期的，还应承担相应违约责任；到期未整改或整改后仍不能通过甲方验收的，乙方应向甲方支付合同总金额（10）%的违约金，并赔偿因此给甲方造成的全部损失。同时，甲方还有权解除本合同，乙方应退还甲方已支付的全部费用。

6. 因乙方原因而导致合同不能继续履行，甲方有权追回已付款项，所有中间成果归甲方所有，且乙方应向甲方支付【0】元的违约金。

7. 乙方违反设计及技术规范而造成的损失或返工，费用由乙方自行承担。

8. 在合同执行过程中，乙方应严格按照国家有关安全、环保法律法规，做好安全环保工作；乙方应对由其造成的安全环保隐患和事故承担全部责任。

9. 乙方应严格按照甲方要求/课题设计书中约定的成果提交时间，按时向甲方提交中间成果、项目成果等。未经甲方书面同意，乙方逾期交付工作成果，每推后一天，应支付总价款1%的违约金；若提交成果达不到合同设计要求而导致返工，返工期间费用由乙方自行承担。若因延期或返工影响甲方总项目进度，乙方应向甲方支付合同价款的30%的违约金；若最终成

果验收不合格，甲方有权拒付剩余价款并可要求乙方支付合同价款的 30%的违约金，且甲方有权解除本合同，乙方应当返还甲方已经支付的全部价款。

10. 未经甲方事先书面同意，乙方不得将本合同项下的权利义务转让给第三方，否则乙方还应向甲方支付【10000】元的违约金，同时甲方还有权解除合同，乙方应当返还甲方已经支付的全部价款。

11. 乙方对本合同的内容、因履行本合同所知悉的甲方的商业秘密及其他保密信息负有保密义务。未经甲方事先书面许可，乙方不得将相关信息披露给任何第三方，乙方违反本条保密约定，应向甲方支付本合同标的金额 30%的违约金，还应承担全部法律责任并赔偿因此给甲方造成的全部损失。本条约定永久有效，不因本合同终止而无效。

12. 除本合同另有约定外，乙方违反合同约定的其他义务的，经甲方催告后【30】日内仍不改正或改正后仍不符合合同约定的，乙方应向甲方支付【10000】元的违约金，同时，甲方有权解除本合同，乙方应退还甲方已支付的全部款项。

13. 因乙方违反本合同约定而需要向甲方支付的任何费用（包括但不限于损失赔偿费用、违约金等），甲方均有权在向乙方支付合同款时予以扣除。

14. 乙方基于本合同应向甲方支付的违约金不足以弥补甲方所受损失的，应当予以补足。本合同所约定的甲方损失包括但不限于甲方经济利益的减损、甲方为证实乙方违约行为所支付的调查取证、公证费用、甲方为寻求救济所支付的诉讼费、保全费、律师代理费、咨询费和调查取证费、差旅费等。

15. 未经甲方事先书面许可，乙方不得将与本合同研究内容相关的任何信息、研究成果，做发表论文、书籍、专著使用。

## 第十五条 不可抗力

1. 如发生不可抗力, 当事一方应立即通知对方, 并在不可抗力发生之日起3日内提交发生不可抗力的有效证明。

2. 若发生不可抗力造成暂时不能履行合同的, 经双方同意可以暂时中止履行合同(或合同的一部分), 待不可抗力消失后, 合同继续履行。

## 第十六条 争议解决

1. 在合同履行期间发生争议的, 双方应友好协商解决。若经友好协商仍达不成一致的, 任何一方均有权向甲方所在地有管辖权的法院起诉。

2. 争议协商、调解及诉讼期间, 双方仍继续履行本合同中规定的义务。

## 第十七条 合同的变更与终止

### 1. 合同变更

在合同执行过程中, 若要变更合同, 需经双方法定代表人或授权代表签字并加盖公章或合同专用章后方可变更。

### 2. 合同终止

2.1 乙方按合同规定的要求, 完成全部技术服务内容和成果归档, 并结清全部价款后终止。

2.2 不可抗力造成合同不能履行, 合同终止。

2.3 乙方超过合同规定期限达1个月未能进行交付的, 视为乙方根本性违约, 甲方可以随时通知乙方, 单方终止合同。

2.4 未经甲方事先书面许可, 乙方擅自变更项目设计或合同明确的设备和人员, 甲方可以单方终止合同。

2.5 乙方提交的技术成果经返工整改后仍不能达到质量标准、合同和设计要求的, 甲方可以单方终止合同。

2.6 经双方书面同意终止合同。

3. 因本条 2.3 款、2.4 款和 2.5 款原因终止合同的, 乙方应返还甲方支付的所有费用, 并支付相应的违约金。

## 第十八条 其它

1. 合同附件是合同的组成部分, 与合同正文具有同等的法律效力。本合同

同附件如下:

1. 1: 项目设计书

2. 本合同未尽事宜, 双方可签订补充协议, 共同遵照执行。

3. 本合同一式 **【8】** 份, 双方各持 **【4】** 份, 经双方法定代表人或授权代表签字并加盖公章或合同专用章后生效。

4. 双方因履行本合同或与本合同有关的一切通知都必须按照本合同中的地址, 以书面形式或双方确认的传真或类似的通讯方式进行。采用信函形式的应使用挂号信或者具有良好信誉的特快专递送达。如使用传真或类似的通讯方式, 通知日期即为通讯发出日期, 如使用挂号信件或特快专递, 通知日期即为邮件寄出日期, 并以邮戳为准。

(以下无正文)



合同编号: 33550000-21-FW0399-0005

单位名称: 中国石油化工股份  
有限公司石油勘探开发研究院

单位名称: 中国石油大学 (北京)

委托方 (盖章):

受托方 (盖章)

负责人或授权委托人

法定代表人或授权委托人

(签字):

(签字):

年 月 日

年 月 日

或禁止与其交易的处理;涉嫌犯罪的,报请司法机关追究其刑事责任。

**第五条** 本责任书经双方签署后生效。

甲乙双方签订交易合同的,本责任书作为交易合同附件,与交易合同具有同等法律效力;未签订交易合同的,本责任书独立有效。

**第六条** 甲乙双方及其人员在交易活动完成后,发生或发现违反本责任书规定的行为,按本责任书约定处理。

**第七条** 本责任书一式两份,甲乙双方各执一份,具有同等法律效力。

甲方单位: (盖章)

法定代表人或

授权委托人(签字):

乙方单位: (盖章)

法定代表人或

授权委托人(签字):



郭浩



李兴成

签订日期: 2021年7月22日

## 《最优传输反射波全波形反演理论和方法》

# 课题设计书

总项目名称: 复杂地表地质条件下弹性波模拟与地震成像反演技术(一期)

委托方: 中国石油化工股份有限公司石油勘探开发研究院

承担方: 中国石油大学(北京)

课题负责人: 姚刚

起止时间: 2021年6月至2022年5月

2021年6月23日

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## 一、目的与意义

### (一) 研究任务 (简要叙述本课题的主要任务, 要求: 如列出甲方提出的工作要求。)

高精度的速度建模是高分辨率、高精度地震成像、反演的关键因素之一。传统的地震速度建模主要基于射线的层析成像, 其只能给出低分辨率的模型。基于波动方程的全波形反演方法是弥补传统层析成像分辨率和精度不够的有效途径, 也是目前的研究热点。理论上全波形反演综合利用了全波场信息, 其速度建模精度高。然而, 全波形反演的适定性仍然是制约其实际应用的瓶颈, 具体表现在全波形反演效果明显依赖于地震数据的低频和初始模型, 以及大偏移距数据。实际地震数据缺乏有效的低频(如 5 Hz 以下)成分, 且初始模型无法提供较准确的旅行时信息时, 全波形反演将陷入局部极值, 产生“周波跳跃”。目前, 实际采集数据的偏移距有限, 大偏移距的透射波穿透深度有限, 限制了全波形反演建模的深度。另外, 在复杂地表和构造地区, 观测数据的信噪比极低, 是目前所有建模方法的主要障碍。针对这些问题, 为了提高全波形反演的适定性, 本课题将开展如下研究任务:

- 1、针对全波形反演中周波跳跃的问题, 本课题将采用数据域的方法, 研究凸性更好的目标函数来抑制周波跳跃, 研究内容包括: ①最优传输距离的目标函数; ②基于该目标函数的全波形反演方法。
- 2、针对实际数据偏移距有限, 透射波穿透深度有限的问题, 本课题将利用反射波, 开展波形反演的研究, 内容包括: ①开发针对反射数据的波形反演算法, 包括优化目标函数, 提取梯度中的层析分量, 引入地质约束; ②探索针对反射波形反演的数据预处理。
- 3、针对复杂地表和构造地区, 观测数据的信噪比极低问题, 本课题将利用初至波, 开展波形反演的研究, 内容包括: ①开发针对初至波的波形反演算法; ②研发起伏地表模型的高效波场模拟算法; ③探索新的地震数据观测系统。

### (二) 研究现状

传统全波形反演方法利用模拟数据和观测数据残差的 L2、L1、或者混合 L1/L2 范数构建目标函数, 并基于局部寻优算法在初始模型所在的凸域搜索目标函数的局部极值, 从而产生让模拟和观测数据达到最佳匹配的速度模型。然而, 传统目标函数将地震数据逐点进行比较, 无法有效利用地震波旅行时信息更新速度模型的低频成分, 反而在反演过程中过分突出振幅信息, 在初始模型不准确的情况下, 导致全波形反演出现周波跳跃, 致使反演结果更像是高频的偏移剖面。目前许多学者已提出了不同的方案来缓解或避免周波跳跃问题, 包括从低频到高频的多尺度反演 (Bunks et al., 1995; Sirgue and Pratt, 2004), 然而实际地

震数据的低频成分往往受噪声干扰并不可用。一些低频预测方法虽然经合成数据验证可行,但还未见到明显的实际数据应用效果。另一种抑制周波跳跃问题的方法是成像域的反演方法,类似于偏移速度分析,通过将模型空间扩展出一维(地下偏移距或时移量)来扩大模型的搜索空间(Symes 2008),有助于跳出局部极值,但这类方法的计算成本高,并且在实际使用中有很多限制。为了避免传统 L2 目标函数过分突出振幅匹配的缺点,一些新的目标函数得以在全波形反演中应用,包括包络目标函数(Wu et al., 2014),互相关目标函数(Van Leeuwen and Mulder 2010; Luo and Schuster, 1991),扩展的 Bump 目标函数(Bharadwaj et al., 2016),基于反卷积的自适应目标函数(Warner and Guasch, 2016)指数衰减目标函数(Choi and Alkhalifah, 2018),匹配滤波目标函数(Sun and Alkhalifah, 2019)等。这些目标函数在一定程度上增强了反演的适定性,但尚未见文献报道这些方法能完全抑制周波跳跃问题。

近些年一些学者将最优传输理论引入全波形反演,并提出了基于最优传输距离目标函数的全波形反演方法。最优传输距离也称 Wasserstein 距离,与传统范数类似, Wasserstein 距离又分为平方形式的 W2 距离和绝对值形式的 W1 距离。Engquist and Froese (2013)最早将 W2 目标函数用于合成地震数据反演,并证实 W2 目标函数对地震数据的时移具有良好凸性,且基于 W2 的反演效果明显优于传统的 L2 目标函数。计算最优传输距离本身是一个独立于全波形反演的最优化问题,最优传输距离目标函数有多种等价或近似的表达形式,求解方法各异,计算成本也不相同。此外,应用最优传输距离目标函数的前提是待比较的两个数据非负且质量(积分)相等,地震数据显然不满足这样的前提,特别是非负这一要求。因此,在全波形反演中使用最优传输距离目标函数时必须对地震数据进行预处理。然而,数据非负化和归一化预处理被证实有可能改变最优传输距离目标函数的凸性,从而削弱该目标函数的优势。Engquist and Froese (2013)将模拟和观测数据拆分为正负两部分,总的目标函数为这两部分在 W2 泛函下差异的和,但这种方法并不适用于全波形反演,因为利用伴随法推导伴随源时要求目标函数是关于模拟数据的可导函数。目前已被学者采用的预处理方法还有线性非负化、幂指数非负化(Engquist et al., 2016; Yang et al., 2018)以及混合的幂指数非负化。这些预处理方法大多是基于 W2 目标函数开展的研究, Yang and Engquist (2018a)讨论了几种预处理方法对 W2 目标函数凸性的影响,同时再次证实利用 W2 目标函数能产生更多的低波数更新以恢复地震波的运动学信息(Yang and Engquist, 2018b)。总之,基于最优传输理论的 W2 目标函数对地震波旅行时信息更敏感,基于 W2 目标函数的全波形反演能获得更丰富的低频信息,抑制周波跳跃,但应用好 W2 目标函数还需要研究更好的数据预处理方法。

此外,许多学者也研究了基于 W1 目标函数的全波形反演方法,与 W2 目标函数相比, W1 目标函数将高维地震数据进行整体比较时,其反演精度更高。在一维情况下,逐道考虑地震数据匹配时,使得 W2 目标函数达到最小的最优传输算子可以解析表示,因此计算效率较高,而将 W2 扩展到多维数据时需要求解 Monge-Ampère 方程,其计算量难以承受。W1 目标函数在考虑高维问题时,能将其转化为便于计算的其他形式。Métivier et al. (2016a, b) 将 W1 距离转化为对偶的 Kantorovich 问题,该方法不是逐道比较地震数据,而是将二维地震数据作为整体进行比较,其中使用了 SDMM (Simultaneous Descent Method of Multipliers) 来求解目标函数。然而,该方法需要需要计算大型块状稀疏矩阵的逆矩阵,当采样点数和道数较多时,计算目标函数所耗费的时间甚至达到了全波形反演一次迭代耗时的 70%,计算效率低。Li et al. (2017) 提出将最优传输问题转化为 L1 泛函最小化问题,这种思路被其他学者借鉴。Yong et al. (2018 年) 使用动态的 Monge-Kantorovich 形式表述 W1 目标函数,并采用主对偶混合梯度 (primal-dual hybrid gradient) 方法求解,将其用于二维数据的全波形反演方法,证实基于 W1 全波形反演方法对低频的依赖弱于常规 L2 目标函数。以上基于 W1 目标函数的全波形反演方法隐式地使用了 Mainini (2012) 提出的适用于非负数据的最优传输方法,不再要求数据非负,但实际上计算的目标函数是  $W_1(f^+ + g^-, g^+ + f^-)$ , 其中  $f$  和  $g$  分别为模拟和观测数据,上标+和-分别表示数据的正、负两部分。该策略也有局限性,要求模拟和观测数据必须有重叠部分,否则寻优的结果可能是数据之间的自传输。Chen and Peter (2018) 将加入熵正则化的最优传输距离引入了全波形反演,该方法仅需要几次迭代就可以计算目标函数,计算效率高,但该方法目前局限于一维。总的来说,与 W2 相比,将 W1 应用于全波形反演的优势在于能处理高维数据,适用于初始模型距离真实模型较远的情况(此时地震数据不仅在时间方向有移动,在炮检距方向也有偏移),但其计算成本较 W2 更高,且由于使用便于计算的近似形式,在一定程度上降低了最优传输距离目标函数的凸性。

目前,工业界的全波形反演主要以超临界角的反射数据和折射波数据为驱动。原因如下:当前全波形反演对工业生产的核心意义是提供更精确的偏移速度模型 (Warner et al., 2013)。偏移速度模型就是地震速度模型中的低频背景,而全波形反演对背景速度模型的修改依赖于其层析模式(其另外一个模式是偏移模式) (Mora, 1989; Zhou et al., 2015; Wu and Alkhalifah, 2017; Yao and Wu, 2017)。在全波形反演中,正传的震源波场和反传的余量波场中的波夹角接近于  $180^\circ$  时,互相关此波主要贡献于目标函数梯度中的层析分量。超临界角的反射数据和折射数据对应的互相关波的夹角接近  $180^\circ$ 。因此,目前工业界的全波形反演对



背景数据的更新是以超临界角的反射数据和折射数据为驱动的。

然而, 以超临界角的反射数据和折射数据为驱动会有如下问题: (1) 由于超临界角反射数据和折射数据穿透地层的深度浅, 波形反演的层析模式有效反演深度小, 往往不能达到油气目标层的深度, 由经验得知, 这种有效深度一般为最大偏移距的  $1/5$  到  $1/3$ ; (2) 大偏移距的折射数据的信噪比低, 这是因为地震波在复杂的地质模型中传播, 受各地层界面反射, 地层衰减, 最后回到地面的折射波能量比较微弱, 非常容易受到噪声干扰。

为了解决以上两个问题, 业界从两个方面进行探索。第一个方面是提升采集设备。增加检波器阵列的长度来记录更深层的超临界角反射数据和折射数据 (Kalinicheva et al., 2017), 如应用 OBC 和 OBN 来采集数据。在这种观测系统中, 气枪震源和检波器是分开的, 因此采集大偏移距数据很容易实现。除了改进接收系统, 震源系统也被改进。超低频可控震源被应用到陆地和海洋数据采集。在陆地上以东方地球物理公司的高精度可控震源系统为代表 (汪恩华等, 2013; Baeten et al., 2013)。在海上, 以 BP 公司的 Wolfspar® 震源系统为代表 (Dellinger et al., 2016)。这些系统的共同点是能够产生强能量的低频信号 ( $\sim 1$  Hz)。

第二个方面是改进反演算法。目前的一个发展方向是反射波波形反演 (RWI - reflection waveform inversion)。反射波波形反演就是以反射波为驱动的波形反演, 其目的是更新背景速度模型。选择反射波进行背景速度更新的主要原因是: 在相同偏移距, 反射波穿透深度远大于超临界角反射波和折射数据。另外, 经济原因也是推动反射波波形反演的一个重要因素。相对于全波形反演和偏移成像, 重新采集数据的成本要高很多。特别是在当前石油行业的低谷期而计算机的运行速度仍然以 Moore 定律每 18 个月性能增加一倍的背景下, 发展反射波波形反演成为了一个重要的研究方向。

基于以上原因, 近几年国内外石油公司、地球物理公司和学术界开始了反射波波形反演的探索。目前, 实施反射波波形的基本思路: (1) 用反射波建立反射界面模型, 此反射界面模型能够较好的拟合上小偏移距的反射数据; (2) 用大偏移距的反射数据并结合波形反演的层析模式来更新背景速度模型; (3) 清除当前已建立的反射界面模型, 重复第 (1) 和 (2) 步。

在第一步中, 反射界面模型可以是反射系数 (Yao and Wu, 2017) 或波阻扰动 (Zhou et al., 2015)。此步骤相当于最小二乘逆时偏移 (Yao and Wu, 2015)。此步骤的目的是建立一个反射界面模型来拟合上小偏移距的数据, 而由此模型产生的预测数据对大偏移距的数据拟合度较低, 特别其走时存在较大差异, 该走时误差包含背景速度模型的误差。



在第二步中, 一个重要的过程就是提取波形反演梯度的层析分量。基于反射数据的波形反演梯度包括层析分量和偏移分量。由于反射界面的反射系数一般远小于 1, 梯度中的偏移分量比层析分量强很多。因此, 如果不对这两种分量进行分离, 波形反演将着重更新界面, 而不是背景速度。目前进行此分离的方法有以下几种: (1) 分离后向散射波和入射波。如果震源波场和余量波场各自被分离成为入射波和散射波, 那么一个波场的散射波和另外一个波场的入射波的互相关产生梯度的层析分量, 然而相同类型的波互相关则产生梯度的偏移分量。从而, 梯度的模式得到分离。实现这种分离的方法有: (a) 将速度模型参数化为低频的背景速度和高频的反射系数 (Yao and Wu, 2017) 或波阻抗扰动 (Zhou et al., 2015); (b) 将波场分解成上、下行波和左、右行波 (Wang 2013; Irabor and Warner, 2016; Wu and Alkhalifah, 2016)。(2) 角度滤波。互相关传播夹角接近  $180^\circ$  的两个波将主要贡献于梯度的层析分量, 而其它角度的波主要贡献于梯度的偏移分量。因此设计一个角度滤波器可以分离这两种分量。角度滤波可以在“空间—时间延迟”域进行, (Alkhalifah, 2015; Wu and Alkhalifah, 2017, 2016), 或通过局部倾角叠加 (Xie, 2015) 或在平面波域滤波 (Yao et al., 2018)。但是目前的这些方法存在一些缺陷。第一类方法分离波场不是很彻底, 存在一些偏移分量泄露到层析分量中, 反之亦然。第二类方法计算量比较大。因此, 较好地实现梯度中两种分量的分离是本课题研究的一个要点。

在第二步中, 另一个重要的过程是振幅匹配。第一步中的反射界面模型只能较好的拟合上小偏移距的数据, 而大偏移距的数据的残差包括了振幅残差和走时残差。振幅残差是由于反射界面模型和真实速度模型的 AVO 的差异引起的。走时残差是由背景速度的误差引起的。因此, 用于更新背景速度模型的信息来源于走时残差而不是振幅残差。目前消除振幅残差的基本方法是振幅加权匹配 (Pratt, 1999)。但是这种方法不能完全消除振幅残差, 并能改变走时残差。因此, 消除振幅残差的振幅匹配是本课题研究的一个要点。

相对于用超临界角反射波和折射波的全波形反演, 用反射数据的反射波波形反演存在一个重要的难题: 零空间 (null space) 更大。其意思是有更多的模型能够完全拟合上观测数据。这是因为: (1) 反射波覆盖模型的角度远小于折射波, 即数据变少; (2) 速度模型被分成了低频的背景速度模型和高频的反射界面模型, 即模型参数变多。从理论上, 消减零空间需要引入约束信息, 包括数学约束条件和更多观测数据。目前, 数学约束包括 Tikhonov 正则化 (Tikhonov and Arsenin, 1977), 全变差 (total-variation) 约束 (Esser et al., 2016) 等; 观测数据包括井约束 (Vigh et al., 2015; Chen et al., 2016)。消减零空间也将是本课题的一个研

究要点。

地震勘探是一个数据观测的学科，其后续的一切数据处理步骤很大程度上都依赖于原始观测记录的质量。在复杂地表和构造区，地震记录的质量基本都很差，信噪比低。因此，阻碍了基于波形的常规全波形反演和反射波波形反演的实施。这也在公开发表的文献中可以看到，陆地数据的全波形反演结果相对海上数据的反演结果差很多（Cheng et al., 2017）。复杂地表和构造区的数据中，初至到时基本上是明确的。因此，初至走时信息能为地震速度建模提供信息。目前针对初至走时信息的反演基本上是基于射线层析（Bishop et al., 1985）。然而，射线是基于高频假设，在非均匀介质中，极易产生焦散和阴影区。基于射线的层析反演，在焦散区会出现过多更新，而在阴影区域更新不足。针对此，基于波动方程的全波形反演可以克服焦散和阴影区的问题。这是本课题的一个研究要点。

目前，地震观测系统设计主要是针对采集反射波。然而，在复杂地表和构造区，地震记录中的反射同相轴不突出。其中有两个原因：首先，复杂的近地表对震源激发的下行波和反射后的上行波有严重的吸收、衰减作用；其次，复杂的构造打破了反射界面的连续性，在回传的能量中振幅更弱的绕射、散射波更发育。因此，基于反射波的建模方法产生的深度速度模型不准确，导致一个普遍的现象：在最需要深度偏移的地区，深度偏移的效果很多时候还不如时间偏移效果好。解决这个问题一个途径是：重新设计观测系统，采用超大偏移距数据中的初至或透射波来建模。本课题将从理论和数值实验两个方面来研究、论证该思路。

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### (三) 存在问题

综合目前的研究现状, 以上三个方面的研究还存在以下问题:

#### 1、基于最优传输距离目标函数的全波形反演

(1) 地震数据并不符合使用最优传输距离目标函数的非负和质量相等假设, 无论是 W2 还是 W1, 适当的地震数据预处理对于保持目标函数的凸性至关重要, 目前已研究的预处理方法仍然存在不足:

(2) 与一维最优传输距离目标函数相比, 二维最优传输距离目标函数能综合利用地震数据在时间和偏移距方向上的差异信息, 理论上能更好地抑制周波跳跃, 但将二维最优传

输距离目标函数应用于全波形反演，其计算成本仍然较高；

(3) 与常规全波形反演方法类似，最优传输距离目标函数的实质也是地震波形匹配，将其用于全波形反演也面临子波估计不准而导致反演向错误方向收敛的问题。

## 2、反射波波形反演

(1) 目前，将波场分离为后向散射波和透射波方法的波场分离效果不是很彻底，存在一些偏移分量泄露到层析分量中的问题，反之亦然。而基于散射角滤波的方法计算量比较大；

(2) 目前，基于振幅差异的 L2、L1 范数为目标函数的反射波波形反演对振幅，特别是大偏移距的振幅，较为敏感，从而影响对背景速度的更新；

(3) 由于观测反射波的孔径有限，反射波波形反演的欠定性较强，反演容易收敛到一个错误模型；

(4) 目前，针对陆地数据反演的数据预处理流程还不是很明确。

## 3、初至波波形反演

(1) 基于振幅匹配的初至波波形反演存在对走时不敏感和周期跳跃等一系列问题；

(2) 针对初至波反演同时兼顾精度和效率的起伏地表模型的波场模拟方法不明确；

(3) 目前，地震采集观测系统主要针对对反射波，不适合初至波反演对中、深层建模。

## (四) 目的意义 (阐述本课题研究对总项目的支撑作用及影响。要求：必须明确课题要达到的目的。)

本课题从三个研究方向来协助总项目的推进，这三个方面旨在缓解或解决全波形反演面临的依赖初始模型和低频数据问题，能为总项目顺利开展基于声波和多分量弹性波全波形反演提供算法借鉴。具体地，包含以下三个方面：

1、在基于最优传输距离目标函数的全波形反演的方向，研究基于最优传输距离目标函数的高效全波形反演方法，从数据匹配的角度出发，研究凸性好、计算效率高的最优传输距离目标函数，并将其用于全波形反演增强其稳健性，目的是降低全波形反演对初始模型和数据低频的依赖，为偏移成像提供高精度精度的深度域速度模型。技术层面要达到以下目标：

(1) 实现一种合适的地震数据预处理方法，最大程度地保证最优传输距离目标函数在全波形反演中的凸性；

(2) 实现一种最优传输距离目标函数的高效计算方法, 使得应用最优传输距离目标函数不显著增加全波形反演的计算量;

(3) 采用不依赖于子波的反演策略和 GPU 并行加速策略, 增强基于最优传输距离目标函数全波形反演的实用性。

2、在反射波波形反演方向, 研究探索基于反射波数据的深度域的深层速度建模, 技术层面要达到以下目标:

(1) 形成一套较完善的反射波波形反演算法, 包括探索出鲁棒的目标数、实现梯度中的层析分量的有效提取、引入地质约束减弱反演的非唯一性;

(2) 探索出针对反射波波形反演的数据预处理流程。

3、在初至波波形反演方向, 研究基于初至波的浅层及中深层的深度域速度建模方法, 在技术层面要达到以下目标:

(1) 形成一套较完善的初至波波形反演算法, 能在实际数据中产生明显的效果;

(2) 开发出兼顾精度和效率的起伏地表模型的高效波场模拟算法;

(3) 探索出基于初至波波形反演方法的对中、深层速度建模的新观测系统。

## 二、研究内容与技术路线

**(一) 研究内容** (根据研究任务的要求, 详细阐述研究内容。要求: 紧扣主题, 分层次描述。)

本课题, 将从三个方面开展研究, 其具体研究内容如下:

1、基于最优传输距离目标函数的全波形反演

(1) 服务于最优传输距离目标函数的地震数据预处理方法

使用最优传输距离目标函数的前提是信号非负, 同时, 两个信号的“质量”相等, 而地震数据并不满足这两个条件, 故需要在反演之前对地震数据进行预处理。现有文献报道的预处理方法包括基于 W2 目标函数的正负分离方法, 线性变换法和正负交替指数函数法。正负分离方法导致目标函数对模拟数据不可导, 因此不适用于基于伴随法的全波形反演。线性变换法能保留原始的相位信息, 计算简单, 在一些合成数据算例中被证实有效, 且反演效果优于传统 L2 目标函数, 但理论分析表明经过线性变换后最优传输距离目标函数的凸性明显降低, 反演存在陷入局部极值的可能。正负交替指数函数法分别对地震数据作用  $e^{\cdot}$  和

$e^{-u}$ ，分别突出地震数据中的正值和负值，反演中先利用正值构建目标函数进行模型更新，再利用负值构建目标函数进行模型更新，由此形成一个完整的模型更新过程。然而，该方法有可能在两次模型更新中产生相反的更新方向，且反演的计算量翻倍。现有文献报道的基于 W1 目标函数的全波形反演方法不要求数据非负，但实际上计算的目标函数是  $W_1(f^+ + g^-, g^+ + f^-)$ ，这要求模拟和观测数据必须有一定的重叠部分，否则寻优的结果可能是数据之间的自传输，没有实现数据匹配。因此，无论是 W1 还是 W2，研究一种合适的地震数据预处理方法至关重要。

## (2) 最优传输算子和伴随源的快速计算方法

仅考虑数据在一个维度上的差异，使用 W2 目标函数具有计算效率方面的优势，此时的最优传输算子可使用数据的积分和反函数解析地表示，免去了寻找最优传输算子的过程，但当模型的准确率低，地震数据不仅在时间方向有误差，在偏移距方向也会发生偏移，显然二维最优传输距离目标函数更适用。高维的 W2 目标函数需要求解复杂的 Monge-Ampère 方程，计算量大，现有文献报道的高维最优传输距离目标函数均是基于 W1 的，并将其转换为其他近似形式进行计算，该计算过程也是迭代进行的，具体的数学算法包括 SDMM (Simultaneous Descent Method of Multipliers) 和 PDHG (primal-dual hybrid gradient)。这些方法仅在数据道数和采样点数较少的情况下具有较高的计算效率，而当道数和采样点数较多时涉及大型矩阵和向量运算，计算成本显著增加。因此，需要研究一种高效的高维最优传输距离目标函数计算方法。将最优传输距离目标函数应用于全波形反演还需要推导相应的伴随源表达式，还需要保证伴随源的快速计算。

## (3) 不依赖于震源子波的最优传输距离反演方法

震源子波对全波形反演的影响很大，虽然理论上全波形反演能同时反演模型参数和震源子波，但多参数反演存在很强的不稳定性，故需要在全波形反演之前估计子波，然而准确提取子波是十分困难的。现有的基于最优传输距离目标函数的全波形反演方法尚未考虑子波不准确的情况，限制了该方法的实用性。因此，有必要在最优传输距离目标函数的框架下研究消除子波影响的全波形反演方法。

## 2、反射波波形反演

### (1) 针对反射波的波形反演系统

反射波波形反演的主要目的是更新背景速度模型。而由反射波产生的梯度中包含了偏



移和层析分量, 并且偏移分量强于层析分量。偏移分量的作用是构建模型的界面, 而层析分量的作用是修正背景速度模型。因此, 构建的反射波波形反演系统需要能有效分离梯度中的这两种分量。另外, 因为反演系统的模拟算子不能完全描述地震数据的振幅特性, 所以预测的数据和观测数据, 特别是在大偏移距上, 振幅存在较大差异。因此, 反射波波形反演系统需要很好地消除振幅上的差异, 强调走时差异。

## (2) 利用约束条件消减反射波波形反演的零空间

由于地震观测系统的观测孔径有限, 记录到的反射数据只在有限的角度内收集地下界面和背景速度的信息, 因此, 导致反射波波形反演系统是一个欠定性很明显的系统, 反演系统中必须引入额外的信息来约束反演, 使其反演结果稳定。

## (3) 针对反射波波形反演的数据预处理

实际观测到的地震数据包含了多种类型的信号和噪声, 而反射波波形反演是针对反射波数据。因此, 除了反射数据, 其它类型的地震信号和噪声都不能为反演提供任何有用的信息, 应该在反演的数据预处理中消除。另外, 常规深度偏移, 包括 Kirchhoff 深度偏移和逆时偏移, 都有一套明确的处理流程, 这些处理流程是否适合反射波波形反演是一个有意义的研究点。

# 3、初至波波形反演

## (1) 针对初至波的波形反演系统

初至波的波形反演主要利用初至波的走时信息来反演近地表的速度模型。由于噪声、模拟内核的不准确性以及初始模型的不精确性, 初至波波形反演需要一个鲁棒的反演系统来克服这三个因素对反演系统的影响。

## (2) 针对起伏地表模型的地震波场的高效模拟

初至波波形反演的模拟算子需要高效、准确地描述地震波的传播, 特别是走时信息。在陆地数据的应用中, 波场模拟算子也需要准确地描述起伏地表。

## (3) 针对中、深层速度建模的观测系统设计

在复杂地表和构造地区, 实际观测到的数据信噪比低, 其中反射波同相轴不明显, 因此基于反射波的速度建模方法, 包括射线层析成像和反射波波形反演, 不能够正确建立速度模型。在这种情况下, 时间偏移的效果往往比深度偏移效果好。然而, 现有观测系统的

初至波穿透的深度不足以实现对中、深层速度的建模。因此，需要设计新的观测系统在不明显地增加采集成本的情况下，实现对深层信息的采集。

## (二) 技术路线

1、总体思路（用一段话描述开展本课题的研究思路。要求：简明扼要。）

基于对地震数据旅行时信息凸性更好的最优传输距离目标函数研发稳健的全波形反演方法，具体实现思路包括：采用适当的地震数据预处理方法满足目标函数对模拟数据（近似）可导以及数据非负的要求；采用 Sinkhorn 距离近似代替最优传输距离，并引入计算效率较高的熵正则化目标函数，在保持目标函数良好凸性的前提下提高计算效率；使用卷积型最优传输距离目标函数消除子波估计不准对全波形反演的影响，增强实用性，并采用 GPU 并行计算提高效率。

反射波波形反演方向，波动方程将被参数化成高频的反射轴模型和低频的背景速度模型，引入缩放因子来增强反射波和透射射波的分离效果，利用“中间数据”（“intermediate data”）和“动态规整”（“dynamic wrapping”）来消除预测数据和观测数据的振幅不一致性，利用各向异性扩散方程来实现“岩石物性沿层变化缓慢”的地质规律，从而约束反演系统，分析和改进常规处理流程来实现数据预处理。

初至波波形反演方向，利用“浸入边界”（immersed boundary）法来实现起伏地表的初至波走时信息的精确模拟，构建针对地表垂直分量数据的波形反演系统，利用“中间数据”来消除振幅的不一致性和周期跳跃的问题，设计和论证在常规采集的观测系统中添加大偏移距炮点来实现初至波对深层信息的采集。

2、技术路线（对照研究内容，逐一描述具体实施的技术方案。要求：详细、思路清楚、可操作，画出路线图）

本课题，将从三个方面开展研究，其具体技术路线如下：

1、基于最优传输距离目标函数的全波形反演

(1) 服务于最优传输距离目标函数的地震数据预处理方法

用  $f$  和  $g$  分别表示模拟数据和观测数据，以  $W_2$  目标函数为例，在经过数据预处理后构建如下形式的目标函数：

$$J(m) = W_2^2(P(f), P(g)) + W_2^2(P(-f), P(-g))。 \quad (2-1)$$

上式中,  $m$  为速度模型,  $P$  为数据预处理算子, 取其表达式为:

$$P(f) = \begin{cases} \frac{1}{b} \left[ f(t) + \frac{1}{c} \right], & f(t) \geq 0 \\ \frac{1}{bc} e^{cf(t)}, & f(t) < 0 \end{cases}, \quad (2-2)$$

其中  $c$  为适当选取的参数,  $b = \int P(f) dt$  为归一化因子。观察预处理算子  $P$  可发现, 当  $c$  足够小时, 预处理效果等价于线性非负化; 当  $c$  足够大时, 预处理突出正值部分, 由于目标函数 (2-1) 中包含相同的正向和负向权重, 因此负值部分的信息在反演中也得以利用。为考查经过预处理后目标函数的凸性, 考虑两个时移的雷克子波, 利用式 (2-2) 进行预处理, 然后计算目标函数随时移量的变化曲线, 图 2-1 显示了经过式 (2-2) 中预处理算子作用后的子波形态, 明显突出了正值部分。图 2-2 为式 (2-1) 中目标函数随时移时移量的变化曲线, 可见经过预处理后  $W2$  目标函数的凸性仍得以保留, 证实了该预处理方法的可行性。

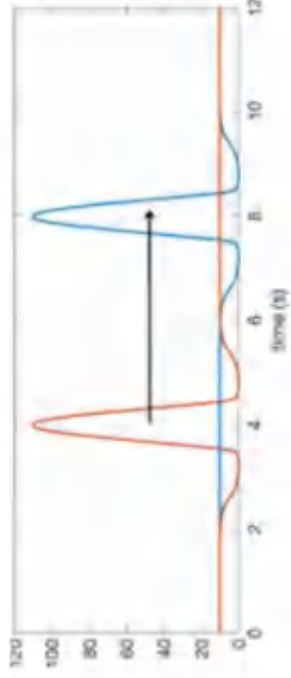


图 2-1 雷克子波经过式 (2-2) 中预处理算子作用后的形态, 红色和蓝色为需要匹配的两个子波

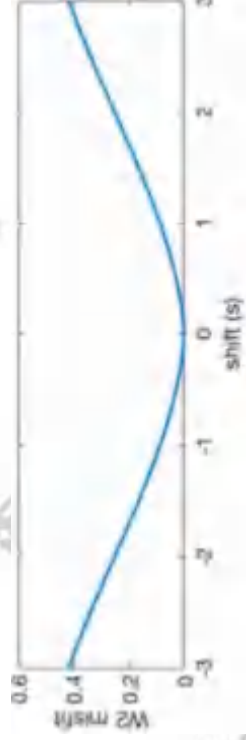


图 2-2 式 (2-1) 中目标函数随时移量的变化曲线

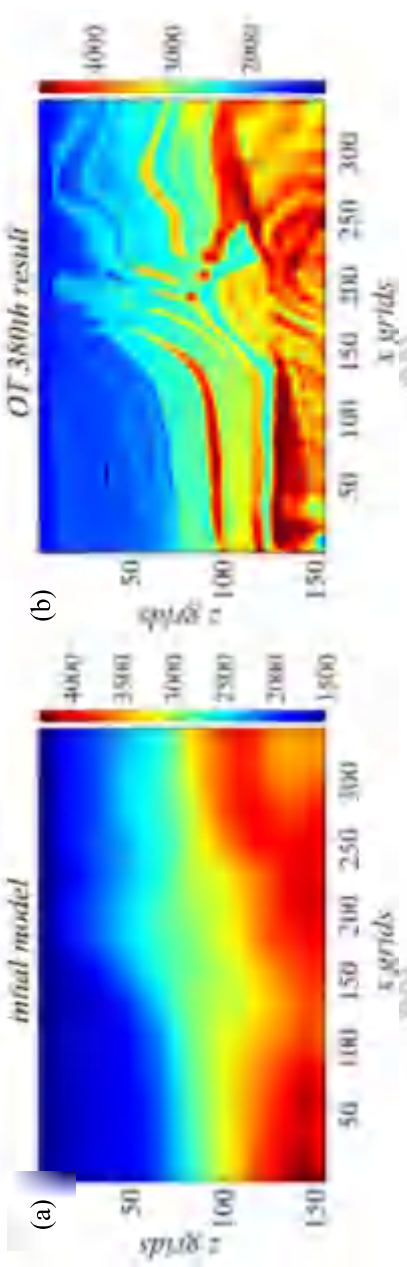


图 2-3 基于熵正则化目标的 Marmousi 模型反演结果 (从 10 Hz 主频数据直接反演, 滤除 4 Hz 以下数据), 左: 初始模型; 右: 反演模型

## (2) 最优传输算子和伴随源的快速计算方法

为了提高最优传输距离目标函数的计算效率, 采用近似的熵正则化目标函数替代, 其形式为:

$$d_{\lambda}^M(\mathbf{f}, \mathbf{g}) = \inf_{\mathbf{T}_{fg}} \left\{ \langle \mathbf{T}, \mathbf{M} \rangle - \frac{1}{\lambda} h(\mathbf{T}) \right\}, \quad (2-3)$$

其中  $\mathbf{T}$  为待求的传输矩阵, 其元素  $T_{ij}$  表示将  $\mathbf{f}$  的第  $i$  个元素移动到  $\mathbf{g}$  的第  $j$  个元素,  $\mathbf{M}$  为成本矩阵, 通常用欧氏距离表示  $M_{ij} = (i - j)^2$ ,  $\lambda > 0$  为正则化因子, 当  $\lambda$  无穷大时, 熵正则化目标函数退化为传统的最优传输距离目标函数。函数  $h$  为正则化形式, 取为:

$$h(T) = -\sum T_{ij} \log(T_{ij}). \quad (2-4)$$

表 2-1 计算熵正则化最优传输距离目标函数的算法流程

输入参数: 正则化参数  $\lambda$ ; 成本矩阵  $\mathbf{M} \in R_+^{N \times N}$  元素为  $m_{ij} = (i - j)^2$ ; 矩阵  $\mathbf{K}$ , 其元

素  $k_{ij} = e^{\lambda m_{ij}}$ ; 模拟和观测记录  $\mathbf{f} \in R_+^N$ ,  $\mathbf{g} \in R_+^N$ ; 误差限  $\sigma$ 。

初始化: 列向量  $\mathbf{u} \in R_+^N$  其元素  $u_i = \frac{1}{N}$  ( $i = 1, 2, \dots, N$ ); 矩阵  $\tilde{\mathbf{K}} = \text{diag}(\mathbf{f}^{-1})\mathbf{K}$

循环迭代:  $\mathbf{u}_{n+1} = 1. / (\tilde{\mathbf{K}}(\mathbf{g} / \mathbf{K}^T \mathbf{u}_n))$  直至:  $\|\mathbf{u}_{n+1} - \mathbf{u}_n\|_2 < \sigma$

令:  $\mathbf{v}_{n+1} = \mathbf{g} / (\mathbf{K}^T \mathbf{u}_{n+1})$

熵正则化最优传输矩阵:  $\mathbf{T} = \text{diag}(\mathbf{u})\mathbf{K}\text{diag}(\mathbf{v})$

最优传输距离目标函数值:  $d = \langle \mathbf{T}, \mathbf{M} \rangle$



$$\text{伴随源: } \boldsymbol{\alpha} = -\frac{1}{\lambda} \log(\mathbf{u}) + \frac{\log(\mathbf{u})^T \mathbf{1}_N}{\lambda N} \mathbf{1}_N$$

目标函数 (2-3) 可写为如下的对偶形式:

$$d_\lambda(\mathbf{f}, \mathbf{g}) = \max_{(\boldsymbol{\alpha}, \boldsymbol{\beta})} \left\{ \boldsymbol{\alpha}^T \mathbf{f} + \boldsymbol{\beta}^T \mathbf{g} - \frac{1}{\lambda} \sum_{ij} e^{-\lambda(m_{ij} - \alpha_i - \beta_j)} \right\}. \quad (2-5)$$

该目标函数可以采用表 2-1 中的迭代算法求解, 计算效率高, 该算法的输出包括目标函数的值, 最优传输算子  $\mathbf{T}$ , 对偶向量  $\boldsymbol{\alpha}$  和  $\boldsymbol{\beta}$ 。由式 (2-5) 可知, 伴随源 (目标函数对模拟数据的导数) 即为  $\boldsymbol{\alpha}$ 。图 2-3 为使用目标函数 (2-3) 对 Marmousi 模型的反演结果, 其中图 2-3a 为初始模型, 2-3b 为反演模型, 证实了上述计算最优传输距离目标函数的可行性。

(3) 不依赖于震源子波的最优传输距离反演方法

为消除子波估计不准对全波形反演的影响, 将式 (2-5) 中的熵正则化目标函数与 Choi and Alkhalifah (2011) 提出的卷积型目标函数相结合, 得到如下新的目标函数形式:

$$d_\lambda(\tilde{\mathbf{f}}, \tilde{\mathbf{g}}) = \max_{(\boldsymbol{\alpha}, \boldsymbol{\beta})} \left\{ \boldsymbol{\alpha}^T \tilde{\mathbf{f}} + \boldsymbol{\beta}^T \tilde{\mathbf{g}} - \frac{1}{\lambda} \sum_{ij} e^{-\lambda(m_{ij} - \alpha_i - \beta_j)} \right\}, \quad (2-6)$$

其中:

$$\tilde{\mathbf{f}} = \mathbf{f}(\mathbf{x}_r, t) * r_g(t), \quad \tilde{\mathbf{g}} = \mathbf{g}(\mathbf{x}_r, t) * r_f(t), \quad (2-7)$$

其中,  $r_g(t)$  和  $r_f(t)$  分别是观测数据和模拟数据中选取的参考道, \* 表示卷积。卷积型目标函数已被众多学者使用, 证实可有效消除子波估计不准导致的波形不匹配问题。由于卷积具有滤波功能, 使用卷积型目标函数还能自动实现从低频到高频的多尺度反演。表 2-1 中的算法仍然适用于求解目标函数 (2-6)。图 2-4 是基于最优传输距离目标函数全波形反演的整体技术路线图。

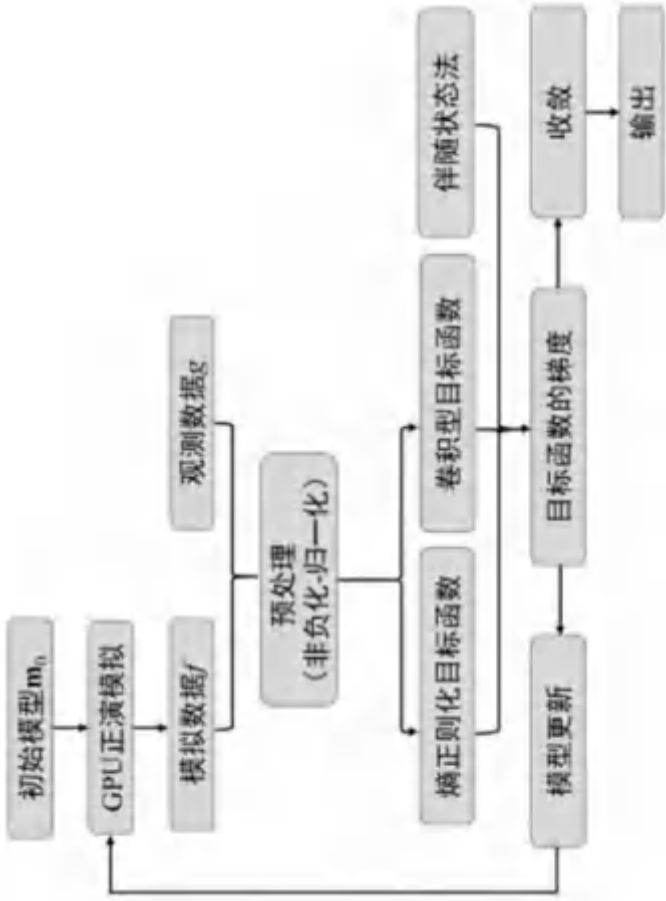


图 2-4 基于最优传输距离目标函数的全波形反演技术流程

## 2、反射波波形反演

### (1) 针对反射波的波形反演系统

反射波波形反演的主要目的是构建模型的背景纵波速度。因此，纵波的走时是反演用到的最重要信息。兼顾计算效率和精度，常密度声波方程可以用来作为反演的模拟算子，即

$$\left[ m_r \frac{\partial^2}{\partial t^2} - \nabla^2 \right] u_r = s, \quad (2-8)$$

上式中， $m_r$  是慢度的平方，它包括了模型的低频背景分量  $m_s$  和高频的反射轴成分  $m_\delta$ ， $u_r$  包括了入射波波场  $u_s$  和反（散）射波波场  $u_\delta$ 。上式可以转化为：

$$\begin{cases} \left[ m_s \frac{\partial^2}{\partial t^2} - \nabla^2 \right] u_s = s \\ \left[ m_r \frac{\partial^2}{\partial t^2} - \nabla^2 \right] u_\delta = -m_\delta \frac{\partial^2}{\partial t^2} u_s \end{cases}, \quad (2-9)$$

上式中， $m_s \frac{\partial^2}{\partial t^2} - \nabla^2$  可以表示为  $\mathbf{A}_s$ ， $m_r \frac{\partial^2}{\partial t^2} - \nabla^2$  可以表示为  $\mathbf{A}_r$ 。在实际反演过程中， $m_\delta$  则通过包含速度和密度的高频扰动信息。

常用的目标函数为预测数据和观测数据振幅差的二范数平方, 即

$$J(m_s, m_\delta) = \frac{1}{2} \|Du_\delta - d_{obs}\|_2^2, \quad (2-10)$$

上式中,  $D$  为检波器算子, 从预测波场中提取检波器处的记录。由于反演中, 波场模拟使用的常密度声波方程, 预测数据的走时是正确的, 而振幅存在误差。因此, 直接使用式 (2-10) 作为目标函数, 反演的鲁棒性不强。为了解决这个问题, 在反演过程中, 构造一个“中间数据”(intermediate data)  $d_{int}$  来取代观测数据  $d_{obs}$ , 该“中间数据”的每个同相轴位于预测数据  $Du_\delta$  和观察数据  $d_{obs}$  之间, 并且离预测数据的距离小于半个周期 (如图 2-5 所示)。该“中间数据”可以通过“动态规整”(dynamic wrapping) 来构造。因此目标函数可以表示为:

$$J(m_s, m_\delta) = \frac{1}{2} \|Du_\delta - d_{int}\|_2^2. \quad (2-11)$$

因此, 目标函数 (式 (2-11)) 关于反射轴分量  $m_\delta$  和背景分量  $m_s$  的梯度表达式为:

$$\frac{\partial J}{\partial m_\delta} = - \left( \frac{\partial^2 u_\delta}{\partial t^2} \right)^T \mathbf{A}_r^{-T} D^T (Du_\delta - d_{int}) \quad (2-12)$$

和

$$\frac{\partial J}{\partial m_s} = -u_\delta^T \left( \frac{\partial \mathbf{A}_s}{\partial m_s} \right)^T \mathbf{A}_r^{-T} D^T (Du_\delta - d_{int}) + u_s^T \left( \frac{\partial \mathbf{A}_s}{\partial m_s} \right)^T \mathbf{A}_s^{-T} \frac{\partial^2}{\partial t^2} m_\delta \mathbf{A}_r^{-T} D^T (Du_\delta - d_{int}) \quad (2-13)$$

在得到目标函数关于模型参数的梯度后, 便可以使用梯度法对模型进行更新。在推导式 (2-12) 和式 (2-13) 计算梯度时, Born 近似被采用, 可以在更新背景速度的步骤中, 将反射轴模型  $m_\delta$  缩小  $\alpha$  倍, 比如  $\alpha=0.1$ , 其预测的记录放大  $1/\alpha$ , 来提高式 (2-13) 对梯度中层析分量和偏移分离效果。

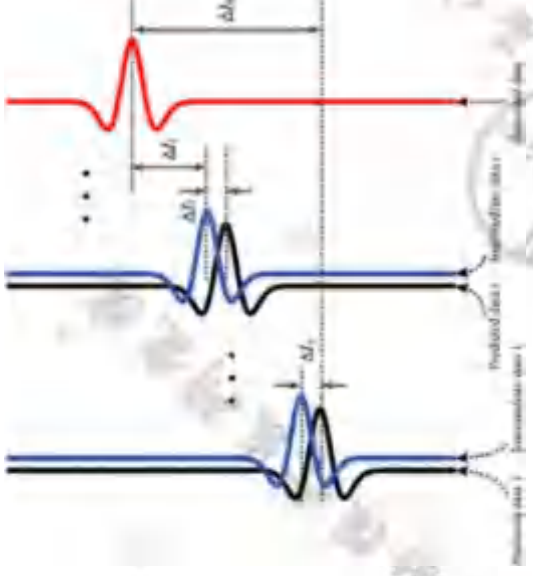


图2-5 “中间数据”产生示意图

## (2) 利用约束条件消减反射波波形反演的零空间

相对于透射波驱动的常规全波形反演，反射波波形反演的欠定性更强。这两方面的原因：首先，相对透射波，观测反射波的孔径更小；其次，反射波波形反演将模型参数化成了背景速度模型和反射轴模型，因此是双参数反演，相对单参数反演，未知数增加一倍。为了减弱反演的欠定性，本课题将“岩石的物性沿层变化缓慢”的地质规律作为先验信息来约束反演。这个地质规律在数学上可以通过“沿层光滑”来实现。在本课题中，“沿层光滑”通过解各向异性扩散方程来实现，该扩散系统可以表示为：

$$\begin{cases} \frac{\partial v(\mathbf{x}, t)}{\partial t} - \nabla \cdot \varepsilon(\mathbf{x}) \mathbf{D}(\mathbf{x}) \nabla v(\mathbf{x}, t) = 0 \\ v(\mathbf{x}, t = 0) = v_0(\mathbf{x}) \\ \left. \frac{\partial v(\mathbf{x}, t)}{\partial \mathbf{n}} \right|_{\mathbf{x} \in \Sigma} = 0 \end{cases}, \quad (2-14)$$

上式中， $v$  表示光滑的速度模型， $v_0$  代表输入的待光滑的速度模型， $\mathbf{D}$  是扩散张量， $\varepsilon$  是一个标量，衡量地层的连续性，在地层中是 1，在地层结束位置，如断层处为 0， $\Sigma$  表示模型的表面， $\mathbf{n}$  表示模型表面的法线方向， $\mathbf{x}$  和  $t$  分别表示空间和时间坐标。上式中，第二个方程表示初始条件，第三个方程表示 Neumann 边界条件。扩散张量  $\mathbf{D}$  的一个特征向量和地层的界面正交，其对应的特征值是零，其它特征向量平行地层，其对应特征值是 1。



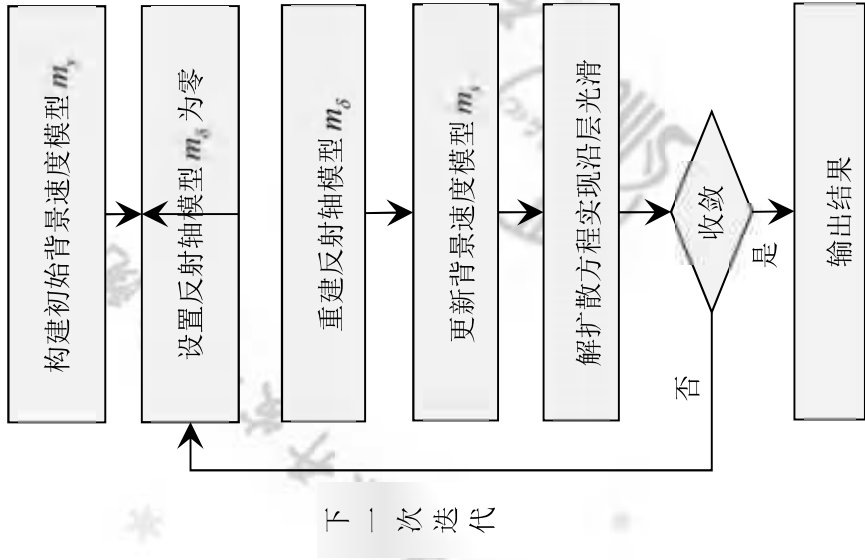


图2-6 反射波波形反演流程

在反演的每次迭代过程中，包括四个步骤：首先，设置反射轴模型为零；然后，重建立反射轴模型；然后更新背景速度；最后，解扩散方程实现沿地层的光滑。因此，反射波波形反演是一个交替迭代的过程，其流程如图 2-6。图 2-7 展示了将上述反演算法应用到 Marmousi 模型的结果。

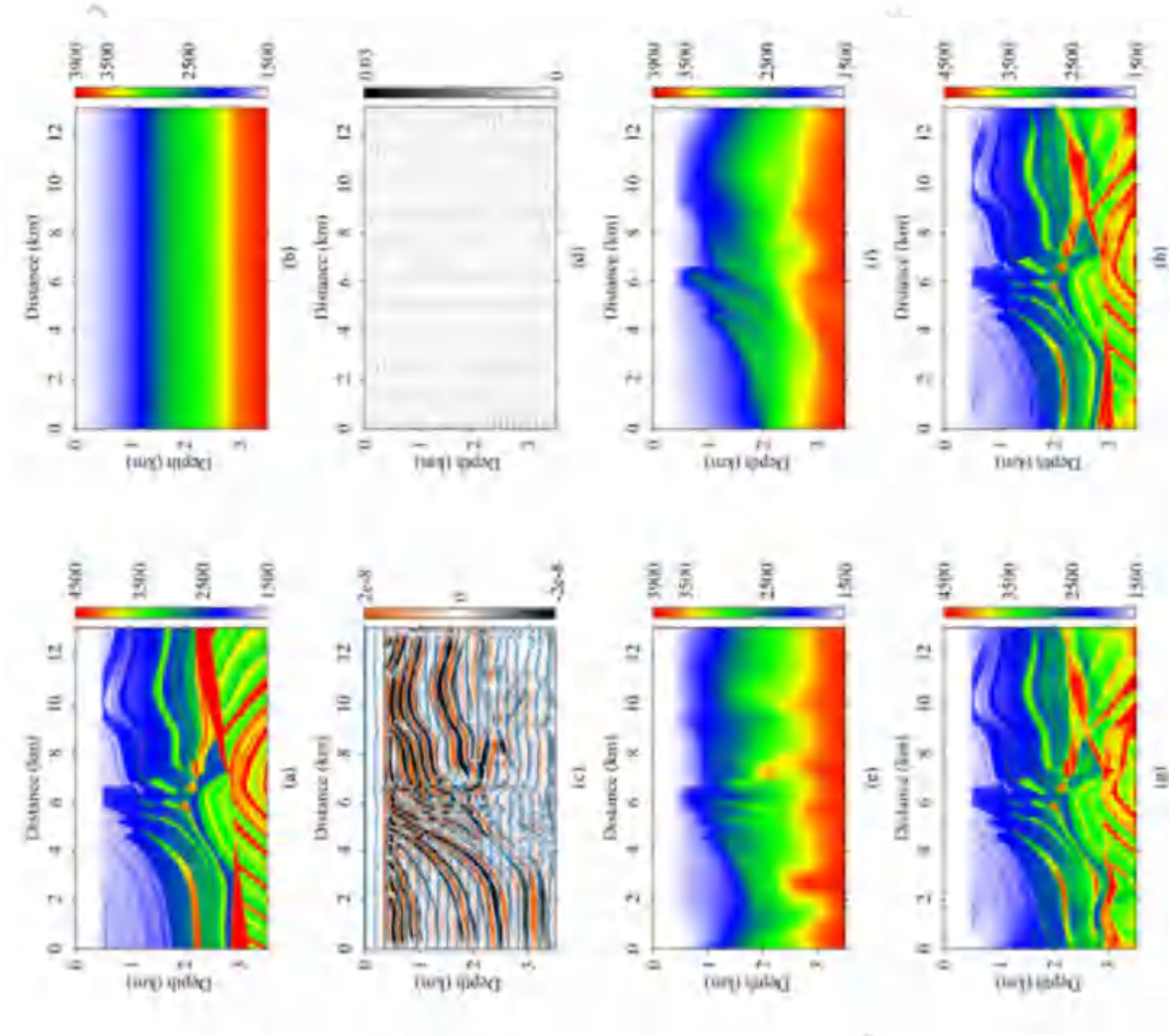


图2-7 在Marmousi模型上的反射波波形反演

(a) 真实速度模型；(b) 初始速度模型；(c) 基于初始速度模型参数的反射轴模型，图上的蓝色小箭头表示扩散张量的非零特征向量；(d) 基于 (c) 上的扩展张量的各向异性扩散的脉冲响应；(e) 非约束反射波波形反演结果，在深层包含了一些假高速异常；(f) 沿层光滑约束的反射波波形反演结果；(g) 以 (e) 为初始模型的常规全波形反演结果；(h) 以 (f) 为初始模型的常规全波形反演结果。

### (3) 针对反射波波形反演的数据预处理

上述的反射波波形反演算法的输入数据是反射数据。因此，其它类型的地震数据和噪声对反演是无效数据，需要在地震数据预处理中清除。反射波波形反演中的建立反射轴模

型的步骤和常规处理的逆时偏移非常类似。因此, 该部分的研究主要测试和研究常规逆时偏移和其它深度偏移方法的数据预处理流程是否适合反射波波形反演。

### 3、初至波波形反演

#### (1) 针对起伏地表模型的地震波场的高效模拟

地震的初至波是纵波, 因此其携带的是纵波速度信息。如果仅考虑地震波的走时信息, 声波方程可以用来模拟初至波的走时, 其可以表示如下

$$\frac{1}{V(\mathbf{x})^2} \frac{\partial^2 p(\mathbf{x}, t)}{\partial t^2} - \rho(\mathbf{x}) \nabla \cdot \frac{1}{\rho(\mathbf{x})} \nabla p(\mathbf{x}, t) = \delta(\mathbf{x} - \mathbf{x}_s) s(t), \quad (2-15)$$

上式中,  $p$  表示压强,  $V$  表示波传播速度,  $\rho$  表示密度,  $s$  表示震源子波,  $\delta$  表示 Dirac Delta 函数。上式方程通常是通过规则矩形网格的有限差分来求解。但是陆地地震勘探时, 地表存在起伏, 因此地震波模拟需要考虑起伏地表。在本课题中, 为了兼顾效率和精确度, 浸入边界法配合矩形网格被用来模拟起伏地表的波场。

浸入边界法的核心思想是: 通过反反对称镜像的方式, 利用不规则界面一下整数网格点的值求取界面以上的整数网格的波场值。图 2-8 是该方法的示意图。由此可以看出, 该方法的关键点在于准确的求解位于分数网格点上的镜像点的波场值。在本课题中, 迭代插值法被用来计算镜像点上的波场值。该方法的过程是: 首先, 设置地表以上所有网格点 (即鬼点) 的波场值为零; 然后, 通过插值的方式求得所有鬼点的镜像点的波场值; 然后, 通过对称镜像点的波场值来更新鬼点的波场值; 然后, 再多次交替更新镜像点和鬼点的波场值。在数学上, 这个过程可以表示为:

$$\begin{cases} p_{mirror}^n = \sum_{i=1}^m c_i p_i^n, \\ p_{ghost}^{n+1} = -p_{mirror}^n \end{cases}, \quad (2-16)$$

上式中,  $p_{mirror}^n$  表示镜像点的波场值,  $p_i^n$  表示整数网格上的波场值,  $c_i$  表示插值系数, 对镜像点的插值是由  $m$  个点实现的,  $p_{ghost}^n$  表示鬼点的波场值, 上标  $n$  代表波场值迭代的次数。首选插值方法是加窗 sinc 函数插值。通常, 20 次迭代就可以精确的求得鬼点的波场值。陆地地震采集通常记录的是位移或质点振动速度, 因此在波场模拟时需要将压力波场转换为质点振动速度。转换公式如下:

$$\frac{\partial \mathbf{v}(\mathbf{x}, t)}{\partial t} = -\frac{1}{\rho(\mathbf{x})} \nabla p(\mathbf{x}, t), \quad (2-17)$$

上式中,  $\mathbf{v}$  表示质点振动速度向量。

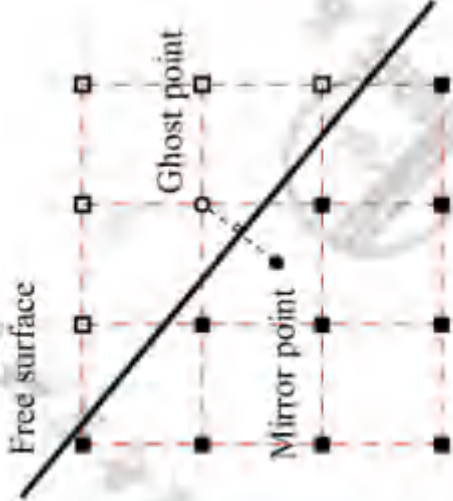
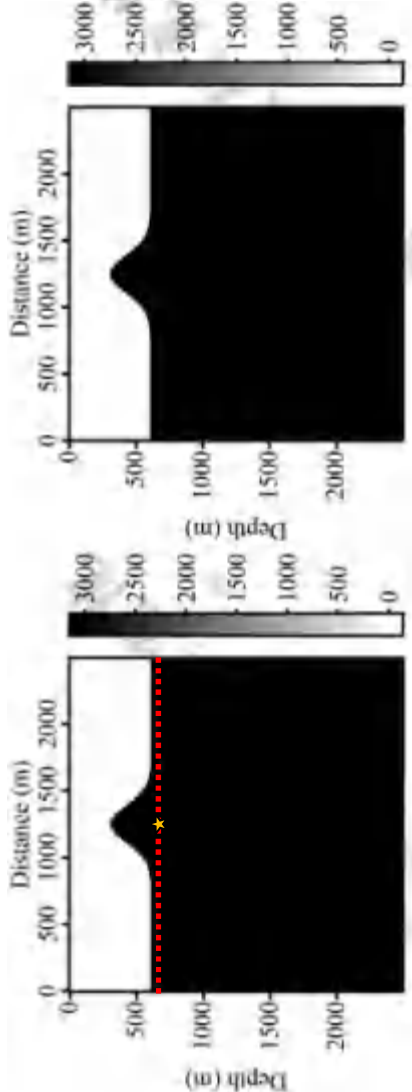


图 2-8 浸入边界法模拟示意图

黑色实线代表地表界面, 界面以下网格是在模型内的计算网格, 未填充圆圈代表鬼点, 填充圆圈代表鬼点关于界面的镜像点, 镜像点在分数网格上。

图 2-9 展示了用浸入边界法模拟 Gaussian 起伏地表模型的波场记录。通过模拟可以看出, 浸入边界法可以精确地描述起伏地表, 并模拟其作为自由表面的响应。





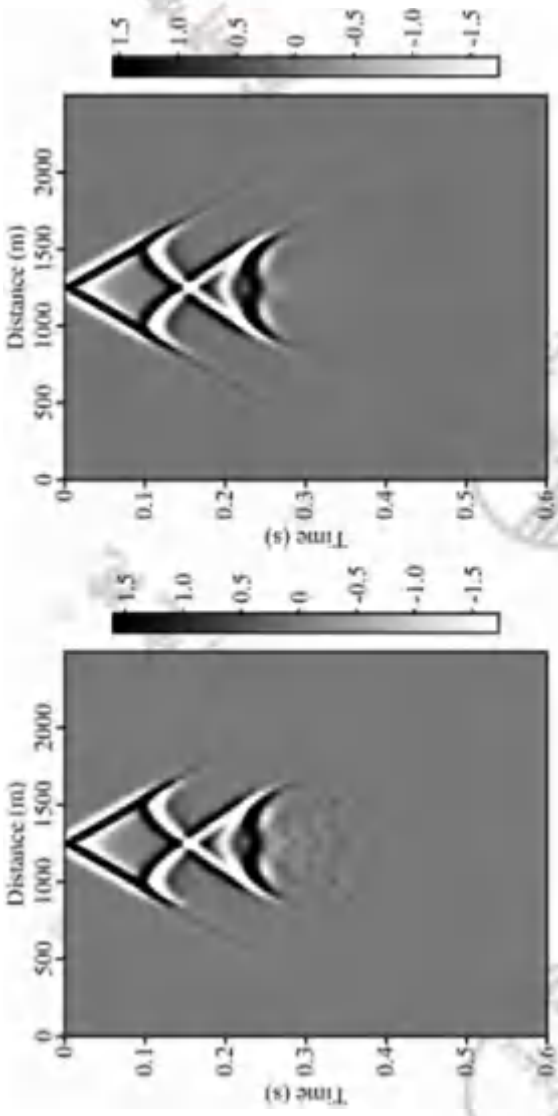


图2-9 Gaussian起伏地表模型的浸入边界法模拟

(a) 离散化为10米网格的模型；(b) 离散化1米的网格模型；(c) 在10米网格下的真空法模拟，假绕射波非常明显；(d) 在10米网格下的浸入边界法模拟，假绕射得到有效消除。(a) 中红色虚线代表检波器位置，五角星“☆”代表炮点位置。

## (2) 针对初至波的波形反演系统

在陆地勘探中，检波器是通常记录地震波的位移或质点振动速度的垂直分量。另外，本课题的初至波波形反演主要反演初至波的走时信息。考虑以上两个因素，一阶声波方程被用来推导其反演系统，即：

$$\begin{cases} \frac{\partial v_x}{\partial t} = \frac{1}{\rho} \frac{\partial p}{\partial x} \\ \frac{\partial v_z}{\partial t} = \frac{1}{\rho} \frac{\partial p}{\partial z} \\ \frac{\partial p}{\partial t} = K \left( \frac{\partial v_x}{\partial x} + \frac{\partial v_z}{\partial z} \right) + s \end{cases}, \quad (2-18)$$

上式中， $v_x$ 、 $v_z$ 和 $p$ 分别表示质点振动速度的水平和垂直分量，以及压强， $\rho$ 表示密度， $K$ 表示体积模量， $s$ 表示子波。如果将上式表示成“矩阵—向量”形式，则有

$$\mathbf{A} \mathbf{u} = \mathbf{s}, \quad (2-19)$$

其中，

$$\mathbf{A} = \begin{bmatrix} \rho \frac{\partial}{\partial t} & 0 & -\frac{\partial}{\partial x} \\ 0 & \rho \frac{\partial}{\partial t} & -\frac{\partial}{\partial z} \\ -\frac{\partial}{\partial x} & -\frac{\partial}{\partial z} & \frac{1}{K} \frac{\partial}{\partial t} \end{bmatrix}, \quad (2-20)$$

和

$$\mathbf{u} = \begin{bmatrix} v_x \\ v_z \\ p \end{bmatrix}. \quad (2-21)$$

基于波形振幅差的 L2 目标函数可以表示为:

上式中,  $\mathbf{d}_{\text{cal}}$  和  $\mathbf{d}_{\text{obs}}$  分别表示预测数据和观测数据, 而  $\mathbf{m}$  代表反演的模型参数。因为模拟算子不能准确的模拟实际数据的波形, 所以如果直接使用上式进行反演, 那么反演将不能对模型进行有效的更新。为了解决这个问题, 初至波波形反演将反演“中间数据”  $\mathbf{d}_{\text{int}}$ , 而非直接反演观测到的数据  $\mathbf{d}_{\text{obs}}$ 。“中间数据”是通过在每次迭代过程中, 将预测数据  $\mathbf{d}_{\text{cal}}$  向观测数据  $\mathbf{d}_{\text{obs}}$  移动小于半个周期的距离。这个过程如图 2-5 所示。因此, 本课题中的初至波波形反演的目标函数是:

$$J(\mathbf{m}) = \frac{1}{2} \left\| W(\mathbf{d}_{\text{cal}} - \mathbf{d}_{\text{int}}) \right\|_2^2, \quad (2-23)$$

上式中,  $W$  是加在初至波上的高斯窗, 用于限定反演只利用初至波信息。式 (2-19) 和 (2-23) 构建了初至波波形反演的系统。其梯度可以通过对该系统求关于纵波速度  $V$  的导数得到:

$$\frac{\partial J}{\partial V} = 2\rho V \frac{\partial J}{\partial K} = \frac{2}{\rho V^3} \frac{\partial \vec{p}}{\partial t}, \quad (2-24)$$

上式中,  $\vec{p}$  和  $\vec{P}$  分别表示正传波场和反传波场的压强。上面在推导梯度的过程中, 用到了二阶声波方程, 但是梯度中只包含了波场的压力, 因此在实施过程中, 可以直接使用二阶声波方程来模拟波场, 以提升计算效率, 并且使用一阶方程组中的第二式来计算质点振动速度的垂直分量。反传波场可以通过解以下方程得到:

$$\frac{1}{V(\mathbf{x})^2} \frac{\partial^2 p(\mathbf{x}, t)}{\partial t^2} - \rho(\mathbf{x}) \nabla \cdot \frac{1}{\rho(\mathbf{x})} \nabla p(\mathbf{x}, t) = \delta(\mathbf{x} - \mathbf{x}_r) \frac{\partial \delta v_z(\mathbf{x}_r, t)}{\partial z}, \quad (2-25)$$

上式中,  $\delta v_z$  表示检波器处的质点振动速度的残差。

如上所述, 整个反演系统通过式 (2-15) 和式 (2-18) 的第二式计算正传波场, 并产生预测数据, 再通过式 (2-23) 计算残差, 再通过式 (2-25) 计算反传波场, 最后由式 (2-24) 计算目标函数关于速度的梯度。在获得梯度后, 可以通过梯度法来更新速度模型。

### (3) 针对中、深层速度建模的观测系统设计

在复杂地表和构造地区, 常规的基于反射波的深度域速度建模方法很难给出一个准确的深度偏移模型。通过观察, 记录中的初至波的到时比较明确。因此, 通过接收更大偏移距的数据能实现对深层信息的接收。本课题将通过理论分析和合成数据验证的方式来改进现有观测系统, 从而在地表接收到中、深层的透射波数据, 并实现利用初至波对中、深层速度建模。

由图 2-10 可以看出, 随着偏移距的增加, 检波器能接收到经过更深地层的透射波, 因此大偏移对基于透射波, 包括初至波, 建模是关键。如图 2-11 所示, 为了增加透射波的穿透深度, 在排列的远端延长线上, 增加额外的炮点, 这样透射波穿透的深度将大幅度增加。在本课题中, 针对这种改进的观测系统, 将开展以下工作:

基于射线追踪, 针对特定模型, 分析观测系统在不同参数下射线分布的密度和覆盖范围;

通过数值实验, 验证在新观测系统下, 初至波波形反演对建立中、深层速度模型的效

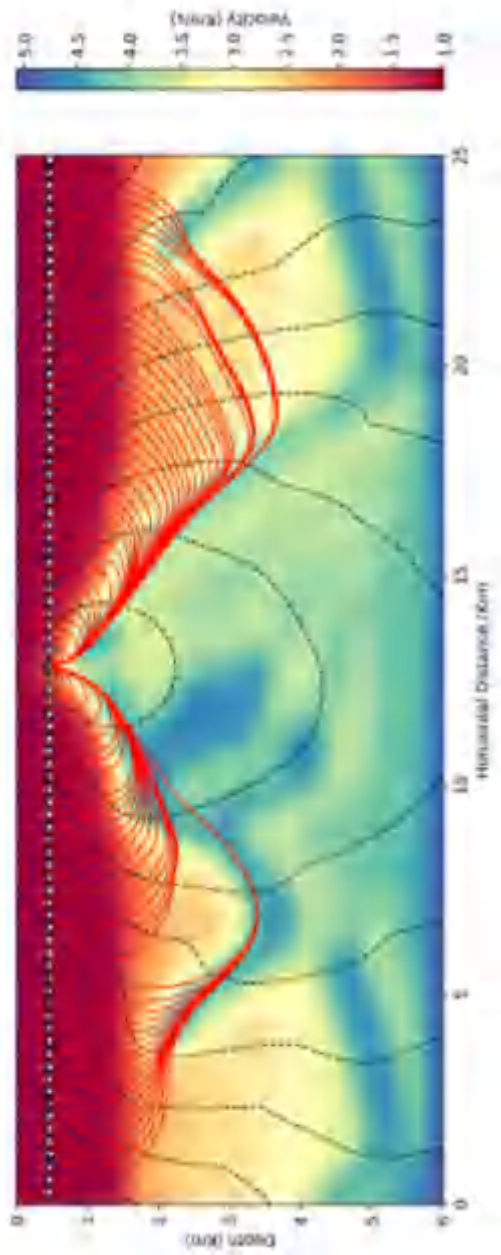


图2-10 复杂模型中的一炮记录的射线分布  
模型中间的五角星“☆”代表炮点位置，倒三角“▽”代表检波器位置，红色实线表示透射波的射线  
路径。

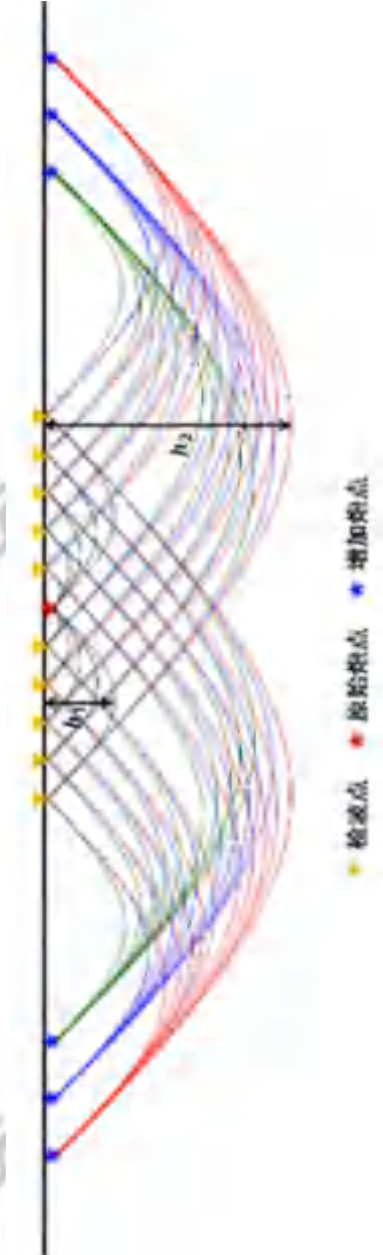


图2-11 改进后观测系统及射线路径示意图

$h_1$ 表示原始观察系统中透射波穿透的最大深度， $h_2$ 表示扩展炮点后透射波穿透的最大深度。

### 三、提交成果与考核指标

(一) 提交成果（包括与研究任务对应的取得的主要研究成果及报告、图件、实验数据等。  
要求：列出甲方要求提交的技术成果。）

针对主要研究内容开展三个方面，即①基于最优传输距离目标函数的全波形反演，②  
反射波波形反演，③初至波波形反演的研究。计划提交成果包括：

OT-FWI、反射波和初至波波形反演算法和二维程序；

提交 2 套理论数据和 1 套实际数据技术应用成果，及相应的浅、中、深层一体化速度  
反演流程；

项目成果报告。

### (二) 技术与经济指标



1、技术指标（指体现课题研究成果的各项技术水平，以及提交成果的量的约定。）

① 针对“基于最优传输距离目标函数的全波形反演”方向，所形成的全波形反演方法具有较好的稳健性，对地震数据中最低频率的要求放宽至 4Hz；在相同迭代次数情况下，基于最优传输距离目标函数全波形反演的收敛性与传统方法相比提升 30%（以目标函数下降量作为衡量指标）；基于最优传输距离目标函数全波形反演单次迭代的计算量较传统 L2 目标函数全波形反演方法的计算量增幅不超过 20%；

② 针对“反射波波形反演”方向，研制的反演程序具有较好的稳定性，对于预处理后反射同相轴明显的数据能给出高精度的深度域速度模型，在复杂区域其相对非约束反射波波形反演，由反演欠定性引起的假异常得到明显压制；

③ 针对“初至波波形反演”方向，研制的反演程序具有较好的稳定性，对初至较明显的实际数据能给出高精度的浅层速度模型，在复杂区域，消除射线层析的焦散和阴影引起的假异常。

2、经济指标（指研究成果推广应用产生的经济价值等指标，根据课题性质而定，有则填写，无则填“无”。要求：列出的技术指标要反映课题的主要研究成果，列出的经济指标要能够量化或具操作性。）

无。

四、进度计划

| 年度   | 起止时间<br>（-月-月）  | 研究内容                                                                                  | 提交成果与考核指标                                                                                        | 备注 |
|------|-----------------|---------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|----|
| 2021 | 合同签订日期<br>至 8 月 | 4) 适用于最优传输距离目标函数的地震数据预处理方法研究<br>5) 研究并分析改进的观测系统的方法，改进初至波反演效果<br>6) 一维 W2 目标函数的全波形反演方法 | 4) 实现一种合适的地震数据预处理方法保证目标函数凸性<br>5) 实现初至波波形反演对中、深层速度模型反演效果的改善<br>6) 编制基于一维 W2 目标函数的全波形反演程序，验证其反演效果 |    |
| 2021 | 9 月             | 反射波波形反演算法研究                                                                           | 编制稳健的反射波波形反演程序，验证其反演效果                                                                           |    |
| 2021 | 10 月            | 基于地层构造约束的反射波波形反演方法研究                                                                  | 在反射波波形反演中加入地层构造约束，改善反演效果                                                                         |    |
| 2021 | 11 月            | 熵正则化目标函数的快速计算方法                                                                       | 利用熵正则化实现最优传输距离目标函数的快速计算                                                                          |    |

|      |      |                             |                                                               |
|------|------|-----------------------------|---------------------------------------------------------------|
| 2021 | 12 月 | 起伏地表地震波场数值模拟方法              | 利用浸入式边界条件实现自由地表条件下的波场模拟，消除网格阶梯状造成的虚假绕射                        |
| 2022 | 1 月  | 起伏地表条件下的初至波波形反演方法           | 编制起伏地表条件下初至波波形反演程序，验证其正确性                                     |
| 2022 | 2 月  | 基于正则化最优传输距离目标函数的全波形反演方法     | 编制基于正则化最优传输距离目标函数的全波形反演程序，验证其正确性                              |
| 2022 | 3 月  | 消除子波影响的正则化目标函数及全波形反演        | 消除子波影响反演程序运行稳定，具有较好的反演效果                                      |
| 2022 | 4 月  | 基于最优传输距离目标函数全波形反演合成和实际数据测试  | 利用典型的合成数据和实际数据测试全波形反演程序，取得明显优于传统 L2 目标函数全波形反演的效果，并形成详细的技术总结报告 |
| 2022 | 5 月  | 初至波波形反演、反射波波形反演方法的合成和实际数据测试 | 利用典型的合成数据和实际数据测试反演程序，取得明显优于传统反演方法的效果，并形成详细的技术总结报告             |

五、保障条件

1、外协单位简介（附加资质扫描件）

中国石油大学（北京）一校两地（北京、克拉玛依），北京昌平校区坐落在风景秀丽的军都山南麓，北京校区校园占地面积 700 余亩；克拉玛依校区位于新疆维吾尔自治区克拉玛依市，校园占地面积 7000 余亩。学校是一所石油特色鲜明、以工为主、多学科协调发展教育部直属的全国重点大学，是设有研究生院的高校之一。1997 年，学校首批进入国家“211 工程”建设高校行列；2006 年，成为国家“优势学科创新平台”项目建设高校。2017 年，学校进入国家一流学科建设高校行列，全面开启建设中国特色世界一流大学的新征程。

经过六十余年的建设发展，学校形成了石油特色鲜明，以工为主、多学科协调发展的学科专业布局。石油石化等重点学科处于国内领先地位，并在国际上形成了一定影响。根据 ESI 最新数据，学校有 6 个学科进入 ESI 排行前 1%，分别是化学、工程学、材料科学、地球科学、计算机科学和环境/生态学，其中工程学进入 ESI 全球前 1%，环境/生态学于 2021 年 1 月首次进入 ESI 全球前 1%。围绕石油石化产业结构，构建起由石油石化主体学科、支撑学科、基础学科和新兴交叉学科组成的石油特色鲜明的学科专业布局，实施了“攀登计划”、“提升计划”和“培育计划”，分别建设石油与天然气工程、地质资源与地质工程等石油石化优势学科，化学、材料科学与工程等基础支撑学科，新能源、新材料和人工智能等新兴交叉学科。

学校坚持把科学研究作为强校之路，按照“搭建大平台、承担大项目、凝聚大团队、取得大成果、做出大贡献”的思路，不断提高科技创新能力和综合科研水平。现有 2 个国家重点实验室、9 个国家级科研创新平台分室以及 23 个省部级各类科研创新平台和 18 个中国石油天然气集团公司重点实验室分室。石油石化科学研究领域优势突出，在多个研究领域居国内领先水平，在非常规油气、新能源等新兴研究领域发展迅速。“十三五”以来，学校共承担国家级科研项目 1467 项，获国家级三大科技奖共 13 项、其中作为第一完成单位的有 5 项；获得省部级及社会力量科技奖 283 项，其中作为第一完成单位的有 173 项。国家级奖励数在 2014 年、2015 年全国高校通用项目中均排名第 10，在 2017 年全国高校通用项目中排名第 7。

中华人民共和国

事业单位法人证书

(副本)

统一社会信用代码 12100000400006110Y

宗旨和

业务范围

住所

法定代表人 吴小林

经费来源 财政补助、上级补助、事业、捐赠收入

开办资金 ¥88670万元

举办单位 教育部

登记管理机关

证书专用章

事业单位登记管理局

请于每年3月31日前向登记管理机关报送上一年度的年度报告

有效期至2016年11月29日 至2021年11月29日





近年完成的项目业绩统计表

| 序号 | 项目名称                                                       | 金额<br>(万元) | 时间                 | 业主名称                 | 服务内容                | 联系人   | 联系电话            |
|----|------------------------------------------------------------|------------|--------------------|----------------------|---------------------|-------|-----------------|
| 1  | 弹性波全波形反演方法研究                                               | 122.55     | 2016.09<br>2018.06 | 中国石油集团东方地球物理勘探有限责任公司 | 三维弹性波全波形反演技术及软件研发   | 周 辉   | 0108973<br>1005 |
| 2  | 高精度地球物理勘探技术研发及应用-多波地震勘探配套技术                                | 2512.45    | 2017.01<br>2019.12 | 中国石油集团东方地球物理勘探有限责任公司 | 研发多波地震勘探技术          | 李 向阳  | 0108973<br>2259 |
| 3  | 高精度油气测井技术与装备研发及应用-测井新方法 with 探测研究                          | 1514.75    | 2017.01<br>2020.12 | 中国石油集团测井有限公司         | 研究高精度测井技术及研发新的测井仪器  | 鞠 晓东  | 0108973<br>3558 |
| 4  | 海相碳酸盐岩大中型油气田分布规律及勘探评价-海相碳酸盐岩地震勘探关键技术-碳酸盐岩岩石物理与地震波场模拟技术     | 189.28     | 2017.01<br>2020.12 | 中国石油化工股份有限公司勘探研究院    | 研究海相碳酸盐地震响应及其储层预测技术 | 魏 建新  | 0108973<br>3553 |
| 5  | 中国典型盆地陆相页岩油勘探开发选区与目标评价-陆相页岩油甜点地球物理识别与预测方法-陆相页岩油储层裂缝与流体预测技术 | 194.80     | 2017.01<br>2020.12 | 中国石油化工股份有限公司勘探研究院    | 陆相页岩气甜点预测理论与技术      | 孙 朗 秋 | 0108973<br>9103 |
| 6  | 近海大中型油气田形成条件及勘探技术-中国近海中深层地震勘探关键技术-宽方位地震数据规则化与有效信号增强方法研究与应用 | 261.58     | 2016.01<br>2020.06 | 中海油研究总院有限责任公司        | 海洋宽方位地震数据处理方法       | 陈 小 宏 | 0108973<br>1512 |
| 7  | 天然气地球物理烃类检测、评价技术及应用-复杂气藏岩石物理与地震波响应研究                       | 102.15     | 2016.01<br>2018.12 | 中国石油集团科学技术研究院        | 天然气等复杂油气藏地震波场响应研究   | 狄 帮 让 | 0108973<br>3550 |
| 8  | 高含水油田提高采收率新技术-井震结合储层精细表征技术-油藏地球物理储层反演新技术与软件研制              | 210.96     | 2016.01<br>2020.12 | 中国石油集团科学技术研究院        | 井震结合地震反演技术及软件研发     | 周 辉   | 0108973<br>1005 |

|   |                                            |        |                    |                     |                |     |                 |
|---|--------------------------------------------|--------|--------------------|---------------------|----------------|-----|-----------------|
| 9 | 低渗透油气藏高效开发钻完井技术-低渗透储层高精度随钻成像技术-高精度随钻成像方法研究 | 315.00 | 2016.01<br>2020.12 | 中国石油化工股份有限公司工程技术研究院 | 高精度随钻成像技术及方法研究 | 柯式镇 | 0108973<br>3317 |
|---|--------------------------------------------|--------|--------------------|---------------------|----------------|-----|-----------------|

(2) 研发支撑条件（要求：如实填写，组织机构代码证、营业执照、税务登记证、相关财务证明等材料扫描附上。一旦发现弄虚作假，合作关系自动终止。）

承担单位中国石油大学（北京）是1997年首批进入国家“211工程”建设高校行列，2006年成为国家“优势学科创新平台”项目建设高校，2017年进入国家一流学科建设高校行列。有两个一级学科为一流学科，其中包括地质资源与地质工程学科。本课题的参与者属于该一级学科所属的勘探地球物理学科。本课题的研究将依托于中国石油大学（北京）的油气资源与探测国家重点实验室和中国石油天然气集团公司物探重点实验室。实验室拥有98节点IBM并行计算机，课题参与人还组装了2个节点8卡NVIDIA P40 GPU并行计算设备，安装了地震资料处理和解释商业软件。项目负责人及参与人所在团队有20多名博士和硕士研究生，有充足的研究队伍资源。在油气资源的地球物理勘探方面有很深的研究功底和研究积累，有承担“973”、“863”、国家自然科学基金重点项目、面上项目和青年项目的经验，也有与生产结合的产学研工作经验。

法人代表





组织机构代码

中华人民共和国国家质量监督检验检疫总局公告

组织机构代码证

证号: 40000611-0

有效期: 自2014年03月25日至2018年03月25日

颁发单位: 全国组织机构代码管理中心

记录号: 组代管100000-909249-1

|      |    |    |
|------|----|----|
| 年份   | 月份 | 日期 |
| 2013 | 06 | 14 |

NO 2013 0614246

中华人民共和国组织机构代码证

证号: 40000611-0

有效期: 自2014年03月25日至2018年03月25日

颁发单位: 全国组织机构代码管理中心

记录号: 组代管100000-909249-1

机构名称: 中国石油大学(北京)

机构类型: 事业法人

法定代表人: 张来斌

地址: 北京市昌平区府学路18号

开户许可证

|                            |                      |
|----------------------------|----------------------|
| 核准号: J1000038880003        |                      |
| 编号: 1000-01951907          |                      |
| 经审查, 中国工商银行(北京) 符合开户条件, 准予 |                      |
| 开立基本存款账户。                  |                      |
| 法定代表人(单位负责人)               | 张永斌                  |
| 开户银行                       | 中国建设银行北京昌平支行         |
| 账号                         | 11001009200056050532 |
| 开户日期: 2010年01月29日          | 发证机关(盖章)             |
| 开户银行: 中国工商银行(北京)           | 开户日期: 2010年01月29日    |







资产负债表

| 资产     |              | 负债      |              |
|--------|--------------|---------|--------------|
| 流动资产   | 1,000,000.00 | 流动负债    | 1,000,000.00 |
| 货币资金   | 500,000.00   | 应付账款    | 500,000.00   |
| 应收账款   | 300,000.00   | 预收账款    | 200,000.00   |
| 其他流动资产 | 200,000.00   | 其他流动负债  | 300,000.00   |
| 非流动资产  | 1,000,000.00 | 非流动负债   | 1,000,000.00 |
| 固定资产   | 800,000.00   | 长期借款    | 800,000.00   |
| 无形资产   | 200,000.00   | 其他非流动负债 | 200,000.00   |
| 所有者权益  | 1,000,000.00 |         |              |
| 实收资本   | 1,000,000.00 |         |              |
| 未分配利润  |              |         |              |

| 资产     |              | 负债      |              |
|--------|--------------|---------|--------------|
| 流动资产   | 1,000,000.00 | 流动负债    | 1,000,000.00 |
| 货币资金   | 500,000.00   | 应付账款    | 500,000.00   |
| 应收账款   | 300,000.00   | 预收账款    | 200,000.00   |
| 其他流动资产 | 200,000.00   | 其他流动负债  | 300,000.00   |
| 非流动资产  | 1,000,000.00 | 非流动负债   | 1,000,000.00 |
| 固定资产   | 800,000.00   | 长期借款    | 800,000.00   |
| 无形资产   | 200,000.00   | 其他非流动负债 | 200,000.00   |
| 所有者权益  | 1,000,000.00 |         |              |
| 实收资本   | 1,000,000.00 |         |              |
| 未分配利润  |              |         |              |

科研业务委托代理人



本件仅用于证明 季汉成 系中国石油大学（北京）科研业务相关委托代理人，他用无效！



本件仅用于证明 季汉成 系中国石油大学（北京）科研业务相关委托代理人，他用无效！

## 无审计报告说明

### 关于无审计报告的说明

#### 中国石化石油勘探开发研究院:

根据《公司法》第一百六十五条“公司应当在每一会计年度终了时编制财务会计报告,并依法经会计师事务所审计。财务会计报告应当依照法律、行政法规和国务院财政部门的规定制作。”但中国石化大学(北京)作为教育部直属高校,属于行政事业单位,执行教育部内部审计规定,不适用于《公司法》,无年度审计报告。

特此说明!

中国石化大学(北京)

2021年05月07日

2、课题负责人简介表

| 姓名               | 姚 刚                                                                                                                                                                                                                                                                                                                                                                | 职称 | 研究员 |
|------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|-----|
| 工作单位             | 中国石油大学（北京）                                                                                                                                                                                                                                                                                                                                                         |    |     |
| 工<br>作<br>简<br>历 | <ul style="list-style-type: none"><li>• 2020.07 - 至今 中国石油大学（北京），非常规油气科学技术研究院，研究员（教授）</li><li>• 2019.01 - 2020.06 中国石油大学（北京），非常规油气科学技术研究院，副研究员，博士/硕士生导师</li><li>• 2018.05 – 2018.12 美国莱斯大学，博士后研究员 Postdoctoral Research Fellow</li><li>• 2014.01 – 2016.12 S-Cube Ltd., 研究员</li><li>• 2013.08 – 2017.12 英国帝国理工大学，博士后助理研究员 Postdoctoral Research Associate</li></ul> |    |     |
| 工<br>作<br>业<br>绩 | <p>（完成的项目、获奖、论文等）</p> <p>项目负责人姚刚教授为中国石油大学（北京）研究员，博士生导师。本、硕毕业于中国地质大学（北京），后在英国帝国理工大学获得地球物理学博士学位。2020 年入选中组部“国家特聘专家”青年项目计划。主要从事地震波波场模拟、成像及反演研究，参与 S-Cube 公司全波形反演软件核心算法研究及代码开发，负责国家自然科学基金面上项目 1 项，国家级人才启动项目 1 项，校级人才启动项目 1 项，参与国家重点研发 2 项，国家自然科学基金面上项目 1 项。发表学术论文近 40 篇，其中 SCI 收录论文 20 篇，获 SEG 年会最佳论文 1 篇，获国家发明专利 4 项。</p>                                             |    |     |



3、研究人员及分工:

| 序  | 姓 名 | 职 称 | 承担的主要工作                            | 备注 |
|----|-----|-----|------------------------------------|----|
| 1  | 姚 刚 | 研究员 | 反射波波形和初至波波形反演理论和方法研究               |    |
| 2  | 周 辉 | 教授  | 全波形反演理论和方法研究                       |    |
| 3  | 陈汉明 | 副教授 | 最优传输距离目标函数及 GPU 并行计算研究             |    |
| 4  | 蒋书琦 | 博士生 | 矫正则化目标函数快速计算方法及在全波形反演中的应用研究        |    |
| 5  | 杨 瀚 | 博士生 | 全波形反演代码测试及优化                       |    |
| 6  | 刘峰良 | 博士生 | 实际数据的全波形反演代码测试                     |    |
| 7  | 李 翔 | 博士生 | 初至波波形反演代码实现及测试, 改进观测系统的理论研究 and 测试 |    |
| 8  | 吴 博 | 博士生 | 反射波波形反演代码实现及测试研究                   |    |
| 9  | 刘能超 | 博士生 | 反射波波形反演数据预处理研究                     |    |
| 10 | 马 啸 | 硕士生 | 初至波波形反演代码测试研究                      |    |
| 11 | 周建业 | 硕士生 | 反射波波形反演代码测试研究                      |    |
| 12 | 富禹鑫 | 硕士生 | 实际数据的全波形反演适用性研究                    |    |
| 13 | 张立府 | 硕士生 | 实际数据的全波形反演数据预处理研究                  |    |

六、经费预算

课题经费预算明细表

| 科目    | 金额<br>(万元) | 主要用途及计算依据                                                                                                                                                |
|-------|------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| 人工费用  | 32.80      | 6名博士生劳务费 3000 元/人/月，4 名硕士生劳务费 1500 元/人/月，共 12 个月，3 名教职工研究人员课题激励：正高 2 人次；1.5 万元/人次*2 人次+副高 1 人次；1.0 万元/人次*1 人次<br>(6×0.3+4×0.15)×12+2×1.5+1×1.0 = 32.8 万元 |
| 分析测试费 | 36.00      | 最优传输距离目标函数全波形反演算法测试费：50 节点*200 小时*12 元/节点/小时=12 万元；初至波波形反演测试 50 节点*200 小时*12 元/节点/小时=12 万元；反射波波形反演测试 50 节点*200 小时*12 元/节点/小时=12 万元                       |
| 资料搜集费 | 2.00       | 实际工区地质图件收集：200 元/件*50 件+地震处理和解释剖面收集：200 元/件*50 件=2 万元                                                                                                    |
| 报告印刷费 | 1.90       | 中间成果图件彩印 100 元/份*30 份=0.3 万元；阶段进展报告打印装订 250 元/份*32 份=0.8 万元；结题成果打印及装订：250 元/份*32 份=0.8 万元                                                                |
| 材料费   | 2.00       | 地震数据绘图仪硒鼓：800 元/个*5 个=0.4 万元；2T 移动硬盘：500 元/个*20 个=1 万元，得力打印纸：200 元/箱*10 箱=0.2 万元，移动 U 盘 256G，500 元/个*8 个=0.4 万元；                                         |
| 其它    | 15.30      | 学校管理费 11.7 万，院系管理费 3.6 万                                                                                                                                 |
| 合计    | 90.00      |                                                                                                                                                          |

## 七、委托方审查意见

### 1、专家审查意见书

#### 附录9 石油勘探开发研究院外协项目立项审查意见书

2021年5月12日,石油勘探开发研究院组织院专家组,对中国石油大学(北京)承担的《最优传输反射波全波形反演理论和方法》项目的开题立项设计进行了审查。意见如下:

##### 一、主要研究内容

1. 最优传输距离目标函数全波形反演方法 (OT-FWI);
2. 反射波波形反演方法: 层析分量提取、地质构造约束;
3. 初至波波形反演方法。

##### 二、预期成果及主要技术、经济指标

###### 1. 预期提交的成果

- 1) OT-FWI、反射波和初至波波形反演算法和二维程序;
- 2) 提交 2 套理论数据和 1 套实际数据技术应用成果, 及相应的浅、中、深层一体化速度反演流程;
- 3) 项目成果报告。

###### 2. 主要技术、经济指标

最优传输目标函数相比常规目标函数收敛性提升 30%。

##### 三、院专家组总体评价

专家组认为, 课题组研究基础雄厚, 课题设计书研究内容充实, 目标合理, 技术路线基本可行, 同意通过开题立项。

##### 四、整改意见及整改期限

注重理论与实际应用结合, 探索应用于重点探区成像。

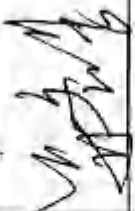
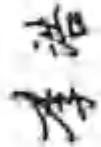
主审人签字:

院专家组组长签字:

2021年5月12日

2、审查组人员名单

外协项目开题专家组名单

| 序号 | 姓名  | 单位  | 职务/职称           | 签名                                                                                  |
|----|-----|-----|-----------------|-------------------------------------------------------------------------------------|
| 1  | 郭齐军 | 石勘院 | 书记<br>/教授级高工    |    |
| 2  | 曲寿利 | 石勘院 | 教授级高工           |    |
| 3  | 朱成宏 | 石勘院 | 院首席专家<br>/教授级高工 |    |
| 4  | 张宏  | 石勘院 | 院首席专家<br>/教授级高工 |   |
| 5  | 李军  | 石勘院 | 院首席专家<br>/教授级高工 |  |
| 6  | 郭元岭 | 石勘院 | 经理<br>/教授级高工    |  |
| 7  | 刘俊州 | 石勘院 | 所长<br>/教授级高工    |  |
| 8  | 李浩  | 石勘院 | 院高级专家<br>/教授级高工 |  |
| 9  | 高君  | 石勘院 | 院高级专家<br>/教授级高工 |  |



## 八、委托方科技发展部审批意见

课题组已按照专家组审查意见对设计进行了修改，可开始研究工作。

科技发展部负责人（签字）：

年 月 日

中国石油化工股份有限公司

石油勘探开发研究院科技发展部（盖章）

# 国家自然科学基金资助项目批准通知

姚刚 先生/女士：

根据《国家自然科学基金条例》和专家评审意见，国家自然科学基金委员会（以下简称自然科学基金委）决定批准资助您的申请项目。项目批准号：41974142，项目名称：各向异性介质中的全分量弹性波波形反演研究，直接费用：64.00万元，项目起止年月：2020年01月至2023年12月，有关项目的评审意见及修改意见见附件。

请尽早登录自然科学基金网络信息系统（<https://isisn.nsfc.gov.cn>），获取《国家自然科学基金资助项目计划书》（以下简称计划书）并按要求填写。对于有修改意见的项目，请按修改意见及时调整计划书相关内容；如对修改意见有异议，须在电子版计划书报送截止日期前向相关科学处提出。

电子版计划书通过自然科学基金网络信息系统（<https://isisn.nsfc.gov.cn>）上传，依托单位审核后提交至自然科学基金委进行审核。审核未通过者，返回修改后再行提交；审核通过者，打印纸质版计划书（一式两份，双面打印），依托单位审核并加盖单位公章后报送至自然科学基金委项目材料接收工作组。电子版和纸质版计划书内容应当保证一致。向自然科学基金委提交和报送计划书截止时间节点如下：

- 1、提交电子版计划书截止时间为**2019年9月11日16点**（视为计划书正式提交时间）；
- 2、提交电子修改版计划书截止时间为**2019年9月18日16点**；
- 3、报送纸质版计划书截止时间为**2019年9月26日16点**。

**请按照以上规定及时提交电子版计划书，并报送纸质版计划书，未说明理由且逾期不报计划书者，视为自动放弃接受资助。**

附件：项目评审意见及修改意见表

姚刚

国家自然科学基金委员会  
2019年8月16日

附件：项目评审意见及修改意见表

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                      |       |      |                     |         |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|-------|------|---------------------|---------|
| 项目批准号                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | 41974142             | 项目负责人 | 姚刚   | 申请代码1               | D040901 |
| 项目名称                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | 各向异性介质中的全分量弹性波波形反演研究 |       |      |                     |         |
| 资助类别                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | 面上项目                 |       | 亚类说明 |                     |         |
| 附注说明                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                      |       |      |                     |         |
| 依托单位                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | 中国石油大学（北京）           |       |      |                     |         |
| 直接费用                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | 64.00 万元             |       | 起止年月 | 2020年01月 至 2023年12月 |         |
| 通讯评审意见：<br><1>具体评价意见：<br>一、请针对创新点详细评述申请项目的创新性、科学价值以及对相关领域的潜在影响。<br><br>申请书开展弹性波波形反演的深入研究，包括①探索在新一代国产CPU上的弹性波场模拟，基于 ARM 构架的 64 核主频 2.6 GHz CPU 鲲鹏 920（华为2019年1 月发布）②提出基于全分量数据的P波、S波分离的半全局优化方法的弹性波波形反演算法，Quantum Particle Swam Optimization - QPSO；③测试声波（纯P波）、单分量、三分量及全分量数据在多种观测系统中对弹性波波形反演效果的影响和串扰的压制；<br>目前压制串扰，有利用Hilbert变换分离上下、左右行波以提高波印延矢量的精度的方法，本项目提出的半全局方法是个全新的思路。<br>科学价值是推动弹性波全波形反演的发展，对多波多分量技术发展、各向异性介质波传播、半全局反演理论有重要推动作用。                                                                                                                                                                                                          |                      |       |      |                     |         |
| 二、请结合申请项目的研究方案与申请人的研究基础评述项目的可行性。<br>研究方案中，全分量数据提供的另外 6 个应力/应变分量，这 6 个分量是对三分量数据信息的补充，在未知数个数是 5 个的情况下，如果只用质点速度信息，则只有两个数据反演方程组是欠定的；如果加上应力分量，则反演方程组已不再欠定。研究方案中P 波能量更新 P 波速度，S 波能量更新 S 波速度，反演系统中不会有能量的串扰，即 Hessian 矩阵的非主对角线块的值为零。而非分离的常规弹性波波形反演中，这些非主对角线块的值不为零。<br>该方案等效于在逆时偏移中利用Hilbert变换分离上下、左右行波（刘法启等2007，费彤等2015）较少串扰的方案，已有多篇研究证实其有效性。方案在弹性波全波形反演中使用有很好的可行性。<br><br>申请人博士生和博士后在英国研究全波形反演，研究基础较好，在国际勘探地球物理领域顶尖杂志Geophysics、Geophysical Prospecting、Journal of Geophysical Research (Solid Earth)，国内顶尖杂志中国科学 (D: Earth Sciences)，国际SCI杂志 Computational Geosciences等杂志发表多篇论文， 2018年 在SEG (Society of Exploration Geophysicists) 年会获得“最佳25篇论文”奖。 |                      |       |      |                     |         |
| 三、其他建议<br>替换波的特性，对逆时偏移有较大影响，由于全波形反演旧精度与逆时偏移有相似的程度，建议注意这种相似性机制可能以不同方式出现。                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                      |       |      |                     |         |
| <2>具体评价意见：<br>一、请针对创新点详细评述申请项目的创新性、科学价值以及对相关领域的潜在影响。                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                      |       |      |                     |         |

选题属于勘探地球物理学前沿课题。申请人提出了基于多分量地震数据P、S波波场分离的半全局优化方法的弹性波全波形反演算法，该研究对于影响弹性全波形反演精度的多参数耦合问题的有效解决具有重要意义。该申请提出的研究方案可行，申请人前期发表了与此有关的多篇论文，具有良好的研究基础。建议进一步聚焦弹性全波形反演多参数耦合问题，把项目书进一步写细，理顺逻辑关系。

二、请结合申请项目的研究方案与申请人的研究基础评述项目的可行性。

三、其他建议

〈3〉具体评价意见：

一、请针对创新点详细评述申请项目的创新性、科学价值以及对相关领域的潜在影响。  
1、常规声波全波形反演已有较多的研究和进展，而弹性波全波形反演，特别是针对各向异性介质下的弹性波全波形反演，国内外研究的相对较少。首先是反演参数的增加带来计算量的急剧增加，其次是多参数反演中不同参数对反演的敏感程度不同，如何平衡其间的权重、建立合理的目标函数等，具有很大的挑战。  
2、申请者以国产CPU为基础，充分利用全波场（纵、横波）、全分量观测数据，对各向异性介质中的全分量全波形反演进行研究，一方面促进其研究更加高效的正、反演算法；另一方面对于评估多波多分量和多参数（如各向异性参数）全波形反演的实际意义和应用效果等都有较大的帮助。

二、请结合申请项目的研究方案与申请人的研究基础评述项目的可行性。

三、其他建议

〈4〉具体评价意见：

一、请针对创新点详细评述申请项目的创新性、科学价值以及对相关领域的潜在影响。  
弹性各向异性全波形反演的多参数耦合问题是地球物理界的一个公开难题，国内外有很多学者在这个方向开展工作。所以选题的科学价值无需置疑，无论从哪一个角度尝试解决该问题都是有益的尝试。申请书中提出的解决方案是将DA SILVA (2018, 2019) 的半全局优化策略用于弹性各向异性FWI，使用QPSO更新各向异性参数，用局部梯度法更新纵横波速度。为了降低QPSO的计算成本，采用按照地层分块的模式压缩各向异性参数模型空间。  
但是首先需要指出申请者使用的P、S波分离的VTI弹性波动方程即便在弱各向异性介质下，分离出来的反射P、S波振幅信息也是有误差的。建议申请者使用更为精确的波模式解算方法，否则在迭代求解时的困难以致收敛困难。其次，尽管申请者压缩了各向异性参数的模型空间，QPSO的计算成本依然很可观，同时全局算法也并不能解决各向异性参数之间的串扰问题，恐怕除了引入更多参数之间先验信息，别无他法。上述两个问题对纵横波背景速度建立或许影响不大，但是对各向异性参数背景的建立影响是很大的，如果各向异性参数的重建精度有问题，那么纵横波波速度的重建精度自然也就难以保障了。  
这些都是申请者在研究中必须要考虑和面对难题。

二、请结合申请项目的研究方案与申请人的研究基础评述项目的可行性。  
申请者之前弹性各向异性FWI方面没有第一作者论文，不过和DA SILVA (2018, 2019) 的两篇合作论文中申请者都是第二作者。课题第二申请人在弹性波正演模拟方面有不错的积累，作者在声波波形反演方面有一定研究基础和技术储备，对利用半全局优化策略尝试求解弹性各向异性FWI应该可以很快着手开展工作。只要申请者能够解决第一部分所提到的两个挑战，申请书中提到的研究方案和技术路线是可行的。

三、其他建议

无

〈5〉具体评价意见：

一、请针对创新点详细评述申请项目的创新性、科学价值以及对相关领域的潜在影响。  
全波形反演较常规的偏移处理能够提供更多的物性参数，在地震波资料处理中得到了广泛应用，也是当下研究的热点。申请人提出利用完整的波动方程、开展弹性波的纵横波速度、密度及各向异性参数的全分量全波形多参数反演，通过开展基于P波、S波分离、全局搜索的弹性波波场反演的算法，开展压制多参数间串扰的新算法研究，从反演成像效果上论证全分量采集的必



|                                                                                                                                                                                                                                                                                                   |                                |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|
| <p>要性。应该说申请者提出的研究内容非常具有挑战性、难度系数非常大，全波形反演目前距离实时数据处理尚有很长的路要走，制约全波形反演最大的问题是反演速度，申请者提出在华为推出的新一代基于ARM构架的众核CPU上进行并行计算，但并没有说明该计算量巨大的全波形全频带参数反演所需的硬件设施，包括全分带全波形参数反演遇到的实际难点问题、怎么提高反演速度等细节讨论并不详细。但考虑到项目研究思路具有一定的创新及实用价值，申请者也发表了多篇高水平论文，具有扎实的研究基础。</p> <p>二、请结合申请项目的研究方案与申请人的研究基础评述项目的可行性。</p> <p>三、其他建议</p> | <p>地球科学部</p> <p>2019年8月16日</p> |
| <p>修改意见：</p>                                                                                                                                                                                                                                                                                      |                                |

合同编号:

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## 技术测试（委托）合同

项目名称：基于随钻测井数据的高精度

井震标定处理及速度建模

委托方（甲方）：中国科学院



地质与地球物理研究所

受托方（乙方）：中国石油大学（北京）

签订时间：2025年9月23日

签订地点：

有效期限：2025年9月23日~2026年1月23日

中华人民共和国科学技术部印制

## 填写说明

一、 本合同为中华人民共和国科学技术部印制的技术开发（委托）合同示范文本，各技术合同登记机构可推介技术合同当事人参照使用。

二、 本合同书适用于一方当事人委托另一方当事人进行新技术、新产品、新工艺、新材料或者新品种及其系统的研究开发所订立的技术开发合同。

三、 签约一方为多个当事人的，可按各自在合同关系中的作用等，在“委托方”、“受托方”项下（增页）分别排列为共同委托人或共同受托人。

四、 本合同书未尽事项，可由当事人附页另行约定，并可作为本合同的组成部分。

五、 当事人使用本合同书时约定无需填写的条款，应在该条款处注明“无”等字样。

## 技术测试（委托）合同

委托方（甲方）： 中国科学院地质与地球物理研究所

住 所 地： 北京朝阳区北土城西路 19 号

法定代表人： 底青云

项目联系人： 张舒扬

联系方式

通讯地址： 北京朝阳区北土城西路 19 号

电 话： 17600207191 邮 编： 100029

电子信箱： zhangshuyang@mail.iggcas.ac.cn

受托方（乙方）： 中国石油大学（北京）

住 所 地： 北京市昌平区府学路 18 号

法定代表人： 金衍（校长）

项目负责人： 姚刚

研发团队成员

其中，校内在职人员： 姚刚

校外人员（含学生）： 刘能超；张平民，陈曲扬，蒋东旭

联系方式

通讯地址： 北京市昌平区府学路 18 号

电 话： 18201008231 传 真：

电子信箱： yaogang@cup.edu.cn



本合同甲方委托乙方数据测试基于随钻测井数据的高精度井震标定处理及速度建模项目，并支付技术测试经费和报酬，乙方接受委托并  
进行此项数据测试工作。双方经过平等协商，在真实、充分地表达各自意愿的基础上，根据《中华人民共和国合同法》的规定，达成如下协议，并由双方共同恪守。

## 第一条 本合同研究开发项目的要求如下：

1. 技术测试目标：智能导钻系统井场实钻试验中需基于实时获取的随钻测井数据快速建立高精度井震标定与速度模型，解决传统方法层位-深度-速度失配导致储层刻画不准问题。处理井场试验得到的12口随钻测井数据，开展子波迭代优选处理、单井合成记录标定及层位联合误差校正分析，构建实时的多井时深关系和高精度速度场，实现时间-深度域精准

映射。

## 2. 技术测试内容：

### (1) 子波反演：

①对12口实钻井的地震数据进行人机交互频谱分析。  
②基于目标层主频的子波反演。通过对12口实钻井的的子波进行优化，消除常规雷克子波假设误差；

### (2) 合成记录标定：

①采用优化后的子波实现12口实钻井的分频合成记录计算。  
②针对12口实钻井开展井震相关系数计算与显示。  
③实现12口实钻井的合成记录与地震数据的人机交互时移匹配；  
④完成12口实钻井及其临井的时深关系曲线计算。

### (3) 层位约束的高精度速度场、反射系数场的建立：

①结合12口实钻井及其临井的时深关系曲线和地质层位趋势，建立符合地质规律的初始速度场1套；

②利用层位的约束，通过12口实钻井的随钻数据来优化初始速度场，形成高精度的速度场1套。

③在12口实钻井的测井数据基础上建立密度场1套，并与速度场结合计算1套反射系数。

3. 测试方法和路线：为得到高精度标定成果（层速度模型、深度域层位等）并应用于地震反演，需以测井层速度模型约束模型，以地震资料构造为基础，建立高精度的速度模型，实现高精度的时深转换。并通过子波反演提取子波，让合成记录的和井旁地震记录匹配度更高，提高地层的标定精度。

（1）子波反演：通过高保真度时变子波反演提升地层标定精度

①方法原理：利用地震记录与测井反射系数匹配，反演目标子波，避免传统雷克子波理想化假设误差；

②关键技术：重点考虑空间与垂向变化特征，结合深度变化的频率动态调整；

③实现方式：以目标层为基准，采用人机交互 + 相关系数自动微调实现时移匹配，提升地层对齐精度；

④优化目标：通过雷克子波与地震记录误差反演目标子波，降低时窗依赖性，增强井震匹配度。

（2）合成记录标定：构建“地震反射—合成记录—速度反馈”关联体系

①反射系数计算：基于声波/密度测井生成反射系数序列，并结合优化子波合成地震记录；

②井震标定策略：

直井：直接取井旁道数据进行标定；

斜井/水平井：依托高精度速度场，计算井轨迹及不规则路径走时，并从对应深度域位置提取地震记录；

③匹配度评价：采用皮尔逊相关系数、互相关系数、归一化互相关系数等作为量化指标，依据需求灵活选择；

④时深关系建立：单井通过时间域剖面标定提取时深曲线，多井数据

整合并以地震层位为空间约束，构建多井时深关系模型，实现工区内高精度时深转换。

### (3) 高精度速度场构建与优化：实现最终深度速度数据体

①数据约束：由测井速度（AC）和地震层位共同约束，按空间位置将单井时深曲线插值为速度剖面；

②质量控制：对比地震构造特征与速度剖面，剔除误差较大的单井数据，筛选高质量测井速度；

③初始速度场：结合时深曲线和地质层位趋势建立初始模型，在时间域拾取层位并沿层插值，得到初始时间域速度场；

④深度域转换：将速度场与层位转换至深度域，并沿层插值测井数据，得到多参数模型；

⑤优化方法：通过多井速度误差统计，采用反距离加权算法分布误差，逐步修正并优化速度模型；

⑥最终成果：生成高精度速度数据体和优化的反射系数模型，为智能导钻系统实钻试验提供可靠的速度场支撑。

**第二条** 乙方应在本合同生效后 10 日内向甲方提交技术测试计划。技术测试计划应包括以下内容：

1. 子波反演技术体系测试方案确定时间节点；
2. 井震标定技术体系测试方案确定时间节点；
3. 层位约束的高精度速度场建立方案确定时间节点。

**第三条** 乙方应按下列进度完成研究开发工作：

1. 合同签订后 1 个月内完成 12 口实钻井及临井的子波反演体系技术测试，包括频谱属性提取与优化、以及适配复杂构造的子波优化方法；
2. 合同签订后 3 个月内完成 12 口实钻井及临井的井震标定体系技术测试，包括直井、斜井与水平井合成记录算法改进、多井井震匹配策略优化以及井震相关性评价方法；

3. 合同签订后 4 个月内完成 1 套层位约束的高精度速度场技术测



试,包括地质层位约束条件定义、速度场反演与迭代优化、以及密度场耦合与反射系数计算。

#### 第四条 甲方应向乙方提供的技术资料及协作事项如下:

1. 技术资料清单: (1) 研究区测井数据(声波、密度、自然伽马)。  
(2) 研究区高精度地震成像数据及目标层位数据。(3) 研究区的已有AC模型数据。

2. 提供时间和方式: 按第三条计划进度提供相应资料。

本合同履行完毕后,上述技术资料按以下方式处理: 双方协商。

#### 第五条 甲方应按以下方式支付研究开发经费和报酬:

1. 研究开发经费和报酬总额为 25.00 万。
2. 技术测试经费由甲方 一次 支付乙方。具体支付方式和时间如下:

(1) 测试服务验收后,由乙方开具发票,甲方付款 25.00 万元,付款比例 100%。

(2) \_\_\_\_\_  
(3) \_\_\_\_\_  
(4) \_\_\_\_\_

乙方单位名称、开户行和帐号如下:

单位名称: 中国石油大学(北京)  
开户行: 中国建设银行北京昌平支行  
帐号: 11001009200056050532

甲方单位发票信息:

单位名称: 中国科学院地质与地球物理研究所  
纳税人识别号: 12100000400002734J  
单位地址: 北京市朝阳区北土城西路 19 号  
联系电话: 010-82998568  
开户银行: 中国农业银行北京健德支行



开户账号： 11190901040000456

**第六条** 本合同的研究开发经费由乙方以 专款专用 的方式使用。甲方有权以 不定期 的方式检查乙方进行研究开发工作和使用研究开发经费的情况，但不得妨碍乙方的正常工作。

**第七条** 本合同的变更必须由双方协商一致，并以书面形式确定。但有下列情形之一的，一方可以向另一方提出变更合同权利与义务的请求，另一方应当在 5 日内予以答复；逾期未予答复的，视为同意。

1. 一方出现设备故障、样品异常等突发因素，无法按期履行合同，由签约各方另行协商并做书面约定，作为本合同的变更文本；

2. 在此过程中，乙方提供的研发结果，甲方技术部门认为无法达到既定目标，可以随时提出暂停合作。

**第八条** 未经甲方同意，乙方不得将本合同项目部分或全部研究开发工作转让第三人承担。

**第九条** 在本合同履行中，因出现在现有技术水平条件下难以克服的技术困难，导致研究开发失败或部分失败，并造成一方或双方损失的，双方按如下约定承担风险损失： 协商解决 的方式认定。认定技术风险的基本内容应当包括技术风险的存在、范围、程度及损失大小等。认定技术风险的基本条件是：

1. 本合同项目在现有技术水平条件下具有足够的难度；

2. 乙方在主观上无过错且经认定研究开发失败为合理的失败。

一方发现技术风险存在并有可能致使研究开发失败或部分失败的情形时，应当在 10 日内通知另一方并采取适当措施减少损失。逾期未通知并未采取适当措施而致使损失扩大的，应当就扩大的损失承担赔偿责任（赔偿额度不超过本合同的技术开发费）。

**第十条** 在本合同履行中，因作为研究开发标的技术已经由他人公开（包括以专利权方式公开），一方应在 10 日内通知另一方解除合同。逾期未通知并致使另一方产生损失的，另一方有权要求予以赔偿（赔偿额度不超过本合同的技术开发费）。

## 第十一条 双方确定因履行本合同应遵守的保密义务如下：

甲方：

1. 保密内容（包括技术信息和经营信息）：由乙方方向甲方提供的所有的技术资料（包括但不限于高精度井震标定处理技术体系、基于随钻测井数据的速度建模）等技术文件、经营信息、报价信息以及乙方相关的一切信息与内容。

2. 涉密人员范围：与项目相关的甲方工作人员及甲方知悉本项目或保密信息的所有人员。

3. 保密期限：合同签订之日起 10 年内。

4. 泄密责任：甲方追加支付乙方已付研发费用的 20%作为赔偿。

乙方：

1. 保密内容（包括技术信息和经营信息）：甲方所提供的，所有资料，乙方未经允许不得用于此合作项目以外的任何场所，包括沟通、交流内容，论文、学术发表等。

2. 涉密人员范围：项目组成员。

3. 保密期限：合同签订之日起 10 年内。

4. 泄密责任：乙方支付甲方已付研发费用的 20% 作为赔偿。

## 第十二条 乙方应当按以下方式向甲方交付技术测试成果：

1. 技术测试成果交付的形式及数量：结题验收多媒体电子版文件 1 份，技术测试文字报告电子版文件 1 份、纸质版文件 1 份，时变子波反演程序代码 1 套，高精度井震标定程序代码 1 套，随钻测井数据约束的速度建模流程及程序代码 1 套，技术测试使用的示例数据集 1 套。

2. 技术测试成果交付的时间及地点：按计划提交。

**第十三条** 双方确定，按以下标准及方法对乙方完成的研究开发成果进行验收：按照第一条、第四条中规定的技术目标和技术内容进行验收，甲方验收确认后再进行约定款项支付。

**第十四条** 乙方应当保证其交付给甲方的研究开发成果不侵犯任何第三人的合法权益。如发生第三人指控甲方实施的技术侵权的，乙方应当



主动向第三方披露该技术系由乙方研制开发的事实,并协助甲方就此项目进行法律诉讼,若败诉,返还甲方已付研发费用。

**第十五条** 双方确定,因履行本合同所产生的研究开发成果及其相关知识产权权利归属,按下列第 1 种方式处理:

1. 双 (甲、双)方享有申请专利的权利。

专利权取得后的使用和有关利益分配方式如下:因本合同产生的专利申请权及专利权归甲方所有,如乙方需要相关资料用于其他用途,应提前与甲方确认,获得 同意使用范围后方可。

2. 按技术秘密方式处理。有关使用和转让的权利归属及由此产生的利益按以下约定处理:

(1) 技术秘密的使用权: 使用权人为甲方。

(2) 技术秘密的转让权: 转让权人为甲方。

(3) 相关利益的分配办法: 双方协商沟通,甲方为利益分配方法的最 终决定者。

双方对本合同有关的知识产权权利归属特别约定如下:如乙方需要相关资料用于其他用途,应提前与甲方确认,获得同意使用范围后方可。

**第十六条** 乙方不得在向甲方交付研究开发成果之前,自行将研究开发成果转让给第三人。

**第十七条** 乙方完成本合同项目的研究开发人员享有在有关技术成果文件上写明技术成果完成者的权利和取得有关荣誉证书、奖励的权利。

**第十八条** 乙方利用研究开发经费所购置与研究开发工作有关的设备、器材、资料等财产,归 乙 (甲、乙、双)方所有。

**第十九条** 双方确定,乙方应在向甲方交付研究开发成果后,根据甲方的请求,为甲方指定的人员提供技术指导和培训,或提供与该研究开发成果相关的技术服务。

1. 技术服务和指导内容: \_\_\_\_\_

2: 地点和方式: \_\_\_\_\_。

3. 费用及支付方式: \_\_\_\_\_。

**第二十条** 双方确定: 任何一方违反本合同约定, 造成研究开发工作停滞、延误或失败的, 按以下约定承担违约责任:

1. 乙方不能按合同规定的工期交付甲方试验报告, 每延误一天扣项目合同总价的 1%, 直至交付甲方为止, 赔付上限不超过甲方已付乙方的技术开发费用 (支付违约金或损失赔偿额的计算方法)。

**第二十一条** 双方确定, 甲方有权利用乙方按照本合同约定提供的研究开发成果, 进行后续改进。由此产生的具有实质性或创造性技术进步特征的新的技术成果及其权利归属, 由 甲 (甲、乙、双) 方享有。具体相关利益的分配办法如下: 双方协商沟通, 甲方为利益分配方法 的最终决定者。

乙方有权在完成本合同约定的研究开发工作后, 利用该项研究开发成果进行后续改进。由此产生的具有实质性或创造性技术进步特征的新技术成果, 归 乙 (甲、乙、双) 方所有。具体相关利益的分配办法如下: 双方协商沟通, 乙方为利益分配方法的最终决定者。

**第二十二条** 双方确定, 在本合同有效期内, 甲方指定 张舒扬 为甲方项目联系人, 联系电话: 17600207191, 电子邮箱: zhangshuyang@mail.lggcas.ac.cn; 乙方指定 姚刚 为乙方项目联系人, 联系电话: 18201008231, 电子邮箱: yaogang@cup.edu.cn。双方往来电子邮箱视为本合同的组成部分。项目联系人承担以下责任:

1. 负责项目进度跟踪

2. 负责项目结题

一方变更项目联系人的, 应当在七日内以书面形式通知另一方。未及时通知并影响本合同履行或造成损失的, 应承担相应的责任 (赔偿额度不超过本合同的技术开发费)。



第二十三条 双方确定，因发生不可抗力或技术风险致使本合同的履行成为不必要或不可能的，一方可以通知另一方解除本合同。

第二十四条 双方因履行本合同而发生的争议，应协商、调解解决。协商、调解不成的，提交乙方所在地人民法院裁判。

第二十五条 本合同一式肆份，双方各执两份，具有同等法律效力。

第二十六条 本合同经双方签字盖章后生效。

甲方：中国科学院地质与地球物理研究所 (盖章)

法定代表人/委托代理人：张绍华 (签名)

2015年9月23日

乙方：中国石油大学(北京) (盖章)

法定代表人/委托代理人：金钊 (签名)

2015年9月23日

印花税票粘贴处:

(以下由技术合同登记机构填写)

合同登记编号:

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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1. 申请登记人: \_\_\_\_\_

2. 登记材料: (1) \_\_\_\_\_

(2) \_\_\_\_\_

(3) \_\_\_\_\_

3. 合同类型: \_\_\_\_\_

4. 合同交易额: \_\_\_\_\_

5. 技术交易额: \_\_\_\_\_

技术合同登记机构 (印章)

经办人:

年 月 日

项目编号: HX20251157

# 研究开发合同

## (弹性介质建模技术研究)

任务委托方(甲方): 中海油田服务股份有限公司天津分公司

任务受托方(乙方): 中国石油大学(北京)

签订地点: 天津塘沽

签订时间: 2025 年 10 月

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本服务合同（以下称“合同”或“本合同”）由以下双方于2025年在天津塘沽签订：

甲方：中海油田服务股份有限公司天津分公司  
注册地址：天津滨海新区塘沽海洋科技园海川路1581号  
乙方：中国石油大学（北京）  
注册地址：北京市昌平区府学路18号

根据《中华人民共和国民法典》及相关法律法规的规定，就乙方为甲方提供弹性介质建模技术研究事宜，经协商一致，双方达成如下合同条款，以兹共同遵守。

第一条 服务内容

1.1 乙方应当按照合同规定进行弹性介质建模技术研究。服务内容和要求见本合同附件一。

第二条 服务期限

2.1 项目完成时间应在合同签订后24个月内，并向甲方提交合格的工作成果。具体服务进度见本合同附件一。

第三条 工作成果及验收

3.1 乙方向甲方提交的工作成果应当包括：详见附件一《弹性介质建模技术研究》项目的服务技术要求。

双方确认，乙方最终完整提交研究成果供甲方验收得时间为合同签订后24个月内，其中分阶段为：

- ★第一阶段：合同签订后2个月内  
目标及任务：完成《弹性介质建模技术研究设计报告》，完成算法选型及详细设计工作。  
提交成果：《弹性介质建模技术研究设计报告》  
要求：详细介绍技术路线和算法选型等内容。
- ★第二阶段：合同签订后12个月内  
目标及任务：完成稳健目标函数设计与验证，研发三维弹性波全波形反演核心算法并优化，实现合成数据的稳定反演。  
提交成果：稳健目标函数算法代码及三维弹性波全波形反演算法代码。  
要求：三维合成数据验证算法正确。
- ★第三阶段：合同签订后24个月内  
目标及任务：完成配套处理流程，在实际数据上完成全流程反演，提交应用成果与技术报告等合同规定的全部研究内容。  
提交成果：最终的三维弹性波全波形反演算法代码、软件安装和使用说明、软件测试报告、项目研究报告等。  
要求：满足附件一要求的技术指标和验收要求。

- 3.2 甲方收到乙方工作成果后，应当通知乙方对工作成果进行验收。工作成果验收采取的形式、验收专家及验收地点由甲方确定。
- 3.3 工作成果验收的标准见本合同附件一。
- 3.4 验收结束后，甲乙双方签署验收记录。验收记录是乙方要求甲方支付服务费的必备付款凭证。验收记录格式见本合同附件二。

#### 第四条 工作进度汇报

- 4.1 乙方应在合同生效后及时在其注册地科技管理部门完成技术开发合同认定登记工作, 最迟不得晚于本合同期限届满之日。
- 4.2 本合同履行过程中, 乙方应按本合同附件一要求的时间或甲乙双方约定的其它时间进行工作成果汇报。
- 4.3 本合同履行过程中, 乙方每一个月以电子邮件或传真形式向甲方报告服务进展情况。

#### 第五条 乙方的陈述和保证

- 5.1 乙方应当按照本合同约定, 提供合格并且富有经验的作业人员和处于安全 and 良好工作状态的设备、零备件、材料以及必要的供应品和消耗品, 完成合同约定的服务工作。
- 5.2 乙方应当指定一名代表, 作为项目负责人, 全权代表乙方与甲方协商解决和处置与合同履行有关的一切事务, 接受甲方代表指令并指挥实施服务工作。乙方变更履约代表或其授权范围的, 应当提前书面通知甲方。因乙方未及时通知甲方而导致双方之间出现合同履行障碍的, 乙方应承担相应的责任并赔偿因此给甲方造成的损失。
- 5.3 乙方利用本合同服务费购置的设备、器材、资料等财产均归甲方所有。
- 5.4 乙方提交最终工作成果的同时, 必须归还从甲方借阅的一切原始资料。乙方不得复制或留存从甲方获得的任何原始资料。
- 5.5 乙方用于服务的原始资料以及分析测试原始资料、记录资料的软盘及其它原始资料应在提交最终工作成果时全部交甲方归档保存。

#### 第六条 服务费

- 6.1 本合同项下服务费为 RMB 1,048,000.00 (大写: 人民币壹佰零肆万捌仟元整)。服务费为含税 (包括增值税) 总金额。其中, 不含增值税服务费为人民币 RMB1,017,475.73 (大写: 人民币壹佰零壹万柒仟肆佰柒拾伍元柒角叁分), 增值税税率为 3%。如果增值税税率因国家增值税税率调整而发生变化, 或因享受优惠政策导致增值税免税, 服务费自动调整, 以保证不含税服务费不变。具体费用及费率见本合同附件三。服务费为乙方提供本合同项下服务工作及完整履行本合同后甲方应支付的全部金额。
- 6.2 前款约定的服务费已经包括税费、保险费用、设备工具使用成本、人员劳务费用支出等乙方履行本合同所支出的所有成本, 应获得的利润和承担的风险及服务过程中可能产生的其它费用等。除非根据本合同规定或国家增值税税率调整引起服务费调整外, 服务费为固定价格, 服务费的数额不受通货膨胀、汇率波动及其它因素变化的影响。
- 6.3 乙方应自行承担因履行本合同应当缴纳的各项税费, 并保障甲方不因乙方未缴纳或未足额缴纳税费而受到任何影响。
- 6.4 服务费经甲方支付给乙方后, 乙方专用于本合同约定的服务项目, 不得挪作他用。甲方有权监督乙方对该服务费的使用。

#### 第七条 付款

- 7.1 支付货币

本合同项下的所有应付款项均应以人民币支付。

- 7.2 付款方式: ☐ 现金; ☒ 银行电汇; ☐ 汇票; ☐ 本票; ☐ 支票; ☐ 其它\_\_\_\_\_。
- 7.3 付款进度: 见本合同附件四。
- 7.4 乙方应当按照付款进度向甲方开具符合中国法律法规要求的发票并提交支持文件。发票应注明合同编号且抬头应为: 中海油田服务股份有限公司天津分公司。如乙方逾期 60 日内向甲方提供上述发票及相关支持文件, 应视为乙方放弃对相应阶段服务费的付款请求权。
- 7.5 甲方收到符合本合同第 7.4 款规定的发票和支持文件后, 经核对无误的, 应于收到该等发票和支持文件之日起 60 日内将应付款支付给乙方。如果甲方对乙方提交的该等发票和支持文件全部或部分有异议, 应及时通知乙方, 乙方应根据甲方要求修改并重新开具发票。乙方因甲方异议重新开具的发票, 付款期限从甲方收到该等重新开具的发票之日起计算。
- 7.6 乙方为甲方开具上述发票所需信息如下:
- 公司名称: 中海油田服务股份有限公司天津分公司
- 统一社会信用代码: 91120116732833745W
- 开户行名称: 中海石油财务有限责任公司
- 银行账号: 020030027-02-1698
- 7.7 甲方或甲方指定的第三方将应付款支付至乙方指定的如下银行账户:
- 公司名称: 中国石油大学(北京)
- 统一社会信用代码: 12100 00040 00061 10Y
- 开户行: 中国建设银行北京昌平支行
- 银行账号: 11001009200056050532

## 第八条 服务风险

- 8.1 在履行本合同过程中, 因现有水平和条件下难以克服的技术困难导致本合同约定的服务部分或全部无法完成而导致的风险应由乙方承担。在此情况下, 甲方有权解除本合同, 乙方应退还甲方支付的相应服务费。

## 第九条 权利保证和知识产权

- 9.1 乙方保证其在提供服务成果的过程中所使用的文件、资料或工艺、技术等以及工作成果不存在侵犯任何第三方的权利(包括知识产权), 并保护甲方不因使用这些文件、资料或工艺、技术等而受到任何第三方有关侵权的指控、索赔或任何争议。如因任何原因导致第三方(包括但不限于乙方员工)对于前述文件、资料或工艺、技术, 或本合同项下工作成果对甲方主张权利的, 乙方应根据甲方的要求进行应诉, 同时甲方有权解除本合同并要求乙方赔偿其因此遭受的全部损失。
- 9.2 乙方提交的工作成果的所有权和知识产权(包括但不限于申请专利权和非专利技术秘密权)归双方共同所有。乙方在为甲方提供服务工作的过程中所产生的所有知识产权归双方共同所有。

## 第十条 保密

- 10.1 乙方及其人员在本合同履行过程中所获得的甲方所有信息和与提供本合同项下服务相关的记录、数据、报告等资料均属甲方的商业秘密。未经甲方书面同意, 乙方及



其人员不得披露、使用、转让、复制或允许第三方使用上述信息或者资料。

10.2 本条有关保密的约定,不因本合同终止或者解除而失效。

## 第十一条 违约责任

11.1 乙方未在合同约定的服务期限内或未在甲方要求的期限内完成服务工作的,每逾期7个工作日(不满7天按7天计算);甲方有权要求乙方支付合同总额的1%作为违约金。如逾期超过五(5)周,甲方有权解除本合同;乙方应向甲方支付本条所约定的违约金并赔偿甲方因此遭受的超出违约金数额的全部损失,同时,乙方应当退还甲方已支付的服务费。

11.2 如发生下列任何一种情况,甲方有权解除本合同,乙方应退还甲方已支付的全部款项,并支付合同总额的20%作为违约金、乙方应同时赔偿甲方因此遭受的超出违约金数额的全部损失。

(1) 乙方未按本合同的要求进行服务或工作成果经验收不合格,且未在甲方规定的合理期限内纠正;

(2) 未经甲方同意,乙方擅自进行转让、分包;

(3) 乙方发生其它严重违约行为。

11.3 乙方按照本合同的约定需要承担违约金或赔偿责任的,甲方有权从应付款项中直接扣除该等违约金或赔偿金。

11.4 甲方因自身原因逾期向乙方支付服务费的,应按照合同订立时1年期贷款市场报价利率和逾期天数向乙方支付逾期付款部分的利息,该等利息合计不超过合同总额的20%。

## 第十二条 保险

12.1 在本合同有效期限内,双方应各自就自己的人员和财产向保险人投保足额保险,并自行承担相应的投保费用。

12.2 甲方有权要求乙方提交保险合同、发票等资料并复印存档。乙方应在接到甲方通知后7日内予以提供。

12.3 本第十二条的规定不能限制或免除乙方在本合同项下的任何义务和责任。

## 第十三条 适用法律和争议解决

13.1 本合同适用中华人民共和国法律。

13.2 因履行本合同发生的或与本合同有关的一切争议,双方首先应友好协商解决,如经协商仍不能解决,双方同意选择以下第(2)种方式予以解决:

(1) 向甲方所在地人民法院起诉。

(2) 提交北京仲裁委员会进行仲裁。仲裁地点在天津。仲裁应根据该仲裁委员会现行有效的仲裁规则进行。仲裁裁决是终局的,对双方均有约束力。除仲裁庭另有裁决外,仲裁费用由败诉方承担。

13.3 争议解决期间,除争议事项外,双方应继续履行本合同。

## 第十四条 联系人

14.1 除非双方另有明确约定,任何一方根据本合同向另一方提供资料和发送通知或者在工作过程中需要对相关技术问题澄清、咨询的联系人和联系方式如下:



甲方联系人: 刘洪翠

电话: 022-59553151

传真:

乙方联系人: 姚刚

电话: 18201008231

传真:

电子邮箱: liuhx24@cosl.com.cn

电子邮箱: yaogang@cup.edu.cn

地址: 天津市滨海新区塘沽海洋科技园 地址: 北京市昌平区府学路18号  
海川路1581号

14.2 上述送达地址适用范围包括就本合同发生争议时相关文件和法律文书的送达(包括争议进入仲裁、民事诉讼程序后的一审、二审、再审和执行程序)。

#### 第十五条 合同期限

15.1 本合同自双方授权代表签字并盖章之日起生效,至双方在本合同项下的全部义务履行完毕之日终止。

#### 第十六条 合同的解除和终止

16.1 如发生以下任一情形,经书面通知乙方,甲方有权立即解除本合同:

- (1) 乙方延期交付工作成果超过五(5)周;
- (2) 乙方发生其它严重违约,且未在甲方要求的期限内纠正。

16.2 无论基于何种原因,经提前15日书面通知乙方,甲方有权随时终止本合同。乙方收到甲方终止合同的书面通知后,应立即停止履行与本合同相关的工作,并对已履行的部分进行结算。甲方收到乙方的结算要求后,应与乙方协商结算服务费、结算费用以乙方为履行合同已实际发生的直接、合理费用为限,乙方应提供书面证明文件。

#### 第十七条 转让和分包

17.1 未经甲方事先书面同意,乙方不得将其在本合同项下的任何权利和义务全部或部分转让给任何第三方,包括乙方关联企业。

17.2 未经甲方事先书面同意,乙方不得将本合同分包给任何第三方,包括乙方关联企业。

17.3 乙方不得将本合同转包给任何第三方,包括乙方关联企业。

#### 第十八条 其它

18.1 在本合同签订时如乙方属于《保障中小企业款项支付条例》(“条例”)规定的小企业,本合同所约定的付款期限、方式、条件和违约责任等交易条件应遵守该条例的规定。如本合同约定的任何交易条件违反该条例,甲方应按照符合该条例规定的交易条件履行合同,并应按照条例的规定与乙方协商变更本合同的该等交易条件,以保障乙方享有条例规定的合法权益。

18.2 乙方应根据法律法规的要求建立并维系自身良好的健康、安全、环保体系。乙方因履行合同造成乙方和/或第三方的人员伤亡和/或财产损失以及环境污染损失由乙方承担全部责任,除非该等损失系甲方故意或重大过失所致。

18.3 乙方应根据甲方要求,无条件接受和配合甲方或甲方委托的会计师事务所进行的与本合同相关的审计。乙方应保存与本合同相关的记录和账目,保存期限为本合同终止后十五(15)年。经提前通知,甲方或甲方委托的会计师事务所所有权检查并复制该等记录和账目。

18.4 本合同附件是本合同的有效组成部分。本合同未尽事宜经双方协商后通过签署书面补充协议确定。补充协议是本合同的组成部分。

18.5 本合同一式贰份, 甲方双方各执壹份, 具有同等法律效力。

18.6 本合同系各方当事人反复协商、讨论的结果, 双方充分理解解合同内容。本合同的内容不是一方当事人事先拟定的, 本合同不属于格式合同, 条款内容不属于格式条款。

甲方: 中海油田服务股份有限公司天津分公司 乙方: 中国石油大学(北京)

(盖章)

(盖章)

法定代表人或授权代表签字:

法定代表人或授权代表签字:



日期: 2025.10.30

日期: 2025.11.17

附件一: “弹性介质建模技术研究”项目的服务技术要求

技术规格书

1. 服务内容

本次采购项目“弹性介质建模技术研究”为集团公司重大科技项目《“海经”框架构建装备3.0 技术研究及产业化体系建设(1期)》课题6《多分量拖缆地震处理技术研究》研究内容的一部分,课题聚焦多分量拖缆地震高分辨率处理的关键技术,重点开展多分量拖缆的三维波场重构、多分量拖缆鬼波压制、高分辨率处理与高分辨率偏移成像技术研究,形成一套针对海洋高分辨率高精度勘探的多分量拖缆地震采集处理成熟解决方案,为海洋目标精细勘探、开发地震等提供地震技术支持。

本次采购集中弹性波全波形反演理论与方法研究,研究三维弹性波全波形反演算法,构建稳健目标函数以突出走时信息、降低对振幅的依赖;设计多参数反演策略,缓解纵横波速度串扰等问题;最后开展地震数据的准备及配套技术研究。整体路线兼顾理论创新与工程实现,旨在提升反演对强阻抗地质体的适应性,推动地震成像由声波向高精度弹性波发展。

2. 服务要求

2.1 主要研究内容

- 1) 弹性波全波形反演理论方法研究;
- 2) 三维弹性波全波形反演算法开发;
- 3) 突出走时信息的目标函数研究;
- 4) 多参数反演策略研究;
- 5) 地震数据全波形反演数据准备及配套技术研究。

2.2 技术指标及验收要求

★关键技术指标:

- 1) 三维弹性波全波形反演算法可稳定运行不低于 72 小时;
- 2) 稳健的目标函数相对于常规最小二乘目标函数收敛效率提升至少 20%,甚至在常规最小二乘目标函数不收敛的情况下达到收敛;
- 3) 应用多参数反演策略后,纵横波串扰程度相对于不应用降低至少 20%;

- 4) 增强抗界面弹性波反演的纵波速度相对于声波反演的纵波速度精度提升至少 10%。

★验收要求:

满足上述技术指标且提供程序源代码, 具体要求如下:

- 1) 一套三维弹性波全波形反演算法软件及源代码;
- 2) 软件测试报告;
- 3) 软件安装和使用手册;
- 4) 研究报告。

2.3 提交成果要求

★提交的成果种类及数量:

- 1) 弹性介质建模技术研究软件及源代码一份;
- 2) 软件安装和使用手册一份;
- 3) 软件测试报告一份;
- 4) 研究报告一份。

2.4 开发人员要求

★项目周期内需要进行驻场服务, 核心开发人员不低于 21 天时间驻场研发。

2.5 进度要求

★(1) 第一阶段: 合同签订后 2 个月内完成《弹性介质建模技术研究设计报告》, 完成技术路线设计、理论模型选型和数据需求分析, 提交开题报告及技术指标, 确保研发方向明确。

★(2) 第二阶段: 合同签订后 12 个月内完成稳健目标函数设计与验证, 研发三维弹性波全波形反演核心算法并优化, 实现合成数据拟合的稳定反演。

★(3) 第三阶段: 合同签订后 24 个月内完成配套处理流程, 在实际数据上完成全流程反演, 提交应用成果与技术报告等合同规定的全部研究内容。

2.6 质保期

★质保期为 3 年。



本项目联系人(签字): 孙国瑞, 联系电话: 18202673654  
课题组长(签字): 马德东, 联系电话: 17602216829  
技术负责人(签字): 孙国瑞, 日期: 2025.9.3  
承担单位主管领导(签字): 孙国瑞, 日期: 2025.9.5  
科技项目承担单位主管领导(签字): 孙国瑞, 日期: 2025.9.8

附件二：验收记录（格式）

| 完工确认单                                                                      |                                |  |  |
|----------------------------------------------------------------------------|--------------------------------|--|--|
| 项目名称                                                                       |                                |  |  |
| 服务单位                                                                       |                                |  |  |
| 合同名称                                                                       | 合同号                            |  |  |
| 合同生效日期                                                                     | 服务地点                           |  |  |
| 工作量及质量                                                                     | 服务单位代表签字（盖章）：      年    月    日 |  |  |
| 注：以上内容由服务单位填写                                                              |                                |  |  |
| 工作量确认及质量评价：                                                                |                                |  |  |
|                                                                            |                                |  |  |
| 需求部门业务人员确认：      年    月    日                                               |                                |  |  |
| 需求部门负责人员审核：      年    月    日                                               |                                |  |  |
| 注：需求部门签字前，服务单位要同时提交员工考勤、工作量等合同付款结算及付材料。<br>本完工报告正本1份作为付款依据及必要附件，复印件双方各执1份。 |                                |  |  |

附件三：服务费及费率

| 序 号 | 项 目        | 数 量 | 单 位 | 不含增值税<br>总 价 | 增 值 税 税 率 | 增 值 税 总 价    |
|-----|------------|-----|-----|--------------|-----------|--------------|
| 1   | 弹性介质建模技术研究 | 1   | 项   | 1,017,475.73 | 3%        | 1,048,000.00 |
| 合 计 |            |     |     | 1,017,475.73 |           | 1,048,000.00 |

#### 附件四：付款进度

甲方收到符合本合同第 7.4 款规定的发票和支持文件后，经核对无误后，应于收到合同发票和支持文件之日起六十（60）日内将分阶段服务款支付给乙方。

投标方应按阶段完成服务内容，通过验收后付款：

**第一阶段**，签订合同后 2 个月内完成并完成《弹性介质建模技术研究设计报告》，完成算法选型及详细设计工作。甲方支付乙方服务款的 25%计人民币 262000.00 元。

**第二阶段**，签订合同后 12 个月内完成稳健目标函数设计与验证，研发三维弹性波全波形反演核心算法并优化，实现合成数据的稳定反演。甲方支付乙方服务款的 35%计人民币 366800.00 元。

**第三阶段**（合同最终验收），签订合同后 24 个月内完成配套处理流程，在实际数据上完成全流程反演，提交应用成果与技术报告等合同规定的全部研究内容。验收合格后，甲方支付乙方服务款的 40%计人民币 419200.00 元。

质保期：合同验收后 36 个月。



附件五: 健康安全环保协议

协议书编号:

# 健康安全环保协议

中海油田服务股份有限公司物探事业部

与

中国石油大学(北京)

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## 第一部分 协议书

甲 方: 中海油田服务股份有限公司物保事业部

乙 方: 中国石油大学(北京)

鉴于, 甲方因执行弹性地质建模技术研究项目, 为落实项目之健康、安全、环保管理, 保障项目顺利运行, 特与乙方签订 HSE 协议如下。

为保障甲乙双方人员、设备在项目执行过程中的安全、完整, 防止发生健康、安全、环保等事故、事件, 或就发生系列相似情况时落实各方责任, 将相关方损失控制到最低;

由于合同或作业期间的临时变动等情况, 除经甲乙双方协商, 并取得双方认可的其他约定时, 遵照其他约定, 否则, 甲乙双方应遵守此协议。

根据《中华人民共和国安全生产法》及相关法律法规, 在遵循平等、自愿、公平和诚实信用原则的基础上, 经协商一致, 双方于 2025 年    月    日签订本协议。

## 第二部分 协议条款

### 第一条 保险

1.1 为履行本合同, 乙方应购买下述保险:

- (1) 为其执行工作的人员购买人身伤害险或雇主责任险;
- (2) 为其工作设备(包括机动车辆和其它运输工具)购买财产险, 承保工作设备因任何原因引起的全部损失或损害;

(3) 根据相关法律法规购买其它保险, 包括但不限于涉及乙方人员、工作及第三方的保险。

1.2 如果乙方将工作的任一部分分包, 乙方应确保分包商购买、维持上述规定的保险, 分包合同保险条款应与本合同一致。

1.3 对于乙方根据本合同应购买的保险, 乙方应确保保险人放弃对甲方、甲方的关联企业及甲方人员的代位求偿权或任何形式的追索权。

1.4 对于乙方根据本合同应购买的保险, 乙方应于合同生效后 7 日内提供保险合同, 并根据甲方要求, 提供全额支付保险费的证明。否则, 乙方不得开始工作。未经甲方同意, 乙方不得取消或变更该等保险。如乙方未根据本合同规定购买、维持相关保险, 甲方有权代其购买并维持, 乙方应承担全部保险费用。甲方有权从合同价款中直接扣除该等费用或凭履约保函要求银行支付该等费用。

1.5 乙方根据本条款规定购买任何保险不得减少、免除乙方本合同下的任何义务或责任。

1.6 乙方根据本合同购买的保险在质保期届满前应持续有效, 适用于质保期届满前发生的所有保险事故。

1.7 如发生保险事故, 乙方应采取一切必要措施减少损失, 并配合甲方进行保险索赔工作。如因乙方不遵守本合同有关健康、安全、环保或质量控制系统规定或乙方其它过错导致甲方不能根据保险全额获赔, 甲方有权向乙方追索差额部分。

1.8 乙方不得实施任何可能导致相关保险中止、失效的行为。如因乙方的任何行为、过错(包括错误陈述、隐瞒事实、失职、违反保险合同条款), 甲方不能获得保险赔偿, 乙方应赔偿甲方因此遭受的全部损失。

1.9 本第九条的规定不能限制并免除乙方在合同项下的任何义务和责任。

## 第二条 乙方人员

### 2.1 一般要求

- (1) 乙方应选聘、组织充足、适任、有经验并具备相关证书的人员执行、完成工作。乙方对派出人员应特别是项目负责人、领队、安全管理人员的安全技能、安全意识和甲方安全管理程度及安全要求进行培训,对派出人员现场作业进行安全指导、支持、监督检查和绩效考核,对“三违”行为,“低老坏”现象进行治理。
- (2) 乙方人员应遵守双方约定的健康、安全、环保体系或规定。
- (3) 项目执行过程中,乙方应对其员工的报酬、福利、社会保险、食宿、交通负责。特殊情况合同中约定食宿、交通有明确约定的,按合同条款执行。
- (4) 项目执行过程中,乙方应建立并维系合法、适当的劳动关系。乙方应采取一切合理必要的措施,避免对工作质量、工期、工作计划和方案及其它方面产生不利影响的劳动争议、纠纷和冲突,如发生该等争议、纠纷或冲突,乙方应及时通知甲方,并妥善解决。
- (5) 乙方应采取措施确保其工作人员在执行工作过程中严格遵守本合同和法律法规的规定,如任何乙方工作人员违反本合同和法律法规,甲方有权要求该等人员停止工作,并离开甲方场地。如因乙方或其工作人员违反本协议和法律法规致使甲方遭受任何罚款、行政处罚或损害,乙方应予全额补偿。
- (6) 针对乙方人员违纪、行为不合规情况,甲方有权要求乙方更换其工作人员,乙方应严格执行甲方的要求。

## 第三条 安全防护和安全设施

- 3.1 乙方人员、设施应配备满足于协议项目的安全防护用品和安全器材,该用品、器材的配备应符合相关法规要求,或双方认可的标准和数量。
- 3.2 乙方保证,其配备的器材和设备应处于良好的工作状态,不存在任何影响工作执行的缺陷。
- 3.3 如甲方发现乙方提供的器材和设备存在任何缺陷或不符合双方约定的规定,有权要求乙方进行修理和更换,乙方不得因工作设施的修理或更换要求影响项目执行。

## 第四条 监督检查

- 4.1 甲方或其委托方有权(包括进入乙方工作场地)对乙方设备设施,人员资质和能力进行监督检查,并就发现的缺陷和隐患向乙方提出改进意见。设备设施情况,包括设备设施的完整性、安全性、专业设备检测检验合规性和施工机具状况,严禁设备设施带病运行,不符合要求的坚决不得安排使用;人员资质和能力,包括人员经验和资质、关键人员变更、规定的教育培训(尤其新员工、转岗员工)。
- 4.2 乙方应积极配合甲方或其委托方的监督检查,确保甲方及其委托方人员有权及时进入相关工作场地,为该等人员提供足够的支持和便利。根据甲方要求,提供工作进度、计划、健康、安全、环保、存在的问题、预防及整改措施及其它工作信息。
- 4.3 在监督检查过程中,如发现乙方工作存在任何缺陷、瑕疵、疏漏或不符合本合同的规定,乙方应根据甲方的要求,立即采取一切必要、合理的补救措施排除该等缺陷、瑕疵和疏漏,乙方应承担因此发生的一切费用。
- 4.4 乙方要制定现场作业项目安全检查表并进行自检自查,检查项目包括但不限于施工机具、人员资质,作业关键步骤及安全要求等内容,作业项目安全检查表要经承包商队伍派出单位主要负责人审核确认并向事业组备案。



4.5 甲方应将乙方隐患纳入统一管理, 监督乙方对隐患整改跟踪情况。

## 第五条 健康、安全和环保

5.1 甲方对乙方在甲方资产界内进行的现场安全管理负主体责任, 对乙方人员进行安全教育, 组织乙方签订现场安全管理协议, 并对乙方人员或要求乙方开展健康安全环保培训及项目健康安全环保技术交流, 两个以上承包商在同一作业区域内进行作业时, 可能危及对方生产安全的, 甲方要牵头组织签订现场安全管理协议。

5.2 甲方对本合同中本方工作范围内的健康安全环保管理工作负责, 并负责协调乙方与其他承包商之间的健康安全环保管理。

5.3 甲方做好与乙方的 HSE 管理衔接工作, 编制的 HSE 桥接文件做到界面清晰, 要求明确, 内容具体, 操作可行, 甲方要在现场对所有参与各方组织桥接文件专题培训。

5.4 甲方建立承包商安全管理包保制, 明确承包商甲方安全管理主要负责人、业务负责人及操作人员并在现场明显位置处设立公示牌, 写明包保负责人的姓名、联系方式及承包商名称、作业内容、作业区域及时间等信息, 接受员工监督。

5.5 乙方对合同约定工作范围内全部工作和相关工作人员的健康、安全、环保负责, 乙方应遵守、并确保其员工, 遵守本协议对健康、安全、环保的规定, 相关法律法规、行业标准及甲方随时发布的相关规定和指示 (包括有关对工作服、面罩、护目器具及工作鞋等安全防护要求)。

5.6 乙方应签署法律法规, 建立并维系自身良好的健康、安全、环保体系。

5.7 乙方对作业现场的安全管理负直接责任, 严格执行现场安全管理制度和操作规程, 要认真学习现场组织的安全培训和安全教育, 熟悉风险提示内容, 了解安全应急要求, 会用各类安全管理工具, 严格遵守“五想五不干”安全行为准则, 严格落实作业安全分析和作业许可证, 未履行完相关手续以及得到现场甲方同意前不得进行作业, 乙方项目负责人或副队长要加强队伍管理, 做好内部培训和教育, 及时查处“三违”行为, 强化考核, 提高安全执行力。

5.8 乙方实施施工时, 应避免任何可能危及人身健康、财产安全的操作, 采取必要的安全和健康预防措施, 不时对所有设施、设备和材料进行健康、安全、环保检查, 乙方人员对不符合要求的指令要及时与现场领队 (负责人) 进行沟通和沟通, 必要时与直属单位和单位主管部门或领导进行反映, 该拒绝的拒绝, 该停工的停工, 坚决杜绝违章作业、冒险蛮干, 乙方应提供工作所需的安设施和安全指南, 保存并提供法律法规及甲方要求的所有事故、伤亡和相关事项的记录、报告。

5.9 乙方应采取合理措施, 防止工作造成作业现场及周边发生任何人身、财产、环境损害, 该等防护措施包括但不限于:

- (1) 防火、防污染措施;
- (2) 提供标识、警示标志;
- (3) 可靠的工具和防护用品;
- (4) 为甲方或甲方其它施工单位正在实施的其它作业提供保护。

5.10 如乙方未采取前述防护措施, 甲方有权自行采取该等措施, 乙方应补偿甲方因此实际发生的费用, 甲方有权从合同总价中直接扣除该等费用。

5.11 乙方应全面负责进入作业现场的工作人员的安全, 如作业现场发生任何人身伤害, 无论是否与工作相关, 乙方应及时将受伤人员送至最近的急救中心或医院进行救助, 乙方应及时甲方汇报任何人身伤害事故, 并配合甲方对该等事故进行全面调查。

5.12 乙方在作业期间组织安全培训, 开展制度、案例学习并有明确的记录。

5.13 未经甲方同意, 乙方不得擅自分包, 严禁将项目转包、违法分包。

## 第六条 责任

- 6.1 无论时间、地点、方式和原因, 乙方、乙方代理或分包商(如有)因执行项目作业造成任何第三方财产损失、损坏、人身伤亡或疾病, 乙方应承担全部责任, 并确保甲方免于所有相关的索赔、损失、损害、费用和和责任, 包括但不限于在甲方因此需向第三方支付任何赔偿时, 乙方均应全额予以补偿。
- 6.2 无论时间、地点、方式和原因, 如执行该作业项目, 乙方及其人员、乙方代理、分包商及其人员(如有)的任何财产(包括但不限于设备、装置、器材等, 且无论该等财产属于自有、租用、租赁或以其它方式提供)发生毁损、灭失或其它损失, 除非该等损失系因甲方故意或重大过失所致, 乙方应自行承担全部损失, 并确保甲方免于所有相关的索赔、损失、损害、费用和和责任。
- 6.3 无论时间、地点、方式和原因, 如执行作业项目而发生的或与履行本合同有关的乙方、乙方代理及分包商(如有)的人员发生人身伤亡或疾病, 除非该等人身伤亡或疾病系因甲方故意或重大过失所致, 乙方应对上述人员的人身伤亡或疾病负责, 并确保甲方免于所有相关的索赔、损失、损害、费用和和责任, 包括但不限于甲方因此需要支付任何赔偿时, 乙方均应全额予以补偿。
- 6.4 无论时间、地点、方式和原因, 如执行作业项目, 乙方造成任何海洋、大气及其它环境污染, 乙方应单独承担全部责任, 包括消除污染源、赔偿污染造成的损失、承担污染产生的法律责任和污染造成的停工损失等, 并确保甲方免于所有相关的索赔、损失、损害、费用和和责任, 包括但不限于在甲方因此需要支付任何赔偿时, 乙方均应全额予以补偿。

## 第七条 事故及应急

- 7.1 乙方发生生产健康安全环保事故,应及时进行救助,并及时向甲方汇报。甲方依据公司《承包商生产安全事战考核方案》落实对乙方跟计记分机制。事故调查按甲方的事故管理程序开展,乙方积极配合甲方进行事故调查并做好后勤保障,善后处理及协助完成事故调查报告编制,并按照“四不放过”原则对相关责任人进行处理,甲方根据事故严重程度对乙方采取约谈、冻结一定期限业务资质、取消合同、拉入“黑名单”的各种措施。
- 7.2 甲方指导乙方制定应急预案,将乙方应急预案纳入本单位应急联动机制,甲方应确保双方应急资源及应急方案有效衔接,明确应急资源共享方案和应急响应流程,确保应急情况发生时,有效调动应急资源及时响应。当乙方应急能力或资源不足时,甲方应提供相应的指导与岸基支持(应急资源)。

- 7.3 甲方应监督检查乙方按制定的计划开展应急培训和应急演练。

## 第八条 其它

- 8.1 如果本协议的任何条款或规定被裁定为无效、不合法或不可强制执行,该条款或规定应视为被删除,本协议其它条款不受影响,仍继续有效。
- 8.2 本协议未尽事宜,应由双方协商确定,并签订补充协议,补充协议与本协议具有同等效力。
- 8.3 本协议一式2份,甲乙双方各持1份,具有同等效力。

甲方: 中海油田服务有限公司  
物探事业部

签字: 陈刚

时间:

乙方: 中国石油大学(北京)

签字:

时间: 2025.11.17



### 第三部分 附件：承包商的最低安全环保要求

#### 第一章 总 则

**第1.1条** 根据中海油田服务股份有限公司（以下简称“甲方”）健康安全环保理念和政策，明确提出甲方对承包商（以下简称“乙方”）的最低安全环保要求，以使甲方与乙方在履行承包合同中共同做好安全环保工作。

**第1.2条** 本要求所阐述的各条款是根据有关的法律、法规和规范，有关的健康安全环保标准、广泛认可的安全生产良好实践而确定，是甲方对乙方在健康、安全和环保方面的最基本要求。

**第1.3条** 如果本要求的任一条款与国家有关的法律、法规和规范有冲突，应认为这一条款将自动修改，其他未受影响的条款仍然适用。本要求中关于安全环保的本意应当得到善意的理解和遵守。

**第1.4条** 只要与本要求不冲突，本要求不排除乙方执行自己的健康安全环保管理体系和已经形成的良好的工作惯例。

**第1.5条** 本协议应与承包合同同时签订并具有相同的法律效力。协议期限应与项目承包合同一致。如果承包合同因故变更期限，协议也应做相同的变更。

**第1.6条** 双方应贯彻“安全第一、预防为主”的方针，查找事故隐患并采取相应措施，避免事故的发生。

**第1.7条 定义：**

**第1.7.1条 用语“有关的法律、法规和规范”**是指：由那些对承包合同的执行、对乙方的活动有行政、司法管辖权和负责安全、职业健康与环境保护的政府部门或机构，已经通过和可能随时制定、通过、颁布或实施的法律、法规、条例、命令、规章、规则和要求，以及与承包合同确定的工程服务、生产和作业有关的许可和认可制度。

**第1.7.2条 用语“有关的健康安全环保标准”**是指：有关的法律和法规规定的，以及承包合同规定和要求的，经甲方和乙方书面同意的所有有关安全、职业健康和环境保护的要求、标准、预防措施、工作程序和已被厂方接受的工业惯例。

**第1.7.3条 用语“甲方和乙方资产”**是指：甲方或乙方所拥有、提供或租用、租赁的资产，包括但不限于按照承包合同中约定的，用于乙方作业的场地、厂区、厂房、工作室、生产设施、生活设施等。

**第1.7.4条 用语“工作场所”**是指：在甲方和乙方资产界内的，生活区或办公室以外的所有区域。

**第1.7.5条 用语“乙方”**是指：向甲方提供修理、生产和作业服务的承包商及其子承包商或分包商、承包商的代理商等。

#### 第二章 健康、安全和环保理念和政策

**第1.8条** 乙方应采取与甲方健康、安全和环保理念和政策一致的方式来执行所有的工作计划。乙方应在所有作业中将有效的健康、安全和环保作为其管理的有机整体。所有乙方必须将员工的安全和健康作为最基本的考虑内容，必须通过执行可靠的技术、程序和步骤来避免对环境的不利影响。

**第1.9条** 以下是甲方健康安全环保理念：

第1.9.1条 员工是甲方最宝贵的资源和财富，以人为本、关爱生命；



第1.9.2条 一切事故都是可以避免的;

第1.9.3条 发展不能以牺牲安全保障为代价;

第1.9.4条 安全培训不到位是重大安全隐患;

第1.9.5条 不破坏环境就是对生态环境最好、最聪明、成本最低的保护。

**第1.10条**.....以下  
是甲方员工层面安全标志行为:

第1.10.1条 现场作业确认“五想五不干”;

第1.10.2条 知晓所处环境应急通道;

第1.10.3条 及时干预不安全行为;

第1.10.4条 驾车系安全带;

第1.10.5条 行人车辆不闯红灯;

第1.10.6条 上下楼梯扶好扶手。

**第1.11条**.....以下  
是甲方健康安全环保政策:

安全第一、预防为主、综合治理;

以人为本、关爱健康、珍惜生命;

保护环境、节能增效、绿色发展。

### 第三章 乙方责任

**第1.12条** 乙方应遵守有关的法律、法规 and 规定, 有关的健康安全环保标准; 理解和接受甲方健康安全环保理念、政策; 遵守甲方健康安全环保管理体系中的有关规定; 遵守甲方资产设施上的各项管理规定。

**第1.13条** 乙方应确保其所有员工熟悉并执行甲方的各项安全环保要求和规定, 熟练掌握基本健康安全环保知识和技能, 建立良好的安全环保理念。在预防事故、控制损失和保护环境方面, 采取积极的态度与甲方合作。

**第1.14条** 当甲方认为乙方的工作程序或工作环境对人身、财产或环境构成了威胁, 违反了有关的法律、法规 and 规定, 违反了甲方安全环保政策、程序或任何有关的健康安全环保标准, 甲方有权随时停止乙方的工作, 令其整改或将其有关员工从工作场所撤换掉。乙方或乙方的人员违反甲方安全环保要求的任何行为均视为对承包合同的违约, 严重违反的行为自然构成提前终止承包合同的理由和依据。

**第1.15条** 乙方不仅对完成的工作成果负责, 而且还要独立承担工作中遭受的意外风险。

**第1.16条** 乙方有责任和义务免除、保护、防护、补偿甲方, 避免甲方由于乙方或乙方的员工直接或间接未能贯彻、执行、遵循和遵守有关法律、法规 and 规定、违反甲方对乙方的最低安全环保要求的原因受到的任何损失、伤害、索赔或债务。在任何时候, 乙方的这种责任都不应被认为可以改变、修正、减少或者重新界定乙方按承包合同应尽的其他应补偿、免除、保险或担保等义务。

**第1.17条** 乙方应依据有关的法律、法规 and 规定, 确保所有人员均已通过必要的职业培训和安全环保培训, 有资格并且可证实能从事承包合同规定的相应工作。所有人员必须能出示有关的培训, 资

格证书。在开始工作之前,确保所有员工都已经熟悉和理解甲方对乙方的最低安全环保要求。

**第1.18条** 乙方应确保那些身心健康,称职的员工完成工作。员工出现下列情形之一者,不能被认为是身心健康的,称职的人员:严重睡眠不足或无力的,患传染病的,严重心脏病的,依政府机构的,酗酒,赌博和吸毒的人员。

**第1.19条** 乙方应为员工提供合适的和性能完好的工具、装备,

**第1.20条** 乙方在所有的作业过程中应首先制定好健康安全环保计划和措施并获得甲方批准。乙方应与甲方现场监督(代表)一起协调所有活动。教育所有员工将任何不安全迹象向其直接主管或者甲方现场监督(代表)报告。

**第1.21条** 乙方应确保所有按承包合同和附件提供的设施、设备、机器、器械、工具和装备等符合有关的健康安全环保标准,同时保持工作场所清洁、有序。

**第1.22条** 乙方应按有关法规要求和甲方要求设置安全管理组织机构,配备满足要求的安全管理人员,确保发挥现场监督作用。

**第1.23条** 乙方从事工种不足一年的人员占作业队伍的最高比例应不高于20%。

#### 第四章 安全投入和资金保障

**第1.24条** 甲方向乙方支付的合同款中包含了安全生产费用,用于乙方人员的工伤保险购买、安全生产检查、隐患排查、安全教育与培训及取证,安全设施及特种设备检测检验、应急救援技术装备的配置及维护保养、现场作业人员安全防护用品的配置与更新、事故逃生和紧急避险设施的配置、应急演练及其他与安全作业直接相关的事项。乙方应当按照合同款 2% (比例)或 7 (金额)用于以上事项中。

**第1.25条** 乙方应当按照相关法律法规、规章和政策文件及本协议,将安全生产费用落实到位、专款专用。甲方就乙方安全投入落实是否到位进行监督检查。

#### 第五章 全员安全生产责任制建立及落实

**第1.26条** 乙方应建立健全全员安全生产责任制,制度中应对责任制的建立、培训、公示、考核等做出要求。

**第1.27条** 乙方应定期开展全员安全生产责任制培训,对安全生产责任制进行公示,确保不同层级、不同岗位人员清楚本岗位安全生产责任内容,并贯彻落实责任制的考核。

#### 第六章 安全风险分级管控

**第1.28条** 双方有责任对项目进行风险辨识和风险评估,并将辨识和评价的结果告知对方。对于辨识出的风险,应明确制定和实施防范措施的责任方。

**第1.29条** 乙方应在全面辨识风险危害因素和风险评估的基础上,按照法规要求建立风险分级管控清单,落实分级管控措施,结合项目情况及时进行更新。发包方应对承包方风险辨识结果和控制措施进行审查和批准,并监督执行。

**第1.30条** 双方应明确风险公告警示的责任方,在醒目位置和重点区域,以安全风险告知栏、岗位安全风险告知卡等形式实施风险风险公告警示,存在重大安全风险的工作场所和岗位,设置明显警示标识。

#### 第七章 隐患排查与治理

**第1.31条** 乙方应建立健全事故隐患排查治理制度,建立台账,及时治理安全隐患并做好记录。

**第1.32条** 乙方应加强对现场作业的安全指导、支持、监督检查,对于重大高风险项目或周期超过6个月的项目,乙方主要负责人或受委托人应在作业期间要到现场进行安全检查,其他检查按照计划进行,及时发现隐患并进行消除。

**第1.33条** 乙方应编制作业项目的安全检查表,明确检查内容,甲方利用安全检查表对承包商作业进行监督检查,检查发现问题要求承包商要及时按照制度或合同约定进行整改。

**第1.34条** 在项目实施的各阶段,甲方有权检查乙方的人员、设备和场地,对检查所发现的问题,乙方应组织整改,发现乙方严重违法规定或存在严重HSE隐患时,甲方有权要求乙方停工整改,逾期整改不合格的,可解除合同。

**第1.35条** 乙方对自检自查、甲方和外部检查、检验检测等发现的隐患建立统一台账,形成清单,定期对隐患排查治理情况进行统计分析,并向甲方报告。

**第1.36条** 乙方在发现重大事故隐患后单方面不能立即治理的,应当采取必要的防范措施,并及时书面报告甲方协商解决,及时消除事故隐患。

**第1.37条** 甲方根据对乙方安全检查发现问题频次、性质和程度,明确乙方所应承担的违约责任,对乙方采取计收违约金、扣减合同价款、责令更换作业人员、暂停乙方作业、终止合同或其他处罚措施。

## 第八章 个人防护装备

**第1.38条** 应明确对从事特定工作的人员提供所需的全部个人防护装备,对所有到工作场所的人员提供必要的个人防护装备的责任人。

**第1.39条** 根据有关的法律、法规和规定、有关的健康安全环保标准,乙方应确保其员工严格遵守个人防护装备穿戴制度和规定,在甲方和乙方资产界内活动都应穿戴好适应工作场所环境的个人防护装备。

**第1.40条** 员工在进入有可能会发生高空坠落物打击危险和可能发生碰撞伤害或其他认定需要戴安全帽以防止伤害的场所、在低于头部的设备上工作,必须穿戴好符合相应安全环保标准的非金属的硬质安全帽。

**第1.41条** 进入所有指定的工作场所,必须穿好符合相应安全环保标准的防滑、防砸的安全鞋或安全靴。  
**第1.42条** 在从事有可能会发生眼睛或面部伤害危险的作业(包括但不限于磨床、铣床、刨工、焊接、抛光、破碎、喷沙及喷涂作业、化学处理作业)时,必须佩戴好符合相应安全环保标准的指定的护目镜或面部保护装置,通常情况下,不允许佩戴隐形眼镜,除非经甲方特别许可。

**第1.43条** 在进入高噪声区之前,必须佩戴好符合规则要求和工业标准的听力保护装置。噪声级别超过85db(A)的区域一般被认定为高噪声区。

**第1.44条** 在工作时,每个人都应将工作服穿戴整齐,包括护肩、长裤和指定穿戴的特殊服装(如隔热服)、个人防护服装应该适合工作条件和气候。在佩戴戒指、项链、头饰、耳坠,或其他宽松的珠宝首饰和手表等有可能对员工造成危害或者对设备有潜在破坏的工作场所,不允许佩戴上述珠宝首饰和手表等。



**第1.45条** 在高温区域,有锋利边角,有化学品,或者有其他可能对手部产生伤害的材料的地方,都应穿戴符合相应安全环保标准的防护手套。在有潜在危险的机械或设备上工作,则不应穿戴手套。

**第1.46条** 应为员工配备足够数量的救生衣或救生背心。凡在船与船之间进行搬运工作,在装卸上工作,在船的后甲板上工作,或从事其他有潜在落水危险的工作之前,必须穿戴好救生衣/救生背心。救生衣或救生背心的数量和型号应符合国家主管部门、机构的规定。

**第1.47条** 员工在标准栏杆不能起到有效保护并存在坠落危险的地方,或其他有可能从2米或2米以上高处掉下的地方作业时,必须穿戴好满足有关安全标准的安全带、保险带或救生索、安全带、保险带或救生索应系在固定的、非活动的构件上,并确认已起到安全保护作用。

**第1.48条** 在进入公认的或怀疑含有危害健康的气体、蒸气、粉尘、灰尘、烟雾或其他物质的空间、空气中氧气浓度过低(氧气浓度低于18%),以及有关法律、法规和规定,有关的健康安全环保标准规定的应配备空气呼吸器的场所之前,必须佩戴空气呼吸器。在某些必要的工作场所,乙方应根据有关法律、法规和规定,有关的健康安全环保标准制定并采取相应的有害气体、氧气浓度监测、控制和防护措施。乙方应培训员工熟练掌握呼吸保护装置的使用和维护。

## 第九章 安全工作惯例

**第1.49条** 甲方的现场监督应有权对乙方的工作计划、设施和设备状况、作业情况进行有关安全环保方面的监督检查。乙方有责任向甲方指定的现场监督报告作业和活动的情况、设施和设备安全环保检查情况,事故隐患及采取的相应措施情况,甲方指定的现场监督有权进行移实,当乙方或乙方的员工的作业程序、方法、步骤、措施、作业环境违反了有关法律、法规和规定或甲方最低安全环保要求,对人身、财产和环境构成了威胁,甲方指定的现场监督有权要求乙方立即中止作业,进行整改。

**第1.50条** 乙方应定期召开所有员工参加的现场安全会议,每次会议都应做会议记录并保存在工作现场,甲方现场监督(代表)有权参加每次的安全会议。

**第1.51条** 在甲方和乙方资产界内,应指定严禁吸烟区域。

**第1.52条** 乙方应接受有关法律、法规和规定,有关的健康安全环保标准以及甲方的有关要求全面系统地建立并维护符合工业惯例的标志体系。要使所有员工熟悉和理解各种标志的内容与含义,所有人员都应遵守在甲方和乙方资产界内的各种标志要求。

**第1.53条** 乙方应发给所有员工每人一本适用于甲方和乙方资产界内的安全环保手册。该安全环保手册的内容应包括但不限于一般安全环保管理、危险区管理、作业管理、火、易燃易爆物管理等。

**第1.54条** 应明确隔离锁定制度以保护员工在动力装置、压缩系统和有限空间等的安全作业。隔离锁定最基本的目的是杜绝不知情员工误进入危险区、操作或误操作,如打开或关闭开关、接通或断开电路、搬动或移动设备等,以免机器和设备因此意外启动或动作而伤害正在作业人员或造成更大意外事故。应特别强调的原则是,隔离标志、禁止操作标志、锁定装置只能由挂牌或上锁人员去除,在摘牌、摘锁前必须预先查验确保安全。

## 第十章 出入管理

**第1.55条** 乙方应事先将要进入甲方和乙方资产界内的人员基本情况书面通知甲方现场监督(代表),包括临时和长期滞留人员。所有人员在进入甲方和乙方资产界内后应先向有关管理人员报到。

**第1.56条** 员工进入甲方和乙方资产界内后,只能在指定区域内活动,行为举止应符合,并禁止到许可范围之外活动。



## 第十一章 交通运输

**第1.57条** 乙方应确保乘客、船人员已掌握安全乘坐知识。

**第1.58条** 包除品应贴附特别标志并办理相关许可手续。

**第1.59条** 所有行驶在甲方场所内的机动车辆应遵守安全标志和限速行驶的规定。如没有限速规定，也应根据道路实际情况，采取一个合理、安全的行车速度。

## 第十二章 工作许可证制度

**第1.60条** 应明确工作许可证制度。如果某项作业或活动是在有可能导致对人员安全和健康、设施和设备产生危害的地方或其周围进行时，则应对此项作业或活动实行工作许可证制度。凡属于工作许可证制度管理的各项作业和活动，在未取得有效的许可证之前，任何人都不能开始这项作业或活动。

**第1.61条** 乙方应建立相应的工作许可证制度，并对实行工作许可证制度的作业和活动做出明确规定，并经甲方现场监督（代表）认可。

**第1.62条** 工作许可证必须有明确的工作地点范围和工作时间范围。如原领取工作许可证的人员不能当班或作业条件、环境已经明显改变，则最初的工作许可证应自动失效，应根据变化重新签发新的工作许可证。

**第1.63条** 所有人员必须按照工作许可证的作业程序和要求进行作业或活动，不允许有任何违反。

**第1.64条** 只要认为合适，许可证签发人可以在事先不通知的情况下，在任何时候取消已经签发的工作许可证。工作许可证取消后，执行该许可证的所有员工应立即停止有关作业，除非这种停止会增加新的危险。在这种情况下，乙方在继续进行有关作业的同时，应采取必要的预防措施来保证员工的的安全和财产不受损失，并立即向甲方现场监督（代表），乙方代表报告。

**第1.65条** 电工作业实行工作许可证制度

**第1.65.1款** 仅允许持有电工作业资格证书的人员从事电工作业，所有的电工作业开始之前须获得电工作业许可证。

**第1.65.2款** 应避免带电作业。作业前应将有关的电路开关、闸和其他电路控制设备断开并挂牌或上锁禁止闭合，必要时，应安排人员看守。

**第1.66条** 爆破作业实行工作许可证制度。

## 第十三章 设备操作员资格

**第1.67条** 设备操作员应依据有关法规和标准得到培训并取得资格。乙方应该提供书面的培训证明，包括姓名、技术状况及限制条件。

**第1.68条** 乙方应按有关的法律、法规和规范、有关的健康安全环保标准和安全管理规定建立和履行各岗位的操作规程。

**第1.69条** 乙方应确保其员工熟悉工作场所、各种设施设备操作规程、在紧急情况下撤离的程序和要采取的行动。

**第1.70条** 在甲方资产设施上，未经甲方书面授权，乙方不能操作任何设备也不能关闭或打开任何阀门、开关和电路，承包合同另有规定除外。

**第1.71条** 乙方用于本项目的设备均应按类别取得出厂合格证或检验合格证书，均应在各方面满足所有有关的健康安全环保标准。

#### 第十四章 焊接和切割

**第1.72条** 乙方应确保所有执行焊接和切割作业的员工都掌握了焊接和切割作业的安全规程以及具体要求。乙方应建立焊接和切割设备预防性维护保养计划,确保设备始终完好,依据有关的法律、法规和规定要求,所有焊工都必须持有资格证书。

**第1.73条** 乙方应根据需要在工作场所设立专门的焊接和切割区,所有的焊接和切割作业应尽可能在专门的焊接和切割区进行。

#### 第十五章 防火与防爆

**第1.74条** 乙方应采取一切必要措施预防火灾、爆炸的发生,并负责对其员工进行含防火、防爆、防毒等方面的培训。

**第1.75条** 船进厂修船期间乙方及任何在本船施工单位防火、防爆、防污染管理工作,设专职安全监督人员负责相关工作区域防火、防爆、防污染监督工作。施工人员无条件严格遵守船上的安全管理制度。

**第1.76条** 明火、热工作业前乙方负责到海事局办理明火作业许可证。在作业前,必须向甲方提交经有权审批机关或部门批准的有効动火作业审批报告和经授权的防火技术部门对重点部位(密闭舱室、油柜、油柜、放置贵重物品精密仪器设备的场所等)的测爆检验合格证,指派专人负责火场监护,并与甲方协商一致,书面批准后方可动火作业。

**第1.77条** 在修船施工前,乙方应根据工程实际情况自备足够、有效的消防、防污器材和到位的消防用水设施,经常检查并保证完好。在甲方无消防、防污能力条件下,乙方负责采取可靠措施,确保安全。

**第1.78条** 船上配备的在航消防、防污器材和应急设施未经甲方许可不得擅自动用,未经甲方许可动用或发生船上配备的在航消防、防污器材和应急设施损坏、丢失,除由乙方负责配齐外,对当事人处以50-200元的罚款。

**第1.79条** 从事修船施工的乙方应向甲方提交上船施工人员名单和特殊工种作业人员名单及有效的特殊工种证书、消防培训的证书,必需持证上岗作业。每次动火、热工作业前,施工单位要以书面形式通知甲方经同意并在乙方检查落实各项防火措施后,方可作业。

**第1.80条** 船进厂后,乙方安全主管部门应向甲方详细介绍火警电话和消防值班员的场所,向甲方提交“防火、防爆、防污染的具体办法及措施”“扑救初期火灾的方案”“发生污染的补救措施”。喷漆、油漆作业前,应向政府主管部门申请,并禁止同时或交叉作业,安全监督人员负责组织监督挂好警戒线和警示牌、备齐应急器材。

**第1.81条** 施工作业人员必须在船上指定地点吸烟。在禁烟区吸烟者处以500-2000元的罚款。

**第1.82条** 遇火警时,乙方组织扑救,需用封舱灭火时,必须经厂、船双方领导批准。

**第1.83条** 除非承包合同另有规定,在属于乙方资产范围内的设施设备上,乙方应提供、安装或配备满足有关的法律、法规和规定,满足有关的健康安全环保标准的消防设备。

**第1.84条** 乙方应建立并保持与 workplace 相适应的防火、防爆、防止意外伤害管理制度。

**第1.85条** 易燃液体,包括但不限于汽油、柴油、燃油、液化石油气等应装在工业上认可的专用的金属容器中运输、存储。易燃液体的使用、运输、存储应符合有关的法律、法规和规定,符合有关的健康安全环保标准。易燃液体存储应远离可能的热源、火种和有爆炸危险的场所。

**第1.86条** 在开始涉及任何爆炸物作业之前,乙方应向甲方提交有关人员安全、仓库安全、搬运和使用

爆炸物的书面作业程序。乙方应该确保所有的乙方、代理商及其员工都取得了储存、搬运和使用爆炸物这种特殊工种资格。乙方应该确保在存储、处理和使用爆炸物时遵守提交的书面作业程序。所有有关爆炸物储存、搬运和使用的法律、法规和安全生产标准规定。

**第1.87条** 在给内燃机注油之前，乙方应停掉内燃机。除非在油口处内燃机足够的远，满足安全注油条件。

**第1.88条** 由于乙方作业造成任何事故，由乙方负责。

#### 第十六章 污染防治

**第1.89条** 乙方应根据有关的法律、法规 and 规定，有关的健康安全环保标准最大程度地减少对陆地和海洋生态环境的破坏和损害。乙方有义务尽其最大努力防止大气、海洋、河流、湖泊、港湾和陆地遭受污染和损害。乙方应尽全部合理努力消除一切可能发生的污染并最大限度地减少污染带来的破坏。

**第1.90条** 乙方应确保每一员工都知道：自己有义务按照甲方的政策和有关的法律、法规要求，防止污染。

#### 第十七章 应急

**第1.91条** 乙方应负责向其工作人员提供求生、急救、消防的应急培训，并随时能出示有关培训证书或证明。

**第1.92条** 乙方应根据工作场所特点建立并保持相应的应急计划和程序。

**第1.93条** 除非承包合同另有规定，在乙方的资产范围内，乙方应保证有一套办法，在发生紧急情况时能够将有信息传达给所有作业人员。

**第1.94条** 乙方应负责提供井培训医疗救生人员、消防队员。

**第1.95条** 工作场所内外的交通要道任何时候都要保持通畅。

#### 第十八章 医疗急救

**第1.96条** 乙方负责安排和提供所有应急医疗救护、急救设施及其后的医疗救治工作，并承担其员工的医疗保险、医疗保健、医护处理、运送等以及与其相关事项所发生的全部费用。

#### 第十九章 事故、人身伤害和风险事件报告

**第1.97条** 乙方应遵守甲方的事故、人身伤害和风险事件报告程序，乙方自己建立的事故、人身伤害和风险事件报告程序，须与甲方的相一致并经甲方认可。

**第1.98条** 事故、人身伤害和风险事件包括但不限于：火灾、爆炸（不论规模，损失程度大小）；职业伤害、人员失踪、食物中毒或严重的流行性传染病；交通事故；环境污染事故；引起媒体、公众、社会强烈关注的其它事件。

**第1.99条** 对于任何事故、人身伤害和风险事件，乙方必须在其发生后24小时内以书面形式通报给甲方现场监督（代表）。报告应包括在当时情况下所能得到的一切信息。只要有可能，在事故、人身伤害和风险事件发生后，最多不超过10天，乙方应提供一份更详细的综合报告，其内容包括受伤人员、财产损失程度，意外事故及风险事件的过程，采取的预防措施。

**第1.100条** 发生下面所列的严重事故、人身伤害和风险事件，乙方应立即口头报告甲方现场监督（代表），并且在24小时内以书面形式描述事故状况。

**第1.100.1款** 所有火灾、爆炸，不论其规模，损失程度大小；



**第1.100.2款**

所有导致乙方的员工残疾或多人住院治疗（住院观察除外）的事件；

**第1.100.3款**

所有导致乙方的员工肢体分离、截肢、残废和预计员工能力丧失超过 72 小时的职业伤害。

**第1.100.4款** 财产损失价值超过十万元人民币的事故。

**第1.101条** 甲方会对事故、人身伤害和风险事件进行调查，乙方和乙方的员工应采取积极合作的态度配合甲方的调查并让甲方了解事故、人身伤害和风险事件的真实情况。

**第二十章 HSE 绩效考核**

（备注：本部分内容应根据具体项目情况、主合同内容等进行约定，确保合法有效。）

**第1.102条** 按照“谁作业、谁负责”“管生产、管安全”原则，搞好安全生产作业是各岗位和各承包商的本职工作。项目完工时由甲方按照《承包商HSE绩效评价表》（见附件1）对乙方所承作业服务的HSE执行情况进行HSE绩效考核评价。

- (1) 对于考核结果为90分及以上的，甲方确认同意后不扣除合同总金额。
- (2) 对于考核结果为75至89分的，甲方有权扣合同总金额的1%。
- (3) 对于考核结果为60至74分的，甲方有权扣合同总金额的2.5%。
- (4) 对于考核结果为低于60分的，甲方有权扣合同总金额的5%。
- (5) 对于发生一票否决项的，暂停市场6-12个月的处理，或给予解除合同。

**第1.103条** 乙方应对自身原因（即乙方负事故或事件的全部/主要责任）引起的事件或事故负责，除支付相关的赔偿外，应接受如下处罚：

- (1) 发生一般事故B级的，扣考核期内实际发生合同总金额的20%。
- (2) 发生一般事故A级及以上的，暂停市场6-12个月的处理，或给予解除合同。
- (3) 因抢救伤员、清理污染、消除损失、赔偿损失、调查处理等发生的直接费用，由责任方承担。

**第1.104条** 因承包商HSE违约而扣除工程进度款，不能减轻或解除承包商在合同中承担的任何责任和义务，也不能是导致承包商降低安全生产投入的借口。

**第1.105条** 因承包商原因造成发包方受到国家或地方执法部门处罚的，按照合同约定对承包商进行处罚，承包商还需负责赔付全部罚款。

**第二十一章 相互沟通**

**第1.106条** 甲方致力于为员工提供一个安全健康的工作环境，并且认为：为了实现这一目标，加强乙方管理层与甲方管理层之间的沟通是十分必要的。

**第1.107条** 双方在对乙方的作业涉及安全环保的内容上发生争议或谈判时，建议以如下步骤解决：

**第1.108条** 甲方现场监督如果对乙方的工作不满意，应通过正常的管理渠道反映，由双方上一层管理者一起跟踪处理该事项。甲方人员不能向乙方施加不应有的压力，迫使乙方做其根据专业技术判断不能做的任何事情。

**第1.109条** 如果乙方感到有直接或间接的压力迫使其他根据其专业技术判断不能做的事情时，乙方有权拒绝去做，并及时向乙方上一层管理者报告，由双方上一层管理者共同商议处理该事项。

**第1.110条** 为保障实现本章的真实目的，双方应事先书面明确争议协调的步骤，上一层管理者、联络渠道和方式。

**附件 1 承包商 HSE 绩效评价表**

**承包商 HSE 绩效评价表**

项目名称:

承包商公司名称:

项目名称:

承包商现场负责人:



| HSE 绩效评分表                                          |                                                               |    |    |
|----------------------------------------------------|---------------------------------------------------------------|----|----|
| 评分项目                                               | 评分标准                                                          | 得分 | 说明 |
| 一、应急管理 (10分)                                       | 1. 发生一般事故A级及以上安全事故任事故的                                        |    |    |
|                                                    | 2. 发生一般及以上等级事故瞒报、迟报的                                          |    |    |
|                                                    | 3. 未按通知及时有灾规定的                                                |    |    |
|                                                    | 4. 预案不符合流程的                                                   |    |    |
| 承包商安全管理 (10分)                                      | 发现一项人员证书过期, 人员未持证上岗, 1人次扣5分                                   |    |    |
|                                                    | 缺少入场教育记录, 缺少培训效果评价, 1人次扣5分                                    |    |    |
|                                                    | 未经甲方同意更换关键决策人员, 1人次扣5分                                        |    |    |
|                                                    | 全员安全生产责任制未覆盖全员, 未进行风险提示, 1人次扣5分                               |    |    |
| HSE 管理计划, 安全措施落实 (10分)                             | 未制定HSE计划或作业方案, 扣10分。                                          |    |    |
|                                                    | 未严格执行HSE计划或作业方案, 扣2分/次;                                       |    |    |
|                                                    | 作业前未开展作业安全分析 (JSA), 扣1分/次;                                    |    |    |
|                                                    | 特殊作业未执行工作许可制度, 扣10分                                           |    |    |
| 现场作业有关人员参加施工前安全、技术交底会, 严格按照交流会的部署进行施工 (10分)        | 违反本规定1人次的, 扣2分                                                |    |    |
|                                                    | 违反本规定2人次的, 扣5分                                                |    |    |
|                                                    | 违反本规定3人次及以上的, 扣10分                                            |    |    |
|                                                    | 违反本规定1人次的, 扣2分;                                               |    |    |
| 现场作业人员应严格遵守甲方和现场单位安全生产规章制度、施工技术方案、操作规程、应急预案等 (10分) | 违反本规定2人次的, 扣5分;                                               |    |    |
|                                                    | 违反本规定3人次及以上的, 扣10分                                            |    |    |
|                                                    | 检查发现承包商1人次的劳保用品不符合本规定的, 扣2分                                   |    |    |
|                                                    | 检查发现承包商2人次的劳保用品不符合本规定的, 扣5分                                   |    |    |
| 承包商必须正确穿戴符合国家标准和行业标准的劳动防护用品 (10分)                  | 检查发现承包商3人次及以上的劳保用品不符合本规定的, 扣10分                               |    |    |
|                                                    | 10分, 现场检查发现所有人员未能按照要求使用工具和设备, 保持良好安全作业方式                      |    |    |
|                                                    | 8分, 现场检查发现个别人员未能按照要求使用工具和设备, 保持良好安全作业方式                       |    |    |
|                                                    | 5分, 现场检查发现少数人员未能按照要求使用工具和设备, 保持良好安全作业方式                       |    |    |
| 承包商正确使用工具和设备, 良好安全的作业方式 (10分)                      | 0分, 现场检查发现多次人员未能按照要求使用工具和设备, 保持良好安全作业方式的                      |    |    |
|                                                    | 扣5分, 扣完为止。                                                    |    |    |
|                                                    | 未签订现场安全生产管理协议或违反现场安全管理协议, 扣10分                                |    |    |
|                                                    | 未按照制度开展隐患排查并建立隐患台账, 扣5分                                       |    |    |
| 施工作业监督考核 (10分)                                     | 发现隐患未整改、未开展风险分析并制定临时管控措施, 1次2分,                               |    |    |
|                                                    | 项目风险分析因不全、控制措施与风险不匹配, 抽查施工现场安全分析中提及的风险控制措施没有落实的, 扣1分/次, 扣完为止。 |    |    |
|                                                    | 承包商未做到“工完、料净、场地清”的要求, 扣2分                                     |    |    |
|                                                    | 承包商未做到“工完、料净、场地清”的要求, 扣5分                                     |    |    |

|                    |  |                  |  |
|--------------------|--|------------------|--|
| 合同编号: 202519407004 |  | 合同名称: 数据跨境传输服务合同 |  |
| 甲方: 北京科技有限公司       |  | 乙方: 上海数据服务有限公司   |  |
| 签订日期: 2025年        |  | 生效日期: 2025年      |  |

附件 6:

数据处理及出境安全条款

1. 乙方需遵守《中华人民共和国数据安全法》《中华人民共和国个人信息保护法》等有关法律法规，监管要求并仅可为履行本合同约定之目的处理数据，未经甲方事先书面同意，乙方不得超出本合同约定的范围使用、提供、共享或跨境传输本合同项下相关数据至境外第三方国家/地区。前述情形下，如果乙方为非中国境内法人、其他组织或自然人，乙方须采取不低于中国法律法規要求的存储及传输加密、身份认证、访问控制、审计日志等技术与管理措施保障数据安全。

2. 乙方承诺并确认，其所有跨境数据传输行为必须符合中国及相关法律法规对个人信息保护、数据安全相关法律法规及监管要求；数据出境前，乙方向甲方提供必要的数据使用方式、存储、用途等相关的书面说明及注意事项，确保按照合法、正当、最小必要及诚信原则使用和存储数据；未经甲方事先书面同意，乙方不得将甲方数据传输出境，且前述数据的采集、传输、存储、使用均应在中国境内处理；经甲方事先书面同意，乙方向中国境外国家/地区传输、共享数据的，应当按照所适用的法律法规以及甲乙双方之间的合同约定履行数据跨境转移的相关合规义务。如前述情形下的数据跨境传输行为按照中国法律法规、监管要求需履行相关监管机构或主管部门申报、评估等程序，则乙方应承诺并确保，在其向中国境外国家/地区传输、共享本合同约定的相关数据前，应履行前述相关法律法规、监管规定的申报、评估等程序；未经履行前述相应程序，乙方不得将甲方数据出境，列于在中国境内存储的甲方数据，境外任何组织或个人不得擅自查询、调取、下载、导出。

3. 若中国境外司法或执法机构及其他相关方根据境外法律或合同约定要求乙方提供中国境内数据，乙方须立即通知甲方，且未经中国主管机关批准及甲方书面同意，乙方不得向中国境外司法或执法机构及其他相关方提供，乙方如需将数据或数据处理活动分包至乙方的合作服务商，则应事先取得甲方的书面同意，且前述情形下，乙方应确保该等服务商应与乙方承担并履行本合同项下的数据安全保护义务。乙方对其服务商处理数据的行为承担责任，并应保证其服务商积极配合甲方和或乙方进行的相关监督抽查工作。乙方及其服务商应接受中国监管机构对数据出境活动的监督检查，并按中国监管机构或甲方要求提供数据安全保护情况书面报告。对于甲方或中国监管机构检查发现乙方及其服务商存在违反法律法规、监管要求或老双方约定进行数据出境活动的，甲方有权要求乙方（如存在服务商，则乙方应再向其服务商提出要求）在一定期限内整改。如果乙方未按甲方要求整改或整改未达到甲方、中国监管机构的相关要求的，甲方有权单方解除本合同，且不承担赔偿责任；由此给甲方造成损失的，乙方应当全额赔偿。

4. 当本合同终止或解除之日起30日内（含本数），乙方应停止处理甲方提供或分享的所有数据并在甲方监督下销毁所有数据（另有约定除外）。如因本合同存在乙方的合作服务商，乙方需保证其合作服务商亦在上述期限内停止处理所有数据并在甲方和乙方的双方共同监督下销毁数据（另有约定除外）；乙方承诺履行数据安全保障义务的，甲方有权立即单方解除合同并迫使甲方遭受的全部损失。

# OBN 地震数据高效全波形反演速度建模技术

## 研究开发合同

(合同编号: CCL2022RCPG0433RCN)

任务委托方 (甲方): 中海石油 (中国) 有限公司北京研究中心

任务受托方 (乙方): 中国石油大学(北京)



签订地点: 北京

签订时间: 2022年9月26日

孙文涛  
d-ndh

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## 第一部分 合同书

甲方：中海石油（中国）有限公司北京研究中心

法定代表人（如有）：米立军

注册地址/住址：北京市朝阳区太阳宫南街6号院1号楼8-14层

乙方：中国石油大学（北京）

法定代表人（如有）：吴小林

注册地址/住址：北京市昌平区府学路18号

鉴于，甲方是一家根据中华人民共和国法律合法设立并存续的企业，希望获得符合本合同和相关法律法规要求的 OBN 地震数据高效全波形反演速度建模技术开发成果；

鉴于，乙方是一家根据 中华人民共和国 法律合法设立并存续的企业，具备提供符合本合同要求的 OBN 地震数据高效全波形反演速度建模技术开发成果的全部资质、资格和条件；

鉴于，乙方在提供研究开发成果、质量保证、研究开发人员等方面具有较强的专业能力和良好信誉，愿意根据本合同的规定向甲方提供 OBN 地震数据高效全波形反演速度建模技术开发成果。

根据《中华人民共和国民法典》及相关法律法规，在遵循平等、自愿、公平和诚实信用原则的基础上，经协商一致，双方订立本合同如下：

### 第一条 研究开发任务

- 1.1 乙方应根据本合同规定完成甲方委托的 OBN 地震数据高效全波形反演速度建模技术开发任务，完成合同规定的工作。
- 1.2 甲方对本合同约定的委托开发任务实行“赛马”规则，乙方除了应按照验收指标完成相关工作内容外，鼓励乙方通过攻关实现或超过合同约定的悬赏指标。
- 1.3 工作的内容、范围、地点等详见本合同附件一。
- 1.4 工作的标准和要求详见本合同附件一。

- 1.5 乙方提供的研究开发成果将用于海底节点高精度成像技术研发及推广应用研究项目/工程。
- 1.6 乙方应在合同签订之日起三个月内在其注册地科技主管部门完成技术开发合同认定工作。

## 第二条 合同价格

- 2.1 本合同项下价格分为两个部分，即确定部分和变动部分，均为含税（包括增值税）价格。确定部分为全部工作验收考核合格应付金额，不含增值税合同金额为 CNY1,310,679.61，增值税税率为 3%，含税合同金额为 CNY 1,350,000.00（大写：人民币壹佰叁拾伍万元）；变动部分为悬赏金额，具体额度经委托方对承揽方工作成果进行考核评估后确定，不含增值税悬赏金额不超过 CNY 194,174.76，增值税税率为 3%，含税悬赏金额不超过 CNY 200,000.00（大写：人民币贰拾万元整）。如果增值税税率发生变化，或因享受优惠政策导致增值税免税，合同金额自动调整，以保证不含税合同金额不变。
- 2.2 本协议中的“相应阶段合同价款确定部分”指的是框架协议项下第一阶段的含税总金额（不含悬赏金额）或之后签署的订单相对应阶段的价款的含税总金额（不含悬赏金额）。
- 2.3 合同价款的各分项价格、单价、费率、组成：**【详见本合同附件二】**。
- 2.4 合同价款的付款详见本合同第二部分专用合同条款第一条。

## 第三条 合同的构成和效力

- 3.1 本合同由以下部分组成：
- (1) 第一部分：合同书
  - (2) 第二部分：专用合同条款
  - (3) 第三部分：通用合同条款
  - (4) 第四部分：附件

附件一：技术委托要求

附件二：价格表

附件三：乙方关键人员

附件四：保密承诺

- 3.2 合同书、专用合同条款、通用合同条款和各附件均构成本合同不可分割的组成部分，各部分之间的内容相互补充、说明，以便对合同予以完整理解。如合同各组成部分之间存在冲突或不一致，以上述序列作为优先顺序进行解释。
- 3.3 本合同构成双方就合同标的达成的全部理解和一致，本合同签署以前双方就合同标的达成的所有口头和/或书面的理解、声明、文件、信件及双方其他形式的通信在本合同生效后自动失效。

#### 第四条 联系方式

- 4.1 除非本合同另有明确规定或双方另行书面同意，任何一方根据本合同向另一方交付资料和发送通知的联系方式如下：

(1) 甲方技术负责人：\_\_\_\_ 孙文博 \_\_\_\_

联系电话：\_\_\_\_ 010-84523755 \_\_\_\_

电子邮箱：\_\_\_\_ sunwb3@cnooc.com.cn \_\_\_\_

地址：\_\_\_\_ 北京市朝阳区太阳宫南街6号院中国海油大厦A1005 \_\_\_\_

甲方商务联系人：\_\_\_\_ 贾怡亭 \_\_\_\_

联系电话：\_\_\_\_ 010-84525473 \_\_\_\_

电子邮箱：\_\_\_\_ jiayt@cnooc.com.cn \_\_\_\_

地址：\_\_\_\_ 北京市朝阳区太阳宫南街6号院中国海油大厦 B1208 \_\_\_\_

(2) 乙方联系人：\_\_\_\_ 姚刚 \_\_\_\_

联系电话：\_\_\_\_ 18201008231 \_\_\_\_

电子邮箱：\_\_\_\_ yaogang@cup.edu.cn \_\_\_\_

地址：\_\_\_\_ 北京市昌平区府学路18号 \_\_\_\_

#### 第五条 合同份数

- 5.1 本合同正本一式玖份，甲方执叁份，乙方执陆份，具有同等效力。



## 第六条 合同生效

6.1 本合同在以下条件全部获得满足之后，自 2022 年 9 月 26 日生效：

- ☒ 双方法定代表人或授权代表签字并盖章；
- ☐ 乙方已根据合同规定提交履约保函；及
- ☐ 其他\_\_\_\_\_。

6.2 本合同至双方在本合同项下的全部义务履行完毕后失效。



(本页无正文，为签章页)

甲方（盖章）

中海石油（中国）有限公司北京研究中心



心

法定代表人或授权代表签字：



日期：

2022/11/11

日期：

2022/11/11

法定代表人或授权代表签字：

王少峰

## 第二部分 专用合同条款

### 第一条 付款

1.1 付款方式: ☐现金; ☒银行电汇; ☐汇票; ☐本票; ☐支票; ☐其他\_\_\_\_\_

1.2 支付货币

本协议下的所有应付款项均应以人民币支付。

1.3 履约保函 (不适用)

本合同 (☐签署; ☐生效) 后【●】日内, 乙方应向甲方提交金额为合同总价【●%】, 即【币种符号】\_\_\_\_\_ (大写:【币种】\_\_\_\_\_)、由甲方认可的商业银行出具的、见索即付、不可撤销的履约保函, 履约保函格式【见本合同附件八】。履约保函应自出具之日起生效, 有效期至【甲方签署工作成果验收证明】后第【三十一 (31)】日。

1.4 履约保函的开立方式 (不适用):

☐ 信开方式

甲方接受保函的地址和联系人为: \_\_\_\_\_

☐ 电开方式

甲方的保函通知银行为: \_\_\_\_\_

1.5 付款进度

(1) 验收考核合格应付金额部分

支付☒合同价款 (适用于总价合同模式) ☐相应阶段合同价款确定部分 (适用于框架协议+订单模式)

第一阶段:

|       |                                                    |                |
|-------|----------------------------------------------------|----------------|
| 第一次支付 | 付款条件: 合同签订生效, 第一阶段中期验收且完成工作量达到 60%, 支付合同第一阶段总额 60% |                |
|       | 金额: 人民币 叁拾万元整                                      | ¥ 300, 000. 00 |
| 第二次支付 | 付款条件: 阶段考核合格且完成工作量达到 100%, 支付合同第一阶段总额 40%          |                |

|  |              |              |
|--|--------------|--------------|
|  | 金额：人民币 贰拾万元整 | ¥ 200,000.00 |
|--|--------------|--------------|

#### 第二阶段：

|           |                                          |              |
|-----------|------------------------------------------|--------------|
| 第一次<br>支付 | 付款条件：第二阶段中期验收且完成工作量达到 65%，支付合同第二阶段总额 65% |              |
|           | 金额：人民币 伍拾伍万贰仟伍佰元整                        | ¥ 552,500.00 |
| 第二次<br>支付 | 付款条件：阶段考核合格且完成工作量达到 100%，支付合同第二阶段总额 35%  |              |
|           | 金额：人民币 贰拾玖万柒仟伍佰元整                        | ¥ 297,500.00 |

#### (2) 悬赏金额部分

根据甲方考评结果及悬赏指标，进行一次性支付。

具备付款条件且甲方收到发票和付款支持文件，经核对无误后 45 日内将应付款项支付给乙方。

对于乙方发生第 11.6 条约定的情形，需要提交经甲方确认的阶段开发成果确认单及相关支持材料，根据完工比例支付相应部分的费用。

#### 1.6 发票要求

(1) 乙方应根据本合同规定的付款条件和进度，按照各期付款数额以及甲方的要求向甲方开具符合国家法律法规的发票和标准的增值税扣税凭证（包括但不限于增值税专用发票）并提供付款相关支持文件（以下简称“付款文件”）。如乙方未按照本条的要求提供付款文件或发票，甲方有权拒付相关合同价款。如果甲方对乙方提供的发票和付款文件无异议，应于收到发票和付款文件之日起四十五（45）日内向乙方付款。如付款到期日非为银行工作日，则付款到期日顺延至下一个银行工作日。如甲方对乙方提供的发票金额或付款文件有异议，应于收到发票或付款文件后十五（15）日内通知乙方。乙方应就无争议部分金额重新提供发票和付款文件，甲方应于收到乙方重新提供的发票和付款文件后四十五（45）日内向乙方付款；对于乙方提供付款文件的有争议部分金额，待双方就付款金额协商并达成一致后，乙方应向甲方重新提供无异议的发票和符合要求的付款文件，甲方应于收到乙方重新提供的发票和付款文件后四十五（45）日内向乙方付款。重新开具发票所产生的税费由乙方承担。甲方有权根据本条的约定延迟支付，无需承担任何责任，且乙方的各项合同义务仍应按合同约定履行。



发票抬头“中海石油（中国）有限公司北京研究中心”。

发票应注明合同号和结算内容（合同名称/合同号/付款期数）。若本合同包含两个或以上不同项目的，乙方应就每个项目分别向甲方开具发票。

（2）乙方开具增值税发票所需甲方银行账户及税务信息如下：

单位名称：中海石油（中国）有限公司北京研究中心

单位地址：北京市朝阳区太阳宫南街6号院1号楼8-14层

银行账号：010020236-01-0458

开户银行：中海石油财务有限责任公司

纳税人识别号：91110105787753355B

公司电话：010-84526210

#### 1.7 付款支持文件及发票、文件的递交

乙方应按甲方要求，根据合同约定的付款进度节点，与甲方技术负责人确认具备以下付款材料后，按照开票通知单上的要求开具并邮寄发票。若因支持文件不齐备、不合格，导致付款延误，甲方不承担任何违约责任。

合同首款：合同原件一份、甲方阶段检查意见或中期检查（如有）、经乙方当地科技主管部门盖章的“技术开发”合同认定证明或拒绝认定证明

合同中期款（如有）：合同原件或复印件一份、甲方中期检查或阶段检查意见（如有）

合同尾款：合同原件或复印件一份、甲方验收意见及验收专家名单

#### 1.8 账户

乙方应通过如下账户收取合同价款及其他款项，并通过该账户向甲方支付与合同有关的任何款项：

乙方名称：中国石油大学（北京）

账 号：11001009200056050532

开户行：中国建设银行北京昌平支行

### 第二条 开工日和工期

2.1 乙方应于开工日开始工作。甲方应在本合同生效后【●】日内以书面方式向乙方

发出开工通知，明确开工日。如甲方未在规定时间内指定开工日，工期相应延长。

（不适用）

2.2 甲方对本合同约定的委托开发任务实行“赛马”规则，甲方有权根据乙方研发进度、成果质量或管理需要暂停或叫停工作或终止委托。因涉及到委托方或其他承揽方的保密信息，委托方有权不告知具体理由。

2.3 除非双方根据本合同规定另行调整，工期见附件一，乙方应于工期内提供每阶段研究开发成果、接受阶段考核评价、完工并完成验收。

2.4 乙方在提交合同约定的阶段考核评价成果后，应在接到甲方书面指令后，启动下一阶段研究开发工作，如乙方自行开展下一阶段工作，甲方不对乙方由此发生的成本等承担任何责任和义务。

2.5 如乙方不能在开工日开始工作，应于开工通知规定的开工日前【●】日向甲方提出延期开工申请，并书面说明延期开工理由。甲方收到申请后【●】日内应书面确认是否同意延期开工。甲方不同意延期开工要求或乙方未在规定时间内提出延期申请，工期不予延长。（不适用）

2.6 甲方有权要求乙方延迟开始工作。如因甲方原因造成乙方不能准时开始工作，工期相应延长，乙方应采取合理措施减少因此对工期的影响。

### 第三条 基础资料（不适用）

3.1 甲方应向乙方提供完成工作所需的基础资料。

### 第四条 工作计划和方案

4.1 本合同生效后【30】日内，乙方应向甲方提交工作计划和方案。甲方有权对工作计划和方案进行审查，乙方应根据甲方的审查意见进行修改，并再次提交甲方审核。

4.2 乙方应严格按照甲方确认的工作计划和方案执行工作，确保工作符合工期的要求，并每月向甲方提交进度报告。乙方应随时（不迟于乙方知悉后（三（3）日内）将任何可能或已经影响工作实际进度的情形通知甲方。

4.3 乙方应接受甲方代表对工作进度的检查、监督。如工作实际进度与工作计划和方

案不符，乙方应按甲方要求提出改进措施（包括增加人力资源、设备、倒班次数、工作时间等），经甲方书面确认后执行。因乙方原因导致工作实际进度与工作计划和方案不符，乙方无权就改进措施要求调整工期或增加费用。如甲方认为乙方采取改进措施后仍不能确保按时完成某项工作且将影响整体工期，甲方有权终止合同，并委托第三方完成相关工作，因此发生的费用由乙方承担，甲方有权从【☒ 合同价款确定部分（适用于总价合同模式）☐ 相应阶段合同价款确定部分（适用于框架协议+订单模式）】余额中直接扣除或凭履约保函要求银行支付该等金额。

## 第五条 工作量记录清单（不适用）

- 5.1 乙方应在完工后【☒】日内向甲方提交工作量记录清单。甲方有权聘请独立的具有专业资质的第三方对乙方工作量进行核实，并以此作为支付合同价款的依据。

## 第六条 验收与奖励

- 6.1 甲乙双方应根据合同规定的合同验收指标对乙方工作及工作成果进行验收，验收的时间、地点、方式、验收标准、条件及双方的责任和义务详见本合同附件一。
- 6.2 甲方对乙方完成悬赏指标情况进行考核评价，达到悬赏条件的出具奖励方案意见，悬赏指标、悬赏条件、考核评价方式等详见本合同附件一，

## 第七条 质保期（不适用）

- 7.1 本合同项下乙方工作的质保期为甲方签署工作成果验收证明之日起【☒】个月。

## 第八条 保险

- 8.1 为履行本合同，乙方应购买下述保险：

- (1) 为其执行工作的人员购买人身伤害险或雇主责任险，事故次数不限；
- (2) 为其工作设备（包括机动车辆和其他运输工具）购买财产险，承保工作设备

因任何原因引起的全部损失或损害；

(3) 根据相关法律法规购买其他保险，包括但不限于涉及乙方人员、工作及第三方的保险。

8.2 如果乙方将工作的任一部分分包，乙方应确保分包商购买、维持上述规定的保险，分包合同保险条款应与本合同一致。

8.3 对于乙方根据本合同应购买的保险，乙方应确保保险人放弃对甲方、甲方的关联企业及甲方人员的代位求偿权或任何形式的追索权。

8.4 对于乙方根据本合同应购买的保险，乙方应于合同生效后七 (7) 日内提供保险合同，并根据甲方要求，提供全额支付保险费的证明，否则，乙方不得开始工作。未经甲方同意，乙方不得取消或变更该等保险。如乙方未根据本合同规定购买、维系相关保险，甲方有权代其购买并维持，乙方应承担全部保险费用，甲方有权从合同价款中直接扣除该等费用或凭履约保函要求银行支付该等费用。

8.5 乙方根据本条规定购买任何保险不得减少、免除乙方本合同下的任何义务或责任。

8.6 乙方根据本合同购买的保险在质保期届满前应持续有效，适用于质保期届满前发生的所有保险事故。

8.7 如发生保险事故，乙方应采取一切必要措施减少损失，并配合甲方进行保险索赔工作。如因乙方不遵守本合同有关健康、安全、环保或质量控制系统设计或乙方其他过错导致甲方不能根据保险全额获赔，甲方有权向乙方追索差额部分。

8.8 乙方不得实施任何可能导致相关保险中止、失效的行为。如因乙方的任何行为、过错（包括错误陈述、隐瞒事实、失职、违反保险合同条款），甲方不能获得保险赔偿，乙方应赔偿甲方因此遭受的全部损失。

8.9 本第八条的规定不能限制并免除乙方在合同项下的任何义务和责任。

## 第九条 知识产权

9.1 双方同意，乙方完成全部或阶段性考核工作、交付全部或阶段性工作成果后，甲方：

■ 自动获得并拥有全部或阶段性工作和工作成果自身附有的和/或为拥有、使用工作成果所需的全部知识产权。



☐ 除以下的知识产权归甲乙双方共有外,自动获得并拥有全部或阶段性工作和工作成果自身附有的和/或为拥有、使用工作成果所需的全部知识产权:

(1) \_\_\_\_\_;

(2) \_\_\_\_\_;

(3) \_\_\_\_\_;

☐ 自动获得并拥有全部或阶段性工作及工作成果自身附有的和/或为拥有、使用工作成果所需的以下知识产权,且乙方同意无偿许可甲方使用与工作和工作成果有关的所有知识产权:

(1) \_\_\_\_\_;

(2) \_\_\_\_\_;

(3) \_\_\_\_\_;

(4) \_\_\_\_\_。

☐ 除非双方另有约定,不自动获得并拥有全部或阶段性工作和工作成果自身附有的相关知识产权,但乙方同意无偿许可甲方使用与工作和工作成果有关的所有知识产权。

9.2 无论乙方是否在“赛马”机制下完成合同约定的全部研究开发任务,均应配合甲方完成知识产权的登记和成果材料移交。

9.3 如果甲乙双方约定知识产权归甲乙双方共有,而乙方因为“赛马”机制或其他任何原因提前退出研究开发的,乙方应允许甲方及其它“赛马”攻关方在项目后续实施过程中以及项目投产后无偿使用共有知识产权或研发成果,不需乙方再单独许可。

9.4 如果甲乙双方约定某专利申请权、专利权归甲乙双方共有,则专利申请费及专利维护费由甲乙双方分摊,乙方应承担的部分直接在合同价款中扣除(详见附件二)。就该专利申请权及专利权,甲方及甲方的母公司中国海洋石油集团有限公司共同持有70%的份额,乙方持有30%的份额。甲方的总公司中海石油(中国)有限公司为专利第一申请人,甲方为第二申请人,乙方为第三申请人。就该专利申请若国家授予专利,则甲方的总公司中海石油(中国)有限公司为第一专利权人,甲方为第二专利权人,乙方为第三专利权人。甲方负责专利的申请与维护。

- 9.5 如果甲乙双方约定某软件版权归甲乙双方共有,则软件登记费用及维护费由甲乙双方分摊,乙方应承担的部分直接在合同总价中扣除(详见附件二)。就该软件版权,甲方持有70%的份额,乙方持有30%的份额。著作权人的排序为甲方、乙方。甲方负责软件版权的登记与维护。
- 9.6 本合同有效期内,如乙方对所许可的专利和/或专有技术有所改进,则乙方应向甲方免费提供技术支持以使该技术改进能顺利投入本合同项下工作成果的使用过程中。
- 9.7 甲方有权对乙方许可甲方使用的专利和/或专有技术予以改进,甲方所作的任何技术改进的专利申请权归甲方所有。
- 9.8 在乙方执行工作期间,如果甲方为此提供任何构思、程序、软件、硬件、设计、图纸、技术、诀窍、发明、商标、专利及其他任何形式的保密信息或知识产权("甲方专有资料"),则无论该等甲方专有资料是否构成合同设备不可分拆的一部分,且无论甲方是否获得与合同设备有关的任何其他知识产权,甲方应始终拥有该等甲方专有资料的所有权及与之相关的知识产权。

- 9.9 若乙方拟生产、使用、推广、国产化本合同涉及的技术所产生的产品或许可他人使用本合同所涉及的技术,需事前获得甲方书面许可,并由双方签署相关技术许可及产业化推广实施协议对如何实施、实施后权益如何分配等问题另行协商予以明确。如果涉及知识产权收益分配的,则分配对象限于专利技术对应而产生的收益。

## 第十条 资产

- 10.1 乙方按照合同约定,建造、购买、试制、制造的房屋、建筑物、设备、器材、工具等固定资产,以及所产生的资料的财产权归甲方所有。
- 10.2 上述固定资产由乙方负责管理和使用,其保管、维护运转费用由乙方承担。甲方使用时,不得收取费用。甲方可以对乙方管理、使用固定资产的情况进行检查,并可以根据情况,对固定资产进行移交、报废等处置。如固定资产需移交给甲方或甲方指定的单位,乙方应协助甲方完成设备或器材的移交。

## 第十一条 违约责任

11.1 乙方发生下列任一违约行为时,应向甲方支付合同【☒合同总价款确定部分(适用于总价合同模式)☐相应阶段合同价款确定部分(适用于框架协议+订单模式)】的30%作为违约金,并赔偿甲方因此遭受的超出违约金部分的全部损失:

- (1) 乙方提供的研究开发成果等不符合本合同的要求;
- (2) 拒绝对不符合本合同要求研究开发成果进行修复或更换;
- (3) 拒绝更换不合格的工作人员;
- (4) 未经甲方许可,擅自更换其负责本项目的关键工作人员;
- (5) 不遵守甲方关于健康、安全和环保的规定;
- (6) 乙方或其雇员对甲方实施欺诈行为;
- (7) 乙方或其雇员的行为损害了甲方的利益或声誉;
- (8) 乙方发生资不抵债、破产清算、丧失履行本合同的资质或者其他致使其不能继续履行本合同的情形;
- (9) 乙方发生其他严重违约,且未在甲方要求的合理期限内纠正。

11.2 乙方未按照本合同专用条款第一条的规定按期提交保函或提交保函不符合本合同规定的,甲方有权中止合同,直至乙方提交符合本合同规定的保函为止。每中止一日,乙方应向甲方支付【☒合同总价款确定部分(适用于总价合同模式)☐相应阶段合同价款确定部分(适用于框架协议+订单模式)】的1%的违约金,但最高不得超过【☒合同总价款确定部分(适用于总价合同模式)☐相应阶段合同价款确定部分(适用于框架协议+订单模式)】的30%,并应承担甲方因合同中止而遭受的超出违约金部分的全部损失。合同中止超过三十(30)日的,甲方有权终止本合同。

11.3 如乙方非因自身主观原因或措施不得力而未能按合同规定的工期内完成全部工作,每延期一日,乙方应向甲方支付【☒合同总价款确定部分(适用于总价合同模式)☐相应阶段合同价款确定部分(适用于框架协议+订单模式)】的1%作为延期违约金。如延期超过三十(30)日,除要求乙方支付违约金外,甲方有权解除本合同,并有权要求乙方赔偿甲方因此遭受的超出违约金部分的全部损失。

11.4 未经甲方同意,乙方擅自进行转让、分包,甲方有权解除本合同,乙方应退还甲

方已支付的全部款项，并支付转让工作对价 100% 的违约金，乙方应同时赔偿甲方因此遭受的超出违约金的全部损失。

11.5 如仅因甲方原因，甲方逾期向乙方付款，乙方应向甲方发出书面催款通知，甲方应在收到该等通知后三十（30）日内付款，否则，即应自该等三十（30）日期间结束之日起，按合同订立时 1 年期贷款市场报价利率计算并支付应付未付合同价款的利息。双方同意，该等利息的支付是甲方就未能如期支付相关合同价款所需承担的全部责任。

11.6 尽管有上述约定，但甲乙双方同意，本合同约定的研究开发任务执行“赛马”机制，出现以下情形的，不视为违约：

(1) 因甲方考核评价安排原因，造成乙方相应延期履行合同，乙方不视为违约，不承担违约责任。

(2) 因执行“赛马制”末位淘汰制，乙方经甲方考核评估处于劣势而终止合同的，如乙方研发成果处于劣势不是因自身主观原因或者措施不得力造成的，乙方不视为违约，不承担违约责任。

(3) 由于本合同约定的委托研究开发任务具有较高的难度和不可预测性，对于阶段性考核评估，乙方经采取合理措施后，研究技术路线无法继续执行，工作成果未达到相关技术指标的，乙方退出研究的不视为违约，可不承担违约责任。

(4) 乙方非自身主观原因或者措施不得力而未达到预期阶段和最终考核指标的，甲乙双方均不被视为违约。

## 第十二条 争议解决

12.1 因履行本合同发生的或与本合同有关的一切争议，双方首先应友好协商解决，如经协商仍不能解决，双方同意选择以下第 1 种方式予以解决：

(1) 向甲方所在地人民法院起诉。

(2) 提交（☒中国国际贸易仲裁委员会；☐中国国际经济贸易仲裁委员会华南分会；☐中国国际贸易仲裁委员会上海分会；☐北京仲裁委员会；☐天津仲裁委员会）进行仲裁。仲裁地点在北京。仲裁应根据该仲裁委员会现行有效的仲裁规则进行。仲裁裁决是终局的，对双方均有约束力。除仲



裁庭另有裁决外，仲裁费用由败诉方承担。

12.2 争议解决期间，除争议事项外，双方应继续履行本合同。

### 第十三条 其他

13.1 在本合同/协议签订时如乙方属于《保障中小企业款项支付条例》（“条例”）规定的中小企业，本合同/协议所约定的付款期限、方式、条件和违约责任等交易条件应遵守该条例的规定。如本合同/协议约定的任何交易条件违反该条例，甲方应按照符合该条例规定的交易条件履行合同，并应按照条例的规定与乙方协商变更本合同/协议的该等交易条件，以保障乙方享有条例规定的合法权益。

### 第三部分 通用合同条款

#### 第一条 定义

##### 1.1 本合同相关词语的定义如下：

- (1) “第三方”指甲乙双方以外的任何自然人、法人、机构、组织、单位、实体等。
- (2) “法律法规”指中华人民共和国各级立法、行政机关不时颁布并生效的法律、法规、规章及其他规范性文件。
- (3) “工作”指乙方提供OBN地震数据高效全波形反演速度建模技术研究开发成果、完整履行本合同应完成的全部工作，工作范围【详见合同附件一】。
- (4) “工作成果”指根据本合同规定，乙方完成工作、完整履行合同应向甲方提交的报告、文件、资料、数据、图纸、计算、建议、评估、测算等。
- (5) “工作变更”指工作内容、范围、要求、验收标准、工期等的改变。
- (6) “工作日”指除星期六、星期日和中华人民共和国法定节假日外的日历日。
- (7) “工期”指乙方完成全部工作、完整履行合同的期限。
- (8) “关联企业”对任何一方而言指，指 (i) 控制该方的公司、企业或实体；(ii) 该方控制的公司、企业或实体；或 (iii) 与该方共受同一主体控制的公司、企业或实体。控制指直接或间接拥有50%以上股份，或有权直接或间接委派董事会或类似管理机构1/2以上成员，或通过其他方式决定其经营管理和决策。
- (9) “合理审慎供应商”指履行合同过程中，乙方应遵循诚实信用的原则，采取一个经验丰富、合格的供应商在同等或类似条件应采取的措施，并具备该等供应商应具备的资质、技术、审慎、判断及其他方面的能力。
- (10) “基础资料”指甲方提供的乙方执行、完成工作应严格遵守的技术规格书、图纸、计算、操作和维护手册及其他任何技术资料（包括技术协议等）。
- (11) “甲方代表”指甲方任命的、全权代表甲方履行本合同的人员。
- (12) “开工日”指甲方指示乙方开始执行工作的日期。
- (13) “日、周、月”指日历日、日历周、日历月。

(14) “验收”指经甲方检验确认，乙方已完成全部工作且工作成果符合合同规定，甲方代表签署工作成果验收证明。

(15) “乙方代表”指经甲方批准，乙方任命的、全权代表乙方履行本合同的人员。

(16) “有效税务发票”指符合中国法律法规要求的发票。

(17) “知识产权”指任何著作权、专利权、商标专用权、以及有关设计新型、商业秘密、成果标记、厂商名称、产地标记、原产地名称等其他知识产权。

(18) “固定资产”指用于生产、提供商品或劳务、出租或为了行政管理目的而拥有的、预计使用年限超过一个会计年度、单位价值在5000元人民币以上的办公设备、办公设施，但单位价值在5000元以下的办公用台式计算机、笔记本电脑以及专业摄影器材等，也作为固定资产处理。包括但不限于房屋、建筑物、机器、机械、运输工具以及其他与生产经营活动有关的设备、器具、工具等。

(19) “中国”指中华人民共和国，为本合同之目的，不包括香港特别行政区、澳门特别行政区和台湾地区。

(20) “赛马制”或“赛马”规则指在项目研究组织过程中，针对项目本身或项目所属同一个攻关任务，允许有两个及两个以上团队同时开展攻关研究，前期实行平行资助，过程中采取阶段考核、优胜劣汰，优中选优的研究组织模式。

## 第二条 工作

2.1 乙方应根据本合同的规定高效、及时、审慎、勤勉地完成全部工作，确保工作实际进度符合工期和工作计划与方案的要求。

2.2 乙方特此承诺，已充分理解并接受工作的内容、范围和性质，包括但不限于：

- (1) 完成工作应实施的全部作业；
- (2) 完成工作应提供的全部人力资源；
- (3) 完成工作应提供的全部设备、材料、器具，备品备件等；
- (4) 工作场地的地质、海况、天气等条件；
- (5) 工期的要求。

即使本合同未对某项工作予以明确规定，但是，如该等工作系提供同类研究开发

成果时，根据合理审慎供应商的标准应预见和完成的作业或为实现本合同目的必需完成的作业，乙方应以符合本合同目的的方式实施该等作业，乙方无权要求调整合同价款和工期。

### 2.3 工作依据

乙方执行、完成工作应符合、并遵守：

- (1) 本合同规定；
- (2) 基础资料；
- (3) 甲方的健康、安全、环保规定；
- (4) 法律法规；
- (5) 行业规范、标准；
- (6) 合理审慎供应商的标准。

如前述工作依据之间存在冲突或不一致，以顺序在先者优先。

2.4 在实施工作过程中，甲方或甲方聘请的第三方检验机构的任何审查、批准、同意、建议、意见，不得视为甲方接受有缺陷的工作，亦不得在任何方面减轻、免除乙方本合同项下及法律法规规定的义务和责任。

## 第三条 工作要求

3.1 乙方应根据合同和基础资料的规定开展研究开发任务并提供成果，其工作应符合本合同和基础资料规定的技术、质量、标准、规格、计算、数据等要求（“工作要求”）。如本合同和基础资料未对相关工作要求予以明确规定，则应适用工作时中国颁布并生效的最新标准、标准和规范的适用顺序为：

- (1) 合同规定的标准和规范；
- (2) 中国最新颁布的相关标准和规范；
- (3) 如没有中国国家标准，适用最新的行业标准；
- (4) 如没有中国国家和行业标准，适用符合本合同目的的标准。

3.2 对于本合同内容、甲方合同签署前已经提供的基础资料，乙方特此承诺，已充分理解、认可该等文件的充分性、完整性与准确性，并对在该等文件基础上形成的任何与工作的技术、质量、标准、规格、计算、数据等相关的文件和资料的充分性、完整性与准确性负责。



- 3.3 对于合同签署后甲方应提供的基础资料，甲方应根据双方确认的交付计划提供。收到甲方提供的基础资料后，乙方应立即进行审查，并于【十五（15）】日内提出书面审查意见。如乙方未在规定时间内提出书面审查意见，视为乙方认可该等文件的充分性、完整性与准确性，并对在该等文件基础上形成的任何提供研究开发成果相关的技术、质量、设计、标准、规格、材料、计算、参数、性能值、数据等相关的文件和资料的充分性、完整性与准确性负责。
- 3.4 如乙方发现本合同内容或基础资料存在任何错误、缺陷、疏忽、冲突和遗漏，乙方应立即但不迟于【二（2）】日通知甲方。甲方收到通知后应对相关问题进行审查，并及时提出意见，乙方应执行甲方的审查意见。未获得甲方意见前，乙方不得开展任何相关工作。
- 3.5 如甲方提供的任何技术、质量、标准、规格、计算、数据通知、信息、要求或基础资料存在错误、缺陷、疏忽、冲突和遗漏（“错误技术信息”），且该等信息是一个合理审慎供应商应该发现的错误技术信息，乙方应及时通知甲方，如因未履行合理审慎供应商的标准而没有发现该等错误，或发现后未予及时通知甲方，乙方应承担因此发生的一切后果，并赔偿甲方因此遭受的任何损失。
- 3.6 在履行本合同过程中，甲方接受、批准乙方关于工作技术、质量、标准、规格、计算等方面的任何建议和要求不得减少、免除乙方本合同项下的责任和义务（包括但不限于乙方对工作质量应承担的责任）。
- 3.7 除非本合同和基础资料另有规定，与工作相关的计量单位均采用中华人民共和国法定计量单位。

#### 第四条 合同价格

- 4.1 除非根据本合同规定因工作变更、国家增值税税率调整、合同书关于合同价款的约定或者其他的明确规定引起合同价款调整外，合同价款为固定价格，不因合同生效后物价上涨、原材料上涨、通货膨胀、汇率或利率变化、税费变化或政策性变化等因素而调整。任何一方不得以情势变更等为由，要求变更合同价款。
- 4.2 合同价款是本合同项下乙方完成工作、完整履行本合同，甲方应支付的全部金额，除非合同另有规定，乙方应承担其在履行本合同义务时产生的全部费用和税

费。乙方确认，其同意合同价格前已经获得了所有信息并已考虑了所有可能影响成本和费用的因素。为避免歧义合同价款包括：完成工作所需的设备、器具、材料、供应品、备品备件等的费用；直接成本、间接成本、人力成本；履行质量保证责任的费用；与合同相关的所有税费；或有费用及合同没有列明但系为实现合同目的所必需的工作和研究开发费用；乙方所有的风险、义务和责任，以及合同中明确说明由乙方承担的成本和费用等。

- 4.3 如根据合同规定发生工作变更，合同价款应进行相应调整，双方应根据本合同规定的对应或类似单价调整；如本合同未规定对应或类似单价，双方应参照市场价格协商确定调整范围。因工作变更引起的合同价款调整，应根据变更后的付款进度结算。

## 第五条 付款

- 5.1 乙方应根据合同规定的付款条件和进度，向甲方开具有效税务发票并提供相关支持文件。如乙方未开具有效税务发票并提供相关支持文件，甲方有权拒付相关合同价款。

- 5.2 如果甲方对乙方开具的有效税务发票和提供的相关支持文件无异议，应按照专用合同条款中约定的付款进度向乙方付款。

## 第六条 权利保证

- 6.1 乙方保证，其执行工作、提供的工作成果未侵犯任何商业秘密、专利权、商标权或其他知识产权；工作成果的所有权及包含的全部专利、商标及其他知识产权均为乙方合法拥有或已获得第三方的合法有效授权。如乙方违反前述保证，导致甲方遭受任何要求、禁令、处罚、索赔或诉讼，乙方应在收到甲方通知后代理甲方尽快予以妥善处理或应诉，或在甲方书面同意的情况下与声称被乙方工作或工作成果侵权的任何第三方达成和解方案，因此产生的全部责任、义务及费用（包括但不限于律师费用、诉讼费用、鉴定费用和赔偿金等）均由乙方承担。如乙方拒绝或怠于处理或应诉，甲方有权自行处理或应诉，或与声称被乙方工作或工作成果侵权的任何第三方达成和解方案，乙方应承担甲方因此发生的全部责任、义务

和费用（包括但不限于律师费用、诉讼费用、鉴定费用、罚款和赔偿金等），甲方有权从合同价款中直接扣除或凭履约保函要求银行支付该等费用及履行上述责任和义务所需承担的费用，不足部分由乙方予以补偿。

6.2 乙方保证，乙方对其提供的为执行工作的工具、设备等享有完整的所有权，且不存在任何形式的担保物权及其他任何权利负担，亦未侵犯任何第三方的权利。如乙方违反前述保证，甲方有权解除本合同，并要求乙方赔偿甲方因此遭受的全部损失。如乙方违反前述保证，导致甲方遭受任何要求、禁令、处罚、索赔或诉讼，乙方应在收到甲方通知后代理甲方尽快予以妥善处理或应诉或在甲方书面同意的情况下与声称被侵权的任何第三方达成和解方案，因此发生的全部责任、义务和费用（包括但不限于律师费用、诉讼费用、鉴定费用、罚款和赔偿金等）均由乙方承担。如乙方拒绝或怠于处理或应诉，甲方有权自行处理或应诉，或与声称被侵权的任何第三方达成和解方案，乙方应承担甲方因此发生的全部责任、义务和费用（包括但不限于律师费用、诉讼费用、鉴定费用、罚款和赔偿金等），甲方有权从合同价款中直接扣除或凭履约保函要求银行支付该等费用及履行上述责任和义务所需承担的费用，不足部分由乙方予以补偿。

6.3 如根据法院判决或仲裁裁决或按照上述规定与声称被侵权的任何第三方之间达成的和解方案，乙方执行工作、工作成果侵犯任何第三方的权益或乙方执行工作、完成工作成果采用的技术、工艺、方法等侵犯任何知识产权，乙方应根据甲方的要求，在确保工作符合本合同的规定和要求的前提下，采取必要的措施获得相关的权利或对工作和工作成果进行必要的调整，确保其履行本合同和工作成果不侵犯任何知识产权。乙方根据本款采取的措施不影响甲方的任何其他权利或补救措施。

6.4 与工作和工作成果有关的所有资料，文件为甲方所有，甲方享有全部权益，工作完成时应全部移交甲方，未经甲方允许，乙方不得使用和转让。

6.5 乙方无权因本条的适用而延长工期或调整合同价款。

## 第七条 保密

7.1 未经甲方同意，乙方不得将甲方保密信息披露给任何第三方（包括与合同无关的乙方员工和政府部门），亦不得将该等信息用于与本合同无关的用途。甲方保密

信息包括但不限于：

- (1) 合同内容；
- (2) 与合同相关的谈判内容；
- (3) 甲方提供的与本合同有关的任何技术信息、图纸、样本、资料等；
- (4) 本合同的履行情况；
- (5) 甲方提供的或履行合同过程中乙方获得的与项目或甲方有关的任何技术和

商务信息。

7.2 除非甲方正常生产经营所致，未经乙方同意，甲方不得将乙方保密信息披露给任何第三方（包括与合同无关的甲方员工和政府部门），亦不得将该等信息用于与本合同无关的用途，乙方保密信息包括：

- (1) 合同内容；
- (2) 乙方提供的与本合同有关的任何技术信息、图纸、样本、资料；
- (3) 乙方提供的或履行合同过程中甲方获得的任何乙方技术和商务信息。

7.3 甲方有权将上述乙方保密信息提供给实施相关项目或为甲方提供相关服务的第三方，甲方向第三方披露乙方保密信息以第三方必须获得相关信息并对信息承担保密义务为前提条件。

7.4 任何一方可在下列情况及范围内披露本属于保密的信息：

- (1) 为履行其在本合同下义务之需要披露给一方员工，但仅限于有合理需要并已作出符合本条第 7.1 款或第 7.2 款承诺的员工；

- (2) 任何对披露信息有管辖权的法律法规或政府机关强制要求的披露；

- (3) 为本合同或与本合同有关的索赔而透露给其专业顾问、或其审计人员、或该方的任何实际或潜在的银行或融资方，或向法院、仲裁庭或其他争议解

决机构披露；

- (4) 另一方已对此等披露事先给予明确的批准。

7.5 本条第 7.1 款和第 7.2 款不应适用于任何由一方披露的本属于保密的信息，但该信息在被披露时：

- (1) 已进入公众领域；
- (2) 披露方事前已从非另一方的合法途径获得，且对其使用及披露无任何限制；
- (3) 由第三方合法、独立地提供给披露方，且该第三方不受任何对该信息使用或披露的限制。



7.6 除上述约定外,乙方应按照附件四保密承诺的要求履行其保密义务。

## 第八条 乙方人员

### 8.1 一般要求

- (1) 乙方应选聘、组织充足、适格、有经验的人员执行、完成工作。
- (2) 本合同履行过程中,乙方应对其员工的报酬、福利、社会保险、食宿、交通负责,相关费用已包含于合同价款中。
- (3) 本合同履行过程中,乙方应建立并维系合法、适当的劳动关系。乙方应采取一切合理必要的措施,避免对工作质量、工期、工作计划和方案及工作其他方面产生不利影响的劳动争议、纠纷和冲突,如发生该等争议、纠纷或冲突,乙方应及时通知甲方,并妥善解决。
- (4) 乙方应采取措施确保其工作人员在执行工作过程中严格遵守本合同和法律法规的规定,如任何乙方工作人员违反本合同和法律法规,甲方有权要求该等人员停止工作,并离开甲方场地。如因乙方或其工作人员违反本合同和法律法规致使甲方遭受任何罚款、行政处罚或损害,乙方应予全额补偿。
- (5) 甲方有权要求乙方更换其工作人员,乙方应严格执行甲方的要求。

### 8.2 乙方代表

- (1) 开工日前,乙方应以书面方式任命一名有经验、具备相应能力和资质的人员担任乙方代表,全权代表乙方履行本合同。乙方任命乙方代表应获得甲方的事先书面批准;未经甲方事先书面批准,乙方不得更换乙方代表。
- (2) 乙方代表向甲方发出的任何与本合同有关的书面通知、请示、要求、批准和确认构成对乙方有约束力的文件。甲方向乙方代表发出的任何与本合同有关的书面通知、文件等视为向乙方发出。
- (3) 经书面通知甲方,乙方代表可将其权限授予其他乙方关键人员,该等通知应注明授权的范围和期限。被授权的其他乙方关键人员无权再转授权给其他人员。
- (4) 甲方可要求乙方更换乙方代表,乙方应根据甲方的要求予以更换。

### 8.3 乙方关键人员

(1) 乙方关键人员应具备其职责要求的资质和能力。

(2) 乙方关键人员的变更应获得甲方的事先书面同意；任何乙方关键人员的变更不得对工期、工作实际进度、工作质量或工作的执行产生不利影响。被更换的乙方关键人员应与新员工工作一段时间，以确保工作顺利交接。

(3) 如存在合理理由，甲方可要求更换乙方关键人员，乙方应根据甲方的要求予以更换。

## 第九条 甲方代表

9.1 开工前，甲方应以书面方式指定一名甲方人员担任甲方代表，全权代表甲方履行本合同。书面通知应载明甲方代表的基本情况和授权范围。甲方代表有权在授权范围内代表甲方签发所有与工作有关的通知、指示、要求、批准和确认，根据本合同的规定签署工作变更确认单。

9.2 甲方代表向乙方发出的任何与本合同有关的书面通知、指示、要求、批准和确认构成对甲方有约束力的文件。乙方向甲方代表发出的任何与本合同有关的书面通知、文件等视为向甲方发出。

9.3 经书面通知乙方，甲方代表有权将其权限授予甲方其他人员，该等通知应注明授权的范围和期限。被授权的甲方人员无权再转授权给其他人员。

## 第十条 工作设施

10.1 除非本合同另有明确规定，乙方应及时提供完成工作所需的全部设施、设备、材料、器具、备品备件等（“工作设施”）。

10.2 乙方保证，其提供的工作设施应处于良好的工作状态，符合本合同和法律法规的要求，不存在任何影响工作执行的缺陷，具备完成相关工作及其通常的用途。

10.3 如甲方发现工作设施存在任何缺陷或不符合本合同的规定，有权要求乙方进行修理和更换，乙方不得因工作设施的修理或更换要求调整合同价款或延长工期。

## 第十一条 监督检查

- 11.1 甲方或其聘任的第三方有权（包括进入乙方工作场地）对乙方工作进度、质量、安全等进行监督和检查。
- 11.2 乙方应积极配合甲方或其聘任的第三方的监督检查，确保甲方及其聘任的第三方人员有权及时进入相关工作场地，为该等人员提供足够的支持和便利。乙方应指派专人负责与甲方或其聘任的第三方联系，根据甲方要求，提供工作进度、计划、质量、健康、安全、环保、存在的问题、预防及整改措施及其他工作信息。
- 11.3 在监督检查过程中，如发现乙方工作存在任何缺陷、瑕疵、疏漏或不符合本合同的规定，乙方应根据甲方的要求，立即采取一切必要、合理的补救措施排除该等缺陷、瑕疵和疏漏/乙方应承担因此发生的一切费用，且无权要求调整工期和合同价款。

## 第十二条 工作成果及验收

- 12.1 乙方应按照本合同附件一的约定，将相关阶段性工作成果报甲方进行考核评估，甲方有权根据考核评估结果决定是否由乙方继续执行合同、与其他受托方联合研究或终止合同。如需进行联合研究，乙方原则上应与甲方进行友好协商，一般不应拒绝进行联合研究。
- 12.2 本合同实行“赛马”机制，即甲方就工作成果是否满足合同约定的验收指标和悬赏指标分别进行验收考核和奖励考核评估。
- 12.3 乙方应提供符合本合同要求的工作成果，并对工作成果的准确性、完整性负责。如乙方提交的工作成果不符合本合同的要求，甲方有权拒绝接受，乙方应根据甲方要求纠正或重新实施相关工作，并赔偿甲方因此遭受的损失。
- 12.4 双方应根据合同规定对乙方工作及工作成果进行验收。如验收过程发现工作存在任何缺陷、瑕疵、疏漏或不符合本合同的规定，乙方应根据甲方的要求，立即采取一切必要、合理的补救措施排除该等缺陷、瑕疵和疏漏。乙方应承担因此发生的一切费用。甲方验收乙方工作不得减少、免除乙方本合同项下的责任和义务（包括乙方对工作应达到合同要求应承担的责任）。



12.5 如乙方提交的工作成果需经主管部门批复,或乙方提交的工作成果组成甲方提交主管部门审批的文件、报告的一部分,甲方可在相关成果、文件、报告审批前先行对乙方工作及工作成果进行验收。无论验收结果如何,在主管部门批准相关成果、文件、报告前,乙方应按照甲方要求对其工作成果进行补充、修改、完善,并承担因此发生的一切费用。

12.6 如要求乙方提交的工作成果中包含专利,而获得专利授予时间较长,甲方可根据实际情况,以国家专利局的受理通知书作为验收依据。无论甲方验收结果如何,在专利授予前,乙方应按照甲方要求完成专利申请。

12.7 如要求乙方提交的工作成果中包含软件,且要求取得软件著作权登记,而获得软件著作权登记时间较长,甲方可根据实际情况,以国家版权局的受理通知书作为验收依据。无论甲方验收结果如何,在软件著作权登记前,乙方应按照甲方要求协助完成软件著作权登记工作。

12.8 如要求乙方提交的工作成果中包含论文、专著,而发表论文、出版专著的时间较长,甲方可根据实际情况,以乙方已被录用的论文及专著作为验收依据。无论甲方验收结果如何,在论文发表、专著出版前,乙方应按照甲方要求协助完成相关论文的发表及专著出版工作。

如果乙方发表论文、专著会影响本合同中要求申请专利的新颖性等专利授予的条件,则在专利申请日前,乙方暂缓发表论文、出版专著。甲方可根据实际情况,以乙方提交的论文及专著作为验收依据。无论甲方验收结果如何,在论文发表、专著出版前,乙方应按照甲方要求协助完成相关论文的发表及专著出版工作。

### 第十三条 质量保证

13.1 乙方承诺,其任何工作和交付的工作成果符合本合同、基础资料、法律法规、行业规范、标准和合理审慎供应商标准的要求,不存在任何缺陷。质保期内,如因其执行的工作或工作成果存在任何缺陷或违反前述质保承诺,乙方应承担质保责任,并采取修复措施或重新实施相关工作,直至消除该等缺陷。

13.2 如果乙方完成的工作或提交的工作成果在质保期内出现任何属于本条第 13.1 款规定的质量保证范围内的问题,甲方应及时通知乙方,乙方应在收到该等通知后



二(2)日内予以回复,并在甲方要求的合理时间内委派技术人员进行修复或重新实施相关工作(“整改工作”)。如乙方人员未能按时实施整改工作,甲方有权委托第三方执行该等工作,因此发生的费用全部由乙方承担。该等费用的结算方式为:甲方将实际发生费用(即相关有效税务发票记载的金额)从本合同质量保证金中扣除或提取履约保函项下款项,如质量保证金/履约保函金额不足,则由乙方凭发票直接向甲方支付。整改后的工作的质保期自修复或重新实施之日起重新计算。

13.3 对于质保期内的任何整改工作,乙方应编制实施方案报甲方批准。相关工作完成后,乙方应进行检验,并出具修复、检验报告。

#### 第十四条 违约责任

14.1 因乙方违约而解除本合同时,如乙方支付的违约金无法补偿甲方因此遭受的超出违约金数额的全部损失,乙方应向甲方另行支付赔偿金。本合同项下的损失包括生产延期的损失、生产暂停的损失、工期延误的损失、甲方可获得商业利润、因为乙方违约导致甲方方向第三方支付的违约金和赔偿金、甲方因第三方索赔而发生的全部费用(包括但不限于律师费用、诉讼费用、鉴定费用和赔偿金等)。

14.2 乙方根据本合同的规定应承担违约金或赔偿责任的,甲方有权从合同价款余额中直接扣除或凭履约保函要求银行支付该等违约金或赔偿款项。

#### 第十五条 健康、安全和环保

15.1 乙方应对全部工作和相关工作人员的健康、安全、环保负责。乙方应遵守、并确保其员工、分包商和来访者遵守本合同对健康、安全、环保的规定、相关法律法规及甲方随时发布的相关规定和指示(包括有关对工作服、面罩、护目器具及工作鞋等安全防护要求)。

15.2 乙方应根据法律法规和合理审慎供应商的标准,建立并维系自身良好的健康、安全、环保体系。

15.3 乙方实施工作时,应避免任何可能危及人身健康、财产安全的操作,采取必要的安全和健康预防措施,不时对所有设施、设备和材料进行健康、安全、环保检查。

乙方应提供工作所需的安全设施和安全指南,保存并提供法律法规及甲方要求的所有事故、伤亡和相关事项的记录、报告。

15.4 乙方应采取合理措施,防止工作造成工程现场及周边发生任何人身、财产损失,该等防护措施包括但不限于:

- (1) 防火措施;
- (2) 提供临时施工围墙、标识、警示标志及路障;
- (3) 消除集聚的粉尘及烟雾;
- (4) 为高架公用工程管线、地下管道、电缆提供保护;
- (5) 为甲方或甲方其他施工单位正在实施的其他作业提供保护;
- (6) 为道路、桥梁及进出工程现场的运输工具提供保护;
- (7) 为工程现场周边的设施、财产提供保护,防止沉陷、坍塌、泄漏及粉尘、烟雾、火灾、化学品、噪声和光线的不良影响。

如乙方未采取前述防护措施,甲方有权自行采取该等措施,乙方应补偿甲方因此实际发生的费用,甲方有权从合同价款中直接扣除该等费用。

15.5 乙方应全面负责进入研究开发现场的工作人员的安全。如研究开发现场发生任何人身伤害,无论是否与工作相关,乙方应及时将受伤人员送至最近的急救中心或医院进行救助。乙方应及时甲方汇报任何人身伤害事故,并对该等事故进行全面调查。

15.6 如乙方在研究开发现场内(无论地上或地下)发现任何危险材料,乙方应暂停相关工作,立即采取充足、合理的应对措施,清理、转移该等危险材料,为工程现场的人员、设施、财产提供充分、合理的保护。如危险材料符合下述任一条件,乙方应自行承担危险材料造成的全部损害,包括清理危险材料的全部费用;

- (1) 危险材料系乙方、分包商带入工程现场;
- (2) 危险材料的危害系乙方、分包商搬运、储存或处理不当引致;或
- (3) 危险材料系乙方、分包商的其他过错引致。

## 第十六条 工作变更

16.1 无论基于何种原因,甲方有权随时向乙方发出工作变更通知,要求进行工作变更。

16.2 收到变更通知后三(3)日内,乙方应向甲方提交变更的实施方案以及变更的影

响；

- (1) 变更对工作的影响；
- (2) 变更对工期的影响；
- (3) 变更对合同价款的影响；
- (4) 实施变更的要求和方案。

对于上述事项，乙方应提供适当的证明文件。

16.3 乙方提交变更影响并经甲方评估后，双方应就工作变更及其影响进行协商。如双方就相关事项达成一致，且甲方决定实施工作变更，双方将共同签署变更确认单或另行签署合同对本合同进行变更，乙方应立即执行。如双方未能就工作变更事项达成一致，甲方有权单方面发出工作变更指令。乙方收到工作变更指令后，应立即实施相关工作。

16.4 未经甲方同意，乙方不得进行任何工作变更。

16.5 乙方也可随时以书面形式提出变更建议书（“变更建议”），变更建议被甲方采纳的前提是：

- (1) 提高研究开发成果质量；
- (2) 缩短工期或降低工作成本；
- (3) 其他有利于甲方的因素。

编制变更建议的费用由乙方承担。甲方可自行决定是否批准或拒绝该变更建议。一旦甲方批准相关的变更建议，应根据本条第 16.1 款签发相应的变更通知。

16.6 下列事项引起的任何乙方工作的增加或变化不应被视为变更：

- (1) 由于乙方在本合同项下义务和责任范围内的原因导致的任何改变、修改或修正均不被视为变更；或
- (2) 为满足在合同生效日时执行的有关法律法规和/或中国政府部门的要求而导致的任何改变和/或费用增加和/或工期延误的，将不被视为变更；或
- (3) 按照合同要求和行业通用标准，对于乙方合理完成合同义务来说是必需的工作，包括为达到研究开发目标要求而进行的工作深化和优化。

## 第十七条 转让

17.1 未经甲方事先书面同意，乙方不得将其在本合同项下的任何权利和义务全部或部

分转让给任何第三方，包括乙方的关联企业。

- 17.2 甲方可以将其在本合同项下的权利和义务全部或部分转让给其关联企业，且无需事先征得乙方的同意，但应书面通知乙方。甲方应保证所转让的那部分义务将得到履行，并且该转让不得使本合同的履行受到妨碍。

## 第十八条 分包

- 18.1 乙方应利用自身的人力资源、设备、技术履行本合同，未经甲方事先书面同意，乙方不得将其在本合同项下的任何义务分包给任何第三方，包括乙方的关联企业。

- 18.2 即使甲方批准乙方将其在本合同项下的任何部分义务分包给第三方，乙方应对分包商工作负责，并承担本合同项下的全部责任和义务，其合同项下责任和义务不因分包而减轻或免除。

- 18.3 甲方有权对分包商进行资格审查，审查内容包括但不限于资质、能力、经验、设备、设施、业绩、管理、人力及特殊作业人员持证状况等。甲方有权拒绝其认为不合格的分包商。

- 18.4 乙方分包部分工作时，应向甲方提供分包商清单及资质等相关证明文件；甲方有权随时查阅乙方与分包商签订的合同文件（不包括价格部分）。甲方有权推荐分包商。如果乙方不能继续履行本合同或本合同终止时，经甲方要求，乙方应向甲方转让所有分包合同，保证工作的继续执行。

- 18.5 如果分包商提供的服务或研究开发成果不符合本合同的规定，甲方有权要求乙方终止分包合同，因分包合同终止产生的纠纷或责任，乙方承担全部责任，甲方不承担任何责任。

- 18.6 甲方有权选择直接向分包方付款，并从合同价款中直接扣除或从凭履约保函要求银行支付该等款项。但是，甲方的上述行为不得视为甲方取代乙方成为分包合同的当事人，分包合同的权利与义务仍由乙方和相应的第三方承担。

- 18.7 乙方应确保所有分包合同的所有重大条款应与本合同保持一致，并应包括以下条款：

- (1) 本合同终止时，经甲方要求，所有分包合同无条件转让给甲方；
- (2) 就分包商承担的工作，分包商应对乙方承担质量保证责任，质量保证责任



的内容应与本合同质量保证条款相同或类似；

(3) 未经甲方事先书面同意，不得将分包合同项下的全部或部分工作进行分包。

18.8 乙方不得将本合同转包给任何第三方，包括其关联企业。

## 第十九条 工作暂停

### 19.1 乙方造成的暂停

如甲方认为乙方的工作存在重大缺陷或与本合同规定不符，甲方有权要求乙方暂停全部或部分工作，直至乙方采取措施消除该等缺陷。乙方消除相关缺陷并经甲方同意后，方能恢复执行工作。甲方对该等工作暂停造成的损失不承担任何责任，乙方无权要求调整合同价款和工期。

### 19.2 甲方造成的暂停

(1) 无论基于任何原因（包括本条第 19.1 款项下的原因），甲方有权随时向乙方发出停工通知，要求乙方暂停全部或部分工作。

(2) 乙方接到停工通知后，应采取下列措施：

- (i) 根据停工通知规定的时间及范围暂停工作；
- (ii) 对于暂停的工作，乙方不再新签任何分包合同、委托合同或其他合同；
- (iii) 对于暂停的工作已签订的分包合同、委托合同或其他合同，乙方应采取必要措施推迟其履行；

(iv) 就暂停工作的相关事项提出处理意见，并妥善保护已完成的工作；

(v) 继续执行未暂停的工作。

(3) 乙方收到甲方复工通知后应立即恢复执行工作。

(4) 对于甲方要求的停工（因本条第 19.1 款项下原因导致的停工除外），甲方应承担乙方因此遭受的合理、直接损失，无需对乙方的任何利润损失及其他间接损失负责，乙方应尽量减少该等损失。乙方提出补偿请求时应提供充分、合理的证明材料。甲方根据前述规定向乙方支付的款项，系乙方根据本款规定暂停工作可获得的全部补偿。

(5) 对于甲方要求的停工（因本条第 19.1 款项下原因导致的停工除外），乙方有权根据停工期限，要求对工期进行调整，乙方应尽量减少停工对工期的影响。

## 第二十条 合同的解除和终止

20.1 甲方根据本合同约定的技术委托要求中设置的攻关阶段,执行严格的阶段考核机制,有权根据阶段考核评估结果对合同继续执行或终止做出以下处理:

(1) 乙方提交的工作成果经阶段考核评估达到甲方的预期考核目标的,由乙方继续开展研究,启动下一阶段工作。

(2) 甲方有权根据考核评估结果,提出乙方与其他攻关方进行合作,联合推进相关研发工作并由甲方或者其他攻关方支付乙方相应研发费用,乙方一般不应拒绝进行联合攻关。具体实施方案由双方或乙方与其他攻关方协商确定。

(3) 阶段考核评估结果未达到甲方的预期考核目标,则乙方应立即停止工作,并做好成果交接等工作。

20.2 如发生以下任一情形,经书面通知乙方,甲方有权解除本合同:

(1) 本合同明确规定甲方有权解除本合同的情形;

(2) 承揽方发生专用合同条款第 11.6 条约定的情形;

(3) 因乙方的原因,工作实际进度与工作计划和方案严重不符,无法符合工期的要求,经甲方通知后十五(15)日内未予采取有效的纠正措施,或采取措施后仍无法符合工期的要求;

(4) 因乙方的原因,工作不符合本合同的要求,经甲方通知后十五(15)日内未予采取有效的纠正措施,或采取纠正措施后仍不符合本合同的要求;

(5) 乙方未根据合同规定提供履约保函;

(6) 乙方发生资金不抵债、破产清算、丧失履行本合同的资质或其他致使其不能继续履行本合同的情形;

(7) 乙方违反安全生产和健康、安全、环保规定;

(8) 乙方非自身主观原因退出研究工作;

(9) 乙方在履行合同过程中违反诚信原则、进行欺诈,或实施其他与其本合同项下义务冲突的行为;

(10) 未经甲方同意,乙方分包任何工作;

(11) 乙方转包任何工作;

(12) 乙方延期完成工作超过三十(30)日;

(13) 乙方发生其他严重违约,且未在甲方要求的合同期限内纠正;

(14) 不可抗力持续超过六十（60）日。

20.3 如因乙方违约甲方解除本合同，乙方应根据本合同规定支付违约金，并且甲方有权要求乙方赔偿其因此遭受的超出违约金的全部损失。甲方有权以适当的条件和方式购买同等研究开发成果，乙方应承担甲方购买同等研究开发成果的合理差额费用。

20.4 无论基于何种原因，经提前三十（30）日书面通知乙方，甲方有权随时终止合同。乙方收到甲方终止合同的书面通知后，应立即停止实施与本合同有关的工作，并对已履行的部分进行结算。甲方收到乙方的结算要求后，应与乙方协商结算数额、因甲方终止合同需向乙方支付的补偿款等事项。甲方因终止合同向乙方支付的补偿款以乙方为履行合同已实际发生的直接、合理费用为限。如甲方已支付的合同价款不足以涵盖该等费用，经乙方提供证明文件后，甲方应向乙方支付差额部分。但是，如甲方已支付的合同价款超过该等费用，乙方应向甲方返还超额部分。甲方向乙方支付的该等补偿款系甲方根据本款规定终止合同时，乙方可获得的全部赔偿。任何时候乙方均无权要求甲方赔偿因合同终止而引起的预期利润的损失或损害。

20.5 如本合同根据本条第20.3款终止，对于合同终止前乙方完成的工作成果，乙方应立即移交给甲方，甲方拥有相关工作成果的全部权益。

20.6 乙方应确保分包合同（如有）包含与本条规定相对应的终止条款。

## 第二十一条 不可抗力

21.1 不可抗力系指本合同的履行过程中，任何一方经合理努力仍不可预见、不可避免并不能克服的客观情况。

21.2 任何一方因不可抗力不能或延迟履行本合同，不承担违约责任。

21.3 如果一方遭受不可抗力，应立即（不迟于24小时内）通知另一方，并采取一切合理、必要的措施减少损失及不可抗力的影响，恢复合同的履行。不可抗力结束后48小时内，遭受不可抗力的一方应向另一方通报不可抗力的情况，包括不可抗力造成的损害、延续时间、受影响的范围、补救措施等，如不可抗力持续发生，遭受不可抗力的一方应及时更新该等信息。

21.4 如发生不可抗力，双方各自承担其人员和财产损失。一旦不可抗力停止或者影响

消除，双方应立即履行其义务，合同的期限应该相应顺延。如果不可抗力的影响持续超过30日，双方应该该共同商议应对措施。

21.5 任何一方迟延履行合同后遭受不可抗力的，不得减少、免除该方在本合同项下的任何义务和责任。

21.6 不可抗力的发生不能造成任何一方支付额外款项、赔偿或其他救济方式，双方放弃对任何此类事项进行索赔的权利。

## 第二十二条 保障

22.1 无论时间、地点、方式和原因，乙方、乙方代理或分包商（如有）因履行本合同造成任何第三方财产损失、损坏、人身伤亡或疾病，乙方应承担全部责任，并确保甲方免于所有相关的索赔、损失、损害、费用和责任，包括但不限于在甲方因此需向第三方支付任何赔偿时，乙方均应全额予以补偿。

22.2 无论时间、地点、方式和原因，如因履行本合同，乙方及其人员、乙方代理、分包商及其人员（如有）的任何财产（包括但不限于设备、装置、器材等，且无论该等财产属于自有、租用、租赁或以其他方式提供）发生毁损、灭失或其他损失，除非该等损失系因甲方故意或重大过失所致，乙方应自行承担全部损失，并确保甲方免于所有相关的索赔、损失、损害、费用和责任。

22.3 无论时间、地点、方式和原因，如因履行本合同而发生的或与履行本合同有关的乙方、乙方代理及分包商（如有）的人员发生人身伤亡或疾病，除非该等人身伤亡或疾病系因甲方故意或重大过失所致，乙方应对上述人员的人身伤亡或疾病负责，并确保甲方免于所有相关的索赔、损失、损害、费用和责任，包括但不限于甲方因此需要支付任何赔偿时，乙方均应全额予以补偿。

22.4 无论时间、地点、方式和原因，如因履行本合同，乙方造成任何江、河、湖、海、陆地、大气及其他环境污染，乙方应单独承担全部责任，包括消除污染源、赔偿污染造成的损失、承担污染产生的法律责任和污染造成的停工损失等，并确保甲方免于所有相关的索赔、损失、损害、费用和责任，包括但不限于在甲方因此需要支付任何赔偿时，乙方均应全额予以补偿。



## 第二十三条 税费

- 23.1 对于在中华人民共和国境内发生的税费，甲乙双方应根据法律法规各自承担。
- 23.2 对于在中华人民共和国境内发生的税费，甲方有权根据中国法律法规和本合同的规定从应支付给乙方的合同价款中扣除应由甲方代扣代缴的乙方应付税费，但应当向乙方提供完税证明。
- 23.3 对于在中华人民共和国境外发生的税费，由乙方承担。
- 23.4 为本条之目的，“中华人民共和国境外”包括香港特别行政区、澳门特别行政区和台湾地区。

## 第二十四条 审计和商业贿赂

- 24.1 乙方应根据甲方要求，无条件接受和配合甲方或甲方委托的会计师事务所进行的与本合同相关的审计，包括配合甲方或甲方委托的会计师事务所对分包商进行的与分包合同相关的审计。乙方应在分包合同中要求其分包商接受与本合同相同的审计要求，包括分包商应无条件接受和配合甲方或甲方委托的会计师事务所对分包商进行的与分包合同相关的审计。
- 24.2 乙方应保存与本合同相关的记录和账目，保存期限为本合同终止后十（10）年。经提前通知，甲方或甲方委托的会计师事务所所有权检查并复制该等记录和账目。
- 24.3 双方确认熟悉并了解合同签订地和履行地关于禁止商业贿赂的政策，并同意遵守这些政策。实施商业贿赂的一方将承担所有不利的法律后果，且另一方有权以此为由随时终止本合同。

## 第二十五条 通知

- 25.1 通知应根据本合同规定以亲自递送、特快专递、传真等方式送达。甲方、乙方或相关第三方的地址、邮政编码、联系人、联系电话、传真号码等如有变更，应及时书面通知对方。
- 25.2 通知在下列情况视为送达：

- (1) 如采用亲自递送方式，于签收确认之时；
- (2) 如采用特快专递方式，于收件人签收之时；
- (3) 如采用传真方式，于确认传输之时。

25.3 通知在接收方正常工作期间送达视为生效。如果不在正常的工作期间，则视为于随后的第一个工作日上午十（10）点送达。

25.4 本合同送达地址适用范围包括就本合同发生争议时相关文件和法律文书的送达（包括在争议进入仲裁、民事诉讼程序后的一审、二审，再审和执行程序）。

## 第二十六条 适用法律

26.1 本合同适用中华人民共和国法律（不含香港特别行政区、澳门特别行政区和台湾地区）。

## 第二十七条 合同语言

27.1 除本合同另有明确规定或双方另行同意外，本合同及本合同项下的任何文件及往来函电均采用中文书写。

## 第二十八条 标题

28.1 本合同各部分及各条款的标题仅为方便阅读而设，不影响对条款实质内容的解释。

## 第二十九条 其他

29.1 本合同未尽事宜，应由双方协商确定，并签订补充协议，补充协议与本合同具有同等法律效力。

29.2 本合同的任何变更、修改或增减，须经双方协商一致、法定代表人或授权代表签署书面文件并盖章后生效。

29.3 本合同系甲乙双方反复协商、讨论的结果，合同内容非一方当事人事先拟定。本

合同不属于格式合同，条款内容不属于格式条款。

- 29.4 未经另一方事先书面同意，任何一方不得以任何方式在其机构外使用另一方的名称、商品商标、服务商标、企业标志、商号或品牌。
- 29.5 如果本合同的任何条款或规定被裁定为无效、不合法或不可强制执行，该条款或规定应视为被删除，本合同其他条款不受影响，仍继续有效。
- 29.6 本合同履行过程中，如乙方发生重组、合并、分立、重大股权或资产转让，应及时通知甲方。经甲方事先书面同意，乙方应安排具有相应资质的主体继续履行本合同，否则乙方不得执行前述重组、合并、分立或转让。乙方应根据甲方的要求，为继续履行本合同的主体安排履约担保。
- 29.7 本合同解除或终止后，本合同项下关于知识产权、保密、保证、责任、适用法律、争议解决和其他具有持续生效力的条款继续有效。

附件一：技术委托要求

一、课题名称

OBN 地震数据高效全波形反演速度建模技术

二、委托内容与技术要求

1. 总体委托内容

充分利用海底节点 (OBN) 地震数据的大偏移距、宽频、宽方位、多分量等方面的优势,开展基于 OBN 数据的声波及弹性波全波形反演建模技术攻关,实现高精度求取地下介质纵横波速度信息,完成 OBN 典型数值模型试验以及靶区 OBN 资料的应用,为国产海底节点装备 OBN 数据采集、处理及解释一体化示范应用提供技术支持。

总体技术委托内容如下:

- (1) OBN 声压分量全波形反演技术研究
- (2) OBN 四分量声-弹耦合全波形反演/OBN 三分量弹性波全波形反演技术研究
- (3) OBN 各向异性弹性波全波形反演技术探索研究
- (4) OBN 多分量地震数据全波形反演数据准备及配套技术研究
- (5) OBN 典型数值模型试验
- (6) 靶区 OBN 实际资料应用

2. 总体技术要求

- (1) OBN 多分量数据正演采用基于声-弹耦合/弹性介质的波动方程
- (2) 声波、声-弹耦合/弹性波波场正演采取有效的抗时间和空间频散算法
- (3) OBN 地震数据声波、声-弹耦合/弹性波全波形反演算法适用于复杂地质模型,

计算稳定性好

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(4) 全波形反演算法采用 CPU/GPU 并行加速, 以满足实际资料规模化应用

### 三、分阶段委托内容及考核指标

#### 1. 第一阶段:

(1) 技术委托内容 (注: 委托内容②和③可任选其一):

##### ① OBN 声压分量全波形反演技术研究

##### ② OBN 多分量地震数据 2D 声-弹耦合全波形反演技术研究

- OBN 多分量地震数据 2D 声-弹耦合全波形反演速度建模原理
- OBN 多分量地震数据 2D 声-弹耦合介质波场正演技术
- OBN 多分量地震数据 2D 声-弹耦合介质波场残差反传技术
- OBN 多分量地震数据 2D 声-弹耦合介质高效稳定的梯度场计算方法

##### ③ OBN 多分量地震数据 2D 弹性波全波形反演技术研究

- OBN 多分量地震数据 2D 弹性波全波形反演速度建模原理
- OBN 多分量地震数据 2D 弹性介质波场正演技术
- OBN 多分量地震数据 2D 弹性介质波场残差反传技术
- OBN 多分量地震数据 2D 弹性介质高效稳定的梯度场计算方法

##### ④ OBN 声压分量全波形反演数据准备及配套技术研究

##### ⑤ 典型数值模型测试

- 3D 典型 OBN 声波介质数值模型纵波速度反演
- 2D 典型 OBN 声-弹耦合介质/弹性介质数值模型纵横波速度反演

##### ⑥ 靶区 OBN 资料全波形反演速度建模技术应用

- 靶区 OBN 声压分量地震数据 3D 全波形反演技术应用
- 靶区 OBN 多分量地震数据 2D 声-弹耦合/弹性波全波形反演技术应用

#### (2) 预期成果:

① 一套高效实用的 OBN 声压分量 3D 全波形反演技术软件代码、原理说明及使用

## 文档

② 一套 OBN 多分量地震数据 2D 声-弹耦合/弹性波全波形反演技术软件代码、原理说明及使用文档

③ 靶区高精度纵横波速度反演数据体

④ 研究报告和工作报告等纸介质一式三份及相应电子文件一份

⑤ 发表专业论文不少于 1 篇，申请发明专利不少于 1 件

### (3) 考核指标：

① 采用 OBN 多分量地震数据 2D 声-弹耦合/弹性波全波形反演技术，有效反演深度范围内计算的纵横波速度与测井速度曲线低频趋势一致，且相较于初始速度，大于 95% 的偏移成像道集拉平效果得到提升；

② 2D 典型 OBN 声-弹耦合/弹性介质数值模型全波形反演的纵横波速度在有效深度范围内误差小于 6%；

③ OBN 声压分量全波形反演技术靶区 OBN 资料应用面积不小于 100 平方公里，速度模型符合地质认识，且有效反演深度范围内计算的纵波速度与测井速度曲线低频趋势一致；

④ 研发的 OBN 声压分量全波形反演技术在总院并行集群上能稳定处理万炮数量级的实际数据；

⑤ 技术软件代码注释率不低于 30%，关键模块参数注释完整清晰。

## 2. 第二阶段

(1) 技术委托内容（注：委托内容①和②可任选其一）：

- ① OBN 四分量地震数据 3D 声-弹耦合全波形反演技术研究
  - OBN 四分量地震数据 3D 声-弹耦合全波形反演速度建模原理
  - OBN 四分量地震数据 3D 声-弹耦合介质波场正演技术
  - OBN 四分量地震数据 3D 声-弹耦合介质波场残差反传技术
  - OBN 四分量地震数据 3D 声-弹耦合介质高效稳定的梯度场计算方法

② OBN 三分量地震数据 3D 弹性波全波形反演技术研究

- OBN 三分量地震数据 3D 弹性波全波形反演速度建模原理
- OBN 三分量地震数据 3D 弹性介质波场正演技术
- OBN 三分量地震数据 3D 弹性介质波场残差反传技术
- OBN 三分量地震数据 3D 弹性介质高效稳定的梯度场计算方法

③ OBN 多分量地震数据 3D 声-弹耦合/弹性波全波形反演数据准备及配套技术研究

究

④ OBN 各向异性介质弹性波全波形反演技术探索研究

⑤ 典型数值模型测试

- 3D 典型 OBN 声-弹耦合介质/弹性介质数值模型纵横波速度反演
- 典型 OBN 各向异性介质模型各向异性参数反演

⑥ 靶区 OBN 多分量地震数据 3D 声-弹耦合/弹性波全波形反演速度建模技术应用

(2) 预期成果:

① 一套 OBN 多分量地震数据 3D 声-弹耦合/弹性波全波形反演技术软件代码、原理说明及使用文档;

② 一套 OBN 多分量地震数据各向异性介质全波形反演技术软件代码、原理说明及使用文档;

③ 靶区高精度纵横波速度反演数据体;

④ 研究报告和工作报告等纸质介质一式三份及相应电子文件一份

⑤ 发表专业论文不少于 1 篇, 申请发明专利不少于 1 件

(3) 考核指标:

① 采用 OBN 多分量地震数据 2D 声-弹耦合/弹性波全波形反演技术, 有效反演深度范围内计算的纵横波速度与测井速度曲线低频趋势一致, 且相较于初始速度, 大于 95% 的偏移成像道集拉平效果得到提升;

② 3D典型OBN声-弹耦合/弹性介质数值模型全波形反演的纵横波速度在有效深度范围内误差小于6%;

③ 研发的OBN多分量地震数据3D声-弹耦合全波形反演技术在总院并行集群上能稳定处理万炮数量级的实际数据;

④ 技术软件代码注解率不低于30%，关键模块参数注释完整清晰

#### 四、进度计划

1. 研究期限： 合同签订后28个月内（第一阶段验收时间为2023年11月30日前，第二阶段验收时间为2025年3月31日前）完成。

#### 2. 关键节点检查计划

| 时间安排        | 完成内容                                                                                                                | 考核指标                                                 | 备注 |
|-------------|---------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|----|
| 合同签订后15日内   | 课题实施方案                                                                                                              | 经项目组审查同意后开展工作                                        |    |
| 合同签订后1.5个月内 | 开展OBN声压分量全波形反演原理、OBN多分量地震数据2D声-弹耦合/弹性波全波形反演原理调研，并制定研发实施方案                                                           | 提交调研报告一份                                             |    |
| 合同签订后6个月内   | 1、完成OBN声压分量全波形反演技术开发<br>2、完成针对声压分量全波形反演技术3D典型数值模型测试<br>3、开展靶区OBN声压分量地震数据3D全波形反演技术应用                                 | 1、通过数值模型验证OBN声压分量全波形反演技术正确性<br>2、反演模块能稳定处理万炮规模级的实际数据 |    |
| 合同签订后10个月内  | 1、完成OBN多分量地震数据2D声-弹耦合/弹性波全波形反演技术开发<br>2、完成针对OBN多分量数据声-弹耦合/弹性介质全波形反演技术的典型2D数值模型测试<br>3、开展靶区OBN多分量地震数据2D声-弹耦合/弹性波全波形反 | 通过数值模型验证OBN多分量地震数据2D声-弹耦合/弹性波全波形反演技术正确性              |    |



|                     | 演技术应用                                                                                                                                                   |                                                                                                                                                                                                                                                                                                                      |
|---------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>合同签订后 12 个月内</p> | <p>1、完成靶区实际数据应用</p> <p>2、第一阶段考核、结题答辩</p>                                                                                                                | <p>1、采用 OBN 多分量地震数据 2D 声-弹耦合/弹性波全波形反演技术，有效反演深度范围内计算的纵横波速度与测井速度曲线低频趋势一致，且相较于初始速度，大于 95% 的偏移成像道集拉平效果得到提升；</p> <p>2、2D 典型 OBN 声-弹耦合/弹性介质数值模型全波形反演的纵横波速度在有效深度范围内误差小于 6%；</p> <p>3、OBN 声压分量全波形反演技术靶区 OBN 资料应用面积不小于 100 平方公里，速度模型符合地质认识，且有效反演深度范围内计算的纵横波速度与测井速度曲线低频趋势一致；</p> <p>4、提交技术模块代码（注解率不低于 30%）、研究报告和工作报告等相关文档。</p> |
| <p>合同签订后 13 个月内</p> | <p>开展 OBN 多分量地震数据 3D 声-弹耦合/弹性波全波形反演技术、3D 各向异性介质全波形反演技术原理调研，并制定研发实施方案</p>                                                                                | <p>提交调研报告一份</p>                                                                                                                                                                                                                                                                                                      |
| <p>合同签订后 21 个月内</p> | <p>1、完成 OBN 多分量地震数据 3D 声-弹耦合/弹性波全波形反演技术开发</p> <p>2、完成针对 OBN 多分量数据声-弹耦合/弹性介质全波形反演技术的典型 3D 数值模型测试</p> <p>3、开展靶区 OBN 多分量地震数据 3D 声-弹耦合/弹性波全波形反演速度建模技术应用</p> | <p>1、通过数值模型验证 OBN 多分量地震数据 3D 声-弹耦合/弹性波全波形反演技术正确性</p> <p>2、反演模块能稳定处理万吨规模级的实际数据</p>                                                                                                                                                                                                                                    |

|              |                                                                                                                          |                                                                                                                                                                                                                                                                      |  |
|--------------|--------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|
| 合同签订后 26 个月内 | <p>1、完成 OBN 各向异性介质弹性波全波形反演技术开发</p> <p>2、完成针对 OBN 各向异性介质弹性波全波形反演技术的典型数值模型测试</p> <p>3、开展靶区 OBN 多分量地震数据各向异性弹性波全波形反演技术应用</p> |                                                                                                                                                                                                                                                                      |  |
| 合同签订后 28 个月内 | <p>1、完成靶区实际数据应用</p> <p>2、第二阶段考核、结题答辩</p> <p>3、完成全部研究工作</p>                                                               | <p>1、采用 OBN 多分量地震数据 3D 声-弹耦合/弹性波全波形反演技术,有效反演深度范围内计算的纵横波速度与测井速度曲线低频趋势一致,且相较于初始速度,大于 95%的偏移成像道集拉平效果得到提升;</p> <p>2、3D 典型 OBN 声-弹耦合/弹性介质数值模型全波形反演的纵横波速度在有效深度范围内误差小于 6%;</p> <p>3、靶区 OBN 资料应用面积不小于 100 平方公里,速度模型符合地质认识;</p> <p>4、提交技术模块代码(注解率不低于 30%)、研究报告和工作报告等相关文档。</p> |  |

## 五、项目管理要求

1. 外委外协课题承担单位应成立课题组,上报课题组织机构,包括课题负责人/主要工作人员的职称及负责的工作内容;
2. 上报外委外协课题技术路线或实施方案,经委托方项目组同意后实施。
3. 每月 23 日前,提交课题月报(详见附件 5-1)。
4. 重大事项报批制度:在课题执行过程中,如遇到工作方案变更、工作计划调整、

课题负责人变更等情况，应以书面形式上报委托方项目/课题组，经委托方项目/课题组书面同意后方可实施。

5. 工作过程的原始数据、资料、记录均应妥善保存并建立存档目录，以确保工作过程的可追溯性。
6. 工作成果应通过外委承担单位的质量管理体系审查后，方可提交委托方审查。
7. 本课题设有阶段考核机制，按照关键节点检查计划在每个阶段工作完成后进行考核，考核认定为继续研究的，则继续履行合同；考核认定为终止的，供应商应立即停止工作，做好成果交接等收尾工作，并履行合同终止流程。

## 六、应提交的成果

1. 一套高效实用的 OBN 声压分量全波形反演软件代码、原理说明及使用文档；
2. 一套 OBN 多分量地震数据 2D 及 3D 声-弹耦合/弹性波全波形反演技术软件代码、原理说明及使用文档；
3. 一套 OBN 多分量地震数据各向异性介质全波形反演技术软件代码、原理说明及使用文档；
4. 靶区高精度纵横波速度模型数据体；
5. 研究报告和工作报告等纸质一式三份及相应电子文件一份；
6. 发表专业论文不少于 2 篇，申请发明专利不少于 2 件。

## 七、阶段考核

委托方对被委托方的阶段性工作成果通过评审会的形式进行检查评估，重点评估反演速度体精度、软件运行效率，并根据评估结果决定是否由被委托方继续攻关或终止攻关。在第一阶段考核中，针对相同的 2D 及 3D OBN 地震资料，在相同运算环境下进行测试两家外委单位的 3D 声波及 2D 声-弹耦合/弹性波全波形反演算法，并对两套反演速度体精度及软件运行效率进行对比评价，优选一家进入第二阶段。

## 八、验收标准与验收方式

### 1. 验收指标

被委托方提交研究成果及靶区资料应用成果，并满足所规定的技术要求。

### 2. 验收方式

由委托方组织专家验收会议，被委托方提供所要求的验收材料，并接受专家质疑，由专家组评审决定是否项目通过验收。

## 九、悬赏指标与悬赏条件

### 1. 悬赏指标

完成 OBN 各向异性弹性波全波形反演技术研究，且有效反演深度范围内计算的纵横波速度与测井速度曲线低频趋势一致，且大于 95% 的偏移成像道集拉平效果优于各向同性速度反演的结果。

### 2. 悬赏条件

完成上述规定的悬赏指标，并通过专家组验收审核，给予被委托方一定额度的悬赏奖金。如完成靶区 OBN 多分量资料各向异性全波形反演技术应用面积不少于 50 平方公里，悬赏奖金额度进一步提升。

## 十、报告封面格式（详见附件 1-2）



项目/课题名称\*\*\*\*\*  
外委课题名称\*\*\*\*\*  
(外委研究期限: ×年×月—×年×月)

## 月 报

(20 XX.XX.24---20 XX.XX.23)

承担单位:

外委课题负责人:

### 一、 课题大事记

课题认为应纳入大事记的内容

### 二、 本月主要完成工作

### 三、 课题执行情况

#### 1. 课题进度百分比;

本月计划进度:

本月计划累计进度:

本月实际进度:

本月实际累计进度:

#### 2. 课题投入工时数 (××人月)

### 四、 下月主要工作计划

### 五、 存在问题

## 外委课题成果封面及内封的格式要求

为规范外委课题成果封面出版的格式,要求承担单位提交成果的封面应符合所规定

格式的要求。

1. 所有文字必须采用 Microsoft Word 排版,版面须控制在 A4 纸张大小(21cm\*29.7cm)的区域内,设置上页边距 2.8cm,下页边距 2.4cm,左页边距 3cm,

右页边距 2.2cm。

2. 外委课题成果报告题目:中文字体为黑体加粗,所有数字英文用 Times New Roman。字号及段落行距视报告题目字数长短而定,置于视觉中间的位置。

3. 封面左上脚框中包括:委托单位名称、委托方项目名称及类别(即外委课题)等三个部分。置于上页边距 2.8cm 和左页边距 3cm 处。字体为宋体小四号,段落行距设置为最小值,设置值 12 磅。

4. 签署单位字体为宋体四号;报告完成日期字体为宋体四号+Times New Roman 三号。

5. 外委课题成果内封应包括技术签署名单,字体为宋体四号,段落行距设置为 2 倍行距,签字应为手签。

6. 文中未指明字体及段落行距的部分,字体设置为宋体小四,段落行距设置为多倍行距,设置值 1.3。

7. 侧封(书脊)的设置依据报告成书厚度而定,书厚 1cm 以上必须设置侧封。侧封内容包括报告名称及承担单位名称,其字体、字号自行设定,侧封下方应留出 4cm 以备设置归档标签。侧封中报告名称应竖排,当汉字、数字及英文混排时,数字和英文应顺时针旋转 90°。承担单位名称排版方式视成书厚度而定,可横排也可竖排。

8. 外委课题成果封面、内封及侧封的模板详见下页。

中海石油（中国）有限公司北京研究中心（或中海油研究总院有  
限责任公司）  
委托方项目名称

空 6 行 宋体 小四

## 外委课题名称

共 XX 册 第 XX 册

（如报告只有一册可不写此行。字体要求：宋体四号+Times New Roman 三号）

承担单位名称（宋体四号）

200x 年 XX 月（宋体四号+Times New Roman 三号）

空6行 宋体 小四

## 外委课题名称

空9行 宋体 小四

编制: \_\_\_\_\_

审核: \_\_\_\_\_

审定: \_\_\_\_\_

批准: \_\_\_\_\_

( 字体为宋体四号, 段落行距设置为 2 倍行距, 签署时先计算机打印再手签)



外委课题名称

共xx册 第xx册

承担单位名称  
20xx年xx月

距底4cm

附件二：价格表

验收考核部分费用明细

第一阶段

| 人工费用   |                             |                         |      |         |               |       |     |
|--------|-----------------------------|-------------------------|------|---------|---------------|-------|-----|
| 序号     | 工作内容分类                      | 投入人力                    |      |         | 人员费率<br>(人、天) | 费用    | 备注  |
|        |                             | 人员级别                    | 数量   | 工作时间(天) |               |       |     |
| 1      | OBN 声压分量<br>三维全波形反<br>演技术研究 | 高级人员                    | 2    | 200     | 0.030         | 12.00 |     |
| 2      |                             | 中级人员                    |      |         |               |       |     |
| 3      |                             | 初级人员                    |      |         |               |       |     |
|        |                             | 小计                      |      |         |               | 12.00 |     |
| 4      | OBN 二维多分<br>量弹性波全波<br>形反演技术 | 高级人员                    |      |         |               |       |     |
| 5      |                             | 中级人员                    | 2    | 300     | 0.020         | 12.00 |     |
| 6      |                             | 初级人员                    |      |         |               |       |     |
|        |                             | 小计                      |      |         |               | 12.00 |     |
| 7      | OBN 声压分量                    | 高级人员                    |      |         |               |       |     |
| 8      | 全波形反演数                      | 中级人员                    |      |         |               |       |     |
| 9      | 据准备及配套                      | 初级人员                    | 1    | 300     | 0.010         | 3.00  |     |
|        | 技术研究                        | 小计                      |      |         |               | 3.00  |     |
| 10     | OBN 声压分量                    | 高级人员                    |      |         |               |       |     |
| 11     | 三维全波形反                      | 中级人员                    |      |         |               |       |     |
| 12     | 演典型数值模                      | 初级人员                    | 1    | 300     | 0.010         | 3.00  |     |
|        | 型试验和实际                      | 小计                      |      |         |               | 3.00  |     |
|        | 资料应用                        |                         |      |         |               |       |     |
|        |                             | 合计                      |      |         |               | 30.00 |     |
| 项目运行费用 |                             |                         |      |         |               |       |     |
| 序号     | 费用类别                        | 计算依据                    |      | 费率      | 费用            | 备注    |     |
|        |                             | 本地交通费                   | 5人次  |         |               |       | 20天 |
| 1      | 差旅费                         |                         |      |         | 1.00          |       |     |
| 2      | 分析测试费                       | CPU 并行节点<br>测试费用        | 30节点 | 200小时   | 0.001         | 6.00  |     |
| 3      | 出版印刷费                       | 最终报告的出版印刷               |      |         | 0.500         | 1.00  |     |
| 4      | 资料使用费                       | 含资料收集费                  |      |         | 0.5437        |       |     |
| 5      | 评审费                         | 项目执行期间专家咨询费             |      |         | 3.00          |       |     |
| 6      | 材料费                         | 移动硬盘: 1000 元/个 5个=0.5万元 |      | 0.100   | 0.50          |       |     |
|        |                             | 合计                      |      |         | 12.0437       |       |     |
| 其它费用   |                             |                         |      |         |               |       |     |

| 序号      | 费用类别 | 费率  | 费用      | 备注 |
|---------|------|-----|---------|----|
| 1       | 管理费  | 13% | 6.50    |    |
| 净价（不含税） |      |     | 48.5437 |    |
| 税率      |      |     | 3%      |    |
| 税费      |      |     | 1.4563  |    |
| 总计（含税）  |      |     | 50.00   |    |

- 注：1. 上述栏目仅为参考，投标方可根据项目实际情况适当增减。  
 2. 办公设备、软硬件使用费包含于人员费用中。  
 3. 如有甲方人员赴乙方办公室公干，所有住宿、差旅费用由甲方承担。

## 第二阶段

| 人工费用   |                                |                                                                |       |         |               |         |       |
|--------|--------------------------------|----------------------------------------------------------------|-------|---------|---------------|---------|-------|
| 序号     | 工作内容分类                         | 投入人力                                                           |       |         | 人员费率<br>(人、天) | 费用      | 备注    |
|        |                                | 人员级别                                                           | 数量    | 工作时间(天) |               |         |       |
| 1      |                                | 高级人员                                                           | 2     | 400     | 0.03          | 24.00   |       |
| 2      | OBN 三维多分量弹性波全波形反演技术            | 中级人员                                                           |       |         |               |         |       |
| 3      |                                | 初级人员                                                           |       |         |               |         |       |
|        |                                | 小计                                                             |       |         |               |         | 24.00 |
| 4      | OBN 多分量三维弹性波全波形反演数据准备及配套技术研究   | 高级人员                                                           |       |         |               |         |       |
| 5      |                                | 中级人员                                                           | 2     | 400     | 0.02          | 16.00   |       |
| 6      |                                | 初级人员                                                           |       |         |               |         |       |
|        |                                | 小计                                                             |       |         |               |         | 16.00 |
| 7      | OBN 多分量三维弹性波全波形反演典型数值模型试验和实际应用 | 高级人员                                                           |       |         |               |         |       |
| 8      |                                | 中级人员                                                           |       |         |               |         |       |
| 9      |                                | 初级人员                                                           | 4     | 400     | 0.010         | 16.00   |       |
|        |                                | 小计                                                             |       |         |               | 16.00   |       |
|        |                                | 合计                                                             |       |         |               | 56.00   |       |
| 项目运行费用 |                                |                                                                |       |         |               |         |       |
| 序号     | 费用类别                           | 计算依据                                                           |       |         | 费率            | 费用      | 备注    |
| 1      | 差旅费                            | 本地交通费                                                          | 10 人次 | 10 天    | 0.01          | 1.00    |       |
| 2      | 分析测试费                          | CPU 并行节点测试费用                                                   | 30 节点 | 250 小时  | 0.001         | 7.50    |       |
| 3      | 出版印刷费                          | 指最终报告的出版印刷                                                     |       |         | 0.500         | 1.00    |       |
| 4      | 资料使用费                          | 含资料收集费                                                         |       |         |               | 0.9743  |       |
| 5      | 评审费                            | 项目执行期间专家咨询费                                                    |       |         |               | 3.00    |       |
| 6      | 材料费                            | 地震数据绘图墨盒：0.5 万元/套*2 套=1 万元<br>电脑配件：32G 内存条：1000 元/条*10 套=1 万元。 |       |         |               | 2.00    |       |
|        |                                | 合计                                                             |       |         |               | 15.4743 |       |
| 其它费用   |                                |                                                                |       |         |               |         |       |
| 序号     | 费用类别                           | 费用                                                             | 费率    | 费用      | 备注            |         |       |

2

date



|   |         |     |         |
|---|---------|-----|---------|
| 1 | 管理费     | 13% | 11.05   |
|   | 净价（不含税） |     | 82.5243 |
|   | 税率      |     | 3%      |
|   | 税费      |     | 2.4757  |
|   | 总计（含税）  |     | 85      |

- 注：1. 上述栏目仅为参考，投标方可根据项目实际情况适当增减。  
2. 办公设备、软硬件使用费包含于人员费用中。  
3. 如有甲方人员赴乙方办公室公干，所有住宿、差旅费用由甲方承担。

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附件三：关键人员名单

| 序号 | 人员  | 职称级别  |
|----|-----|-------|
| 1  | 姚刚  | 高级职称  |
| 2  | 周辉  | 高级职称  |
| 3  | 陈汉明 | 副高级职称 |
| 4  | 吴迪  | 副高级职称 |
| 5  | 刘能超 | 初级职称  |
| 6  | 吴博  | 初级职称  |
| 7  | 富禹鑫 | 初级职称  |
| 8  | 邹孝哲 | 初级职称  |
| 9  | 张平民 | 初级职称  |
| 10 | 方鑫宇 | 初级职称  |

#### 附件四：保密承诺

就为签署本合同、签署本合同过程中及履行本合同过程中乙方获得的甲方的保密信息，乙方承诺：

##### 一、 保密信息定义

保密信息是指：

1. 甲方拥有的任何商业秘密或国家秘密级及以上的数据、信息和资料。
2. 甲方向乙方披露的以及乙方从甲方获取的所有信息，包括但不限于提供的图纸、基础资料、生产数据、技术资料，设计文件，各种技术说明，计算机程序、软件、数据库、合同及信函等。无论甲方以何种形式披露，口头、书面或电子文本，无论信息载体上是否标有“保密”字样。
3. 乙方从甲方获知的任何技术成果及与工程有关的任何实施工艺、步骤，技术秘密。
4. 乙方获知的与甲方有关的任何信息，包括但不限于甲方的财务资料和数据，财务管理模式，供应商资讯，经营统计数据，货物来源、数量，物流，经营文件等。
5. 双方为专门目的签署的，包括但不限于本合同的价格，任务的内容，涉及双方利益关系的谈判等。
6. 本合同的履行情况，以及在合同履行过程中乙方或其他关联方在完成工作任务时研究开发出的任何技术信息。

##### 二、 乙方应履行的保密义务

1. 保证仅为履行合同的目的是使用甲方披露的保密信息。除为履行合同目的而必须知悉该保密信息的人员，乙方不将与甲方相关的或属于甲方所有的保密信息披露给乙方其他人员。
2. 保证不超出履行合同的所允许的必要限度，复制、摘录和转移任何甲方的保密信息。
3. 保证未经甲方事先书面同意，乙方不将保密信息向任何第三方披露。不采用任何形式对保密信息的全部或部分予以披露、传播、转让等。

4. 保证告知并以适当方式要求其参与履行本合同之雇员遵守承诺的规定，若任何乙方之雇员违反任何保证的规定，对甲方造成损害，乙方承担连带责任。
5. 保证采取一切合理措施对甲方保密信息保密，避免该等保密信息被不当披露或使用，采取该等措施时持与保护自身保密信息相同程度的谨慎态度。
6. 保证不以任何方式将甲方所提供的保密信息用于合同外的其他任何目的。
7. 保证若发现有误用或滥用甲方的保密信息的情形时，应及时将该情形书面通知甲方。
8. 保证在依据法律的强制性规定或政府命令需要披露甲方的保密资料时，在合法的前提下，在披露前书面通知甲方。
9. 保证在履行本合同结束后，按照甲方要求及时销毁或归还甲方提供的所有保密信息。

### 三、 保密信息的返回

根据甲方的书面要求，乙方应在收到甲方的书面要求之日起5日内销毁或归还甲方提供的所有保密信息。任何形式的保密信息，不论是分析、汇编、论文、翻译或其他由/或为甲方准备的文件，乙方应按甲方的要求持有或根据要求自行销毁该保密信息。乙方销毁或返还保密信息及保密信息存储介质并不减轻或免除乙方的保密义务。

### 四、 乙方违反保密义务的责任

乙方违背承诺的保密义务，甲方有权要求停止违背承诺的行为，并赔偿因该行为而对甲方造成的所有损失，包括（但不限于）可能出现的诉讼费用、所有损失或损害等等。

### 五、 保密期

除非甲方通过书面通知明确说明某项保密信息可以不用保密，乙方将按承诺对收到的保密信息进行保密。



合同编号:

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|

## 技术服务（委托）合同

项目名称: 变质岩破碎带初至波波形反演探测

方法测试

委托方（甲方）: 中国科学院

地质与地球物理研究所

受托方（乙方）: 中国石油大学（北京）

签订时间: 2025 年 9 月 1 日

签订地点: \_\_\_\_\_

有效期限: 2025 年 9 月 ~ 2025 年 12 月



中华人民共和国科学技术部印制

## 填写说明

一、 本合同为中华人民共和国科学技术部印制的技术开发（委托）合同示范文本，各技术合同登记机构可推介技术合同当事人参照使用。

二、 本合同书适用于一方当事人委托另一方当事人进行新技术、新产品、新工艺、新材料或者新品种及其系统的研究开发所订立的技术开发合同。

三、 签约一方为多个当事人的，可按各自在合同关系中的作用等，在“委托方”、“受托方”项下（增页）分别排列为共同委托人或共同受托人。

四、 本合同书未尽事项，可由当事人附页另行约定，并可作为本合同的组成部分。

五、 当事人使用本合同书时约定无需填写的条款，应在该条款处注明“无”等字样。

## 技术服务（委托）合同

委托方（甲方）：中国科学院地质与地球物理研究所

委托主体：深层油气理论与智能勘探开发重点实验室

住 所 地：北京市朝阳区北土城西路 19 号

法定代表人：底青云

项目联系人：李学良

联系方式

通讯地址：北京市朝阳区北土城西路 19 号

电 话：13701057885 邮 编：100029

电子信箱：lxl@mail.iggcas.ac.cn

受托方（乙方）：中国石油大学（北京）

住 所 地：北京市昌平区府学路 18 号

法定代表人：金钊（校长）

项目负责人：姚刚

研发团队成员

其中，校内在职人员：姚刚

校外人员（含学生）：刘能超，许琳，张平民

联系方式

通讯地址：北京市昌平区府学路 18 号

电 话：18201008231 邮 编：102249

电子信箱：yaogang@cup.edu.cn

本合同甲方委托乙方技术服务 变质岩破碎带初至波波形反演探测方法测试 项目，并支付技术服务经费和报酬。乙方接受委托并进行此项数据技术服务工作。双方经过平等协商，在真实、充分地表达各自意愿的基础上，根据《中华人民共和国民法典》及国家有关法律、法规，达成如下协议，并由双方共同恪守。

### **第一条** 本合同研究开发项目的要求如下：

1. 技术服务目标：本项目旨在针对变质岩区起伏地表复杂勘探条件下反射波成像困难，常规射线层析法获得的速度场分辨率低的问题，分析并评估一套基于初至波运动学和动力学特征的地球物理反演技术流程，以期获得高分辨的速度场，该速度场不仅可以直接用于变质岩区断层、破碎带等精细构造的识别，同时有助于反射波成像。

2. 技术服务方法和路线：该项目遵循“正演模拟-走时反演-波形反演”的递进式技术服务路线。首先，针对工区起伏地形开展波场模拟，验证正演模拟的可行性与准确性；然后，通过走时伴随层析反演构建宏观背景速度场；最后，基于全波形反演的算法框架，进行初至波波形反演，实现速度模型从背景到细节的迭代优化。最终，通过定量与定性分析相结合的方法，系统评估反演方法对变质岩破碎带结构的精细刻画能力。

**第二条** 乙方应在本合同生效后 10 日内向甲方提交技术服务计划。按照行业标准与规范保证技术服务的质量，技术服务主要内容如下：

1. 根据实际地表高程数据，构建速度模型，针对该工区起伏地表模型开展高精度地震波正演模拟工作；

2. 利用工区测线的初至走时数据开展伴随层析反演，获取低波数宏观背景场，构建长波长特征的速度模型；

3. 基于走时层析建立的背景速度模型开展初至波波形反演，针对变质岩破碎带发育形态和构造细节作进一步迭代更新。

### **第三条** 乙方应按下列进度完成研究工作：

1. 合同签订后3个月内根据实际高程坐标，构建起伏地表速度模型，



完成不规则地表的高精度正演模拟,为后期开展初至波波形反演的可行性和有效性提供分析;

2. 合同签订后3个月内完成两条测线实际数据的初至波射线层析建模,评估伴随层析构建的宏观速度模型的可靠性和有效性;

3. 合同签订后3个月内完成两条测线实际数据的初至波波形反演工作,得到更准确的速度模型,实现针对变质岩破碎带地下介质的精细刻画,正确描述变质岩破碎带的发育形态。

第四条 甲方应向乙方提供的技术资料及协作事项如下:

1. 技术资料清单: (1) 研究区炮点坐标及高程信息。 (2) 研究区检波点接收排列坐标及高程信息。 (3) 研究区两条测线对应的初至波原始数据。

2. 提供时间和方式: 按第三条计划进度提供相应资料。

本合同履行完毕后,上述技术资料按以下方式处理: 双方协商。

第五条 甲方应按以下方式支付研究开发经费和报酬:

1. 服务经费和报酬总额为 壹拾伍 万元 (150,000.00 RMB)。

详细收费标准如下:

| 服务内容                               | 名称   | 单位 | 数量 | 单价 (元)<br>含税 3% | 总价 (元)<br>含税 3% | 备注 |
|------------------------------------|------|----|----|-----------------|-----------------|----|
| 起伏地表<br>波场模拟                       | 技术服务 | 件  | 1  | 50000.00        | 50000.00        | /  |
| 伴随层析<br>反演                         | 技术服务 | 件  | 1  | 50000.00        | 50000.00        | /  |
| 初至波波形<br>反演                        | 技术服务 | 件  | 1  | 50000.00        | 50000.00        | /  |
| 总金额: 150000.00 (大写: 拾伍万元整) 含 3%增值税 |      |    |    |                 |                 |    |

2. 技术服务经费由甲方一次支付乙方。具体支付方式和时间如下:

(1) 乙方完成技术服务后, 服务内容经验收, 将结算单告知甲方后, 由乙方开具发票, 甲方以转账方式一次性支付乙方 15.00 万元, 付款

比例 100%。

**第六条** 本合同的研究开发经费由乙方以专款专用的方式使用。甲方有权以不定期的方式检查乙方进行研究开发工作和使用研究开发经费的情况，但不得妨碍乙方的正常工作。

**第七条** 本合同的变更必须由双方协商一致，并以书面形式确定。但有下列情形之一的，一方可以向另一方提出变更合同权利与义务的请求，另一方应当在5日内予以答复；逾期未予答复的，视为同意。

1. 一方出现设备故障、样品异常等突发因素，无法按期履行合同，由签约各方另行协商并做书面约定，作为本合同的变更文本；
2. 在此过程中，乙方提供的研发结果，甲方技术部门认为无法达到既定目标，可以随时提出暂停合作。

**第八条** 未经甲方同意，乙方不得将本合同项目部分或全部研究开发工作转让给第三人承担。

**第九条** 在本合同履行中，因出现在现有技术水平和条件下难以克服的技术困难，导致研究开发失败或部分失败，并造成一方或双方损失的，双方按如下约定承担风险损失：协商解决的方式认定。认定技术风险的基本内容应当包括技术风险的存在、范围、程度及损失大小等。认定技术风险的基本条件是：

1. 本合同项目在现有技术水平条件下具有足够的难度；
  2. 乙方在主观上无过错且经认定研究开发失败为合理的失败。
- 一方发现技术风险存在并有可能致使研究开发失败或部分失败的情形时，应当在10日内通知另一方并采取适当措施减少损失。逾期未通知并未采取适当措施而致使损失扩大的，应当就扩大的损失承担赔偿责任（赔偿额度不超过本合同的技术开发费）。

**第十条** 在本合同履行中，因作为研究开发标的技术已经由他人公开（包括以专利权方式公开），一方应在10日内通知另一方解除合同。逾期未通知并致使另一方产生损失的，另一方有权要求予以赔偿（赔偿额度不超过本合同的技术开发费）。

## 第十一条 乙方应当按以下方式向甲方交付技术服务成果：

1. 技术服务成果交付的形式及数量：起伏地表波场模拟数据 1 套、伴随层析反演建模数据 1 套、初至波波形反演数据 1 套和文字报告 1 套。
2. 技术服务成果交付的时间及地点：按计划提交。

**第十二条** 双方确定，按以下标准及方法对乙方完成的研究开发成果进行验收：按照第一条、第四条中规定的技术目标和技术内容进行验收，甲方验收确认后再进行约定款项支付。

**第十三条** 乙方应当保证其交付给甲方的研究开发成果不侵犯任何第三人的合法权益。如发生第三人指控甲方实施的技术侵权的，乙方应当主动向第三方披露该技术系由乙方研制开发的事实，并协助甲方就此项目进行法律诉讼，若败诉，返还甲方已付研发费用。

**第十四条** 双方确定，因履行本合同所产生的研究开发成果及其相关知识产权权利归属，按下列第 1 种方式处理：

1. 双 （甲、双） 方享有申请专利的权利。

专利权取得后的使用和有关利益分配方式如下：因本合同产生的专利申请权及专利权归甲方所有，如乙方需要相关资料用于其他用途，应提前与甲方确认，获得 同意使用范围后方可。

2. 按技术秘密方式处理。有关使用和转让的权利归属及由此产生的利益按以下约定处理：

（1）技术秘密的使用权：使用权人为甲方。

（2）技术秘密的转让权：转让权人为甲方。

（3）相关利益的分配办法：双方协商沟通，甲方为利益分配方法的最 终决定者。

双方对本合同有关的知识产权权利归属特别约定如下：本合同产生的相关科学数据和实物资料，其成果与知识产权归甲乙双方共有。五年内，甲方享有数据成果发布权，乙方及其工作人员享有署名权、获得奖励权利以及数据成果的再利用权利；五年期满后，双方享有同等权利，乙方有权自行使用数据结果，不需经得甲方同意。



**第十五条** 数据成果涉密的，根据《中华人民共和国保密法》的规定，由双方共同承担保密责任。

**第十六条** 乙方不得在向甲方交付研究开发成果之前，自行将研究开发成果转让给第三人。

**第十七条** 乙方完成本合同项目的研究开发人员享有在有关技术成果文件上写明技术成果完成者的权利和取得有关荣誉证书、奖励的权利。

**第十八条** 乙方利用研究开发经费所购置与研究开发工作有关的设备、器材、资料等财产，归乙（甲、乙、双）方所有。

**第十九条** 双方确定：任何一方违反本合同约定，造成研究开发工作停滞、延误或失败的，按以下约定承担违约责任：

1. 违反本合同约定，违约方应当按照《中华人民共和国民法典》有关条款的规定承担违约责任。

**第二十条** 双方确定，甲方有权利用乙方按照本合同约定提供的研究开发成果，进行后续改进。由此产生的具有实质性或创造性技术进步特征的新的技术成果及其权利归属，由甲（甲、乙、双）方享有。具体相关利益的分配办法如下：双方协商沟通，甲方为利益分配方法的最最终定者。

乙方有权在完成本合同约定的研究开发工作后，利用该项研究开发成果进行后续改进。由此产生的具有实质性或创造性技术进步特征新的技术成果，归乙（甲、乙、双）方所有。具体相关利益的分配办法如下：双方协商沟通，乙方为利益分配方法的最最终定者。

双方的权利和义务：甲方为乙方提供必要的原始资料（包括样品等）；乙方应按照合同约定完成技术服务后及时向甲方提供相关数据和结果报告等材料；甲方应按照合同约定及时将技术服务费用支付给乙方。

**第二十一条** 双方确定，在本合同有效期内，甲方指定李学良为甲方项目联系人，联系电话：13701057885，电子邮箱：lxl@mail.iggcas.ac.cn；乙方指定姚刚为乙方项目联系人，联系电话：18201008231，电子邮箱：yaogang@cup.edu.cn。双方往来电子邮箱视为



本合同的组成部分。项目联系人承担以下责任：

1. 负责项目进度跟踪

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2. 负责项目结题验收

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一方变更项目联系人的，应当在七日内以书面形式通知另一方。未及时通知并影响本合同履行或造成损失的，应承担相应的责任（赔偿额度不超过本合同的技术开发费）。

**第二十二条** 双方确定，因发生不可抗力或技术风险致使本合同的履行成为不必要或不可能的，一方可以通知另一方解除本合同。

**第二十三条** 双方因履行本合同而发生的争议，应协商、调解解决。协商、调解不成的，可申请北京仲裁委员会仲裁。。

**第二十四条** 违反本合同约定，违约方应当按照《中华人民共和国合同法》有关条款的规定承担违约责任。

**第二十五条** 本合同一式肆份，双方各执两份，具有同等法律效力。

**第二十六条** 本合同经双方签字盖章后生效。双方履行各自权利和义务后，本合同自然终止。

**第二十七条** 本合同未尽事宜，经双方协商一致，可签订补充协议。补充协议也是合同的组成部分。

# 技术服务合同签字（盖章）页

|             |             |                      |                                                                                                           |
|-------------|-------------|----------------------|-----------------------------------------------------------------------------------------------------------|
| 委托人<br>(甲方) | 单位名称        | 中国科学院地质与地球物理研究所      | 技术服务合同章<br>或单位公章<br><br> |
|             | 法定代表人或委托代理人 | 底青云                  |                                                                                                           |
|             | 委托主体        | 深层油气理论与智能勘探开发重点实验室   |                                                                                                           |
|             | 负责人或联系人     | 李学良                  |                                                                                                           |
|             | 通讯地址        | 北京市朝阳区北土城西路 19 号     |                                                                                                           |
|             | 邮政编码        | 100029               |                                                                                                           |
|             | 联系电话        | 13701057885          |                                                                                                           |
|             | 开户银行        | 中国农业银行北京健德支行         |                                                                                                           |
|             | 账号          | 111909010400000456   |                                                                                                           |
|             | 税号          | 12100000400002734J   |                                                                                                           |
| 受托人<br>(乙方) | 单位名称        | 中国石油大学（北京）           | 技术服务合同章<br>或单位公章<br><br>乙方代表（签字）<br><br>年 月 日                                                             |
|             | 法定代表人或委托代理人 | 金衍                   |                                                                                                           |
|             | 受托主体        | 油气资源与工程全国重点实验室       |                                                                                                           |
|             | 负责人或联系人     | 姚刚                   |                                                                                                           |
|             | 通讯地址        | 北京市昌平区府学路 18 号       |                                                                                                           |
|             | 邮政编码        | 102249               |                                                                                                           |
|             | 联系电话        | 18201008231          |                                                                                                           |
|             | 开户银行        | 中国建设银行北京昌平支行         |                                                                                                           |
|             | 账号          | 11001009200056050532 |                                                                                                           |
|             | 税号          | 12100000400006110Y   |                                                                                                           |

注：本页请勿跨页。

印花税票粘贴处：

\_\_\_\_\_  
(以下由技术合同登记机构填写)

合同登记编号：

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1. 申请登记人：\_\_\_\_\_

2. 登记材料：(1) \_\_\_\_\_

(2) \_\_\_\_\_

(3) \_\_\_\_\_

3. 合同类型：\_\_\_\_\_

4. 合同交易额：\_\_\_\_\_

5. 技术交易额：\_\_\_\_\_

技术合同登记机构（印章）

经办人：

年 月 日

# 国家自然科学基金资助项目批准通知

## (预算制项目)

姚刚 先生/女士:

根据《国家自然科学基金条例》、相关项目管理办法规定和专家评审意见，国家自然科学基金委员会（以下简称自然科学基金委）决定资助您申请的项目。项目批准号：U23B20159，项目名称：全波形地震成像与弹性参数同步反演理论及核心算法研究，直接费用：259.00万元，项目起止年月：2024年01月至 2027年 12月，有关项目的评审意见及修改意见附后。

请您尽快登录自然科学基金网络信息系统 (<https://grants.nsf.gov.cn>)，认真阅读《国家自然科学基金资助项目计划书填报说明》并按要求填写《国家自然科学基金资助项目计划书》（以下简称计划书）。对于有修改意见的项目，请您按修改意见及时调整计划书相关内容；如您对修改意见有异议，须在电子版计划书报送截止日期前向相关科学处提出。

请您将电子版计划书通过自然科学基金网络信息系统 (<https://grants.nsf.gov.cn>) 提交，由依托单位审核后提交至自然科学基金委。自然科学基金委审核未通过者，将退回的电子版计划书修改后再行提交；审核通过者，打印纸质版计划书（一式两份，双面打印）并在项目负责人承诺栏签字，由依托单位科研、财务管理等部门审核、签章并在承诺栏加盖依托单位公章，且将申请书纸质签字盖章页订在其中一份计划书之后，一并报送至自然科学基金委项目材料接收工作组。纸质版计划书应当保证与审核通过的电子版计划书内容一致。**自然科学基金委将对申请书纸质签字盖章页进行审核，对存在问题的，允许依托单位进行一次修改或补齐。**

向自然科学基金委提交电子版计划书、报送纸质版计划书并补交申请书纸质签字盖章页截止时间节点如下：

1. **2023年12月06日16点**: 提交电子版计划书的截止时间；
2. **2023年12月13日16点**: 提交修改后电子版计划书的截止时间；
3. **2023年12月20日**: 报送纸质版计划书（一式两份，其中一份包含申请书纸质签字盖章页）的截止时间。



请按照以上规定及时提交电子版计划书，并报送纸质版计划书和申请书纸质签字盖章页，逾期不报计划书或申请书纸质签字盖章页且未说明理由的，视为自动放弃受资助；未按要求修改或逾期提交申请书纸质签字盖章页者，将视情况给予暂缓拨付经费等处理。

附件：项目评审意见及修改意见表

国家自然科学基金委员会

2023年11月26日

附件：项目评审意见及修改意见表

|       |                           |       |      |                     |       |
|-------|---------------------------|-------|------|---------------------|-------|
| 项目批准号 | U23B20159                 | 项目负责人 | 姚刚   | 申请代码1               | D0408 |
| 项目名称  | 全波形地震成像与弹性参数同步反演理论及核心算法研究 |       |      |                     |       |
| 资助类别  | 联合基金项目                    |       | 亚类说明 | 重点支持项目              |       |
| 附注说明  | 企业创新发展联合基金                |       |      |                     |       |
| 依托单位  | 中国石油大学（北京）                |       |      |                     |       |
| 直接费用  | 259.00 万元                 |       | 起止年月 | 2024年01月 至 2027年12月 |       |

通讯评审意见：

<1>该项目拟开展全波形地震成像与弹性参数同步反演的理论与核心算法研究，该项研究是工业界和学术界共同聚焦的热点领域，具有重要的科学研究意义和应用前景。申请人提炼的科学问题明确，研究方案有创新的学术思想。项目的总体研究方案合理、可行。申请人多年从事该领域的研究，活跃在科学研究的前沿，有良好的工作基础和研究条件。项目研究队伍结构合理。

<2>本项目拟解决的关键科学问题明确，包括复杂介质中地震波传播过程的准确模拟、弱敏感介质参数全波形建模、以及复杂介质中多波耦合条件下的高精度成像，具体突出的创新性学术思想。落实了与之密切相关的研究内容和目标，包括起伏地表粘弹各向异性波场高精度模拟、各向异性介质多参数全波形反演、以及粘弹各向异性介质纵横波偏移成像，实现复杂地表、衰减和速度都为各向异性的弹性波场模拟，发展面波、透射波和反射波全波形反演，形成系统的参数反演方法和流程，多波多分量数据逆时偏移的高精度成像。

申请人近5年负责承担过国家自然科学基金面上项目1项；代表性论著中发表本专业国际顶级重要期刊等代表性论文第一作者4篇，以及国内SCI期刊论文第一作者1篇；获得了省部级个人奖1项、本专业国际顶级会议最佳论文奖1篇，国家发明专利5件；具有较高的学术水平、较强的组织能力及团队协作能力，主要参与者主要是中青年技术骨干，具有结构合理的研究队伍和扎实的研究工作基础。如获得资助，本项目的预期研究工作可望取得突破性进展，获得显著的实际应用效果。经费预算合理，包括适当比例的设备费、材料费、测试加工费、燃料动力费、学术交流费、知识产权费、劳务费和专家费。

该项目创新性强，有重要科学研究价值和应用前景，总体研究方案合理可行，具备良好的工作基础和研究条件。建议给予优先立项和优先资助。

<3>基于目前丰富的多波多分量地震数据，弹性波全波形地震成像及反演已经成为学界的研究热点，具有重要的科学意义和应用前景。本项目科学问题明确，围绕粘弹地表各向异性模拟、各向异性介质多参数全波形反演、粘弹各向异性纵/横波偏移成像等几个关键环节开展研究，形成对复杂地表多波地震数据直接进行全波形反演及成像的技术体系，具有很强的创新性。拟采用的研究方案和技术路线合理，重点突出。研究团队为院校与企业联合团队，具备良好的工作基础和研究条件。建议优先资助。

<4>申请项目聚焦全波形地震成像和弹性参数同步反演理论及算法研究，提炼出如下三个拟研究的科学问题：（1）起伏地表粘弹各向异性波场高精度模拟，（2）各向异性介质多参数全波形反演，（3）粘弹各项异性介质纵横波偏移成像。针对上述三个科学问题，申请人提出了创新性的学术思想和技术方案，拟实现如下的研究目标：（1）解决起伏地表各向异性粘弹介质波场模拟的精度和效率问题，实现起伏地表粘弹介质高精度和高效率的波场模拟；（2）实现基于深度学习的地质信息约束的各向异性弹性介质多参数全波形反演；（3）实现粘弹各向异性介质中纵横波解耦及逆时偏移。申请项目聚焦地震勘探领域的痛点和难点，基础理论与应用研究相结合，拟解决的科学问题明确，预期研究成果对我国油气地震勘探领域具有重要的应用价值，有望推动新一代地震采集技术落地应用并提升油气勘探的精度和效率。申请人及其团队就该申请项目的研究内容前期已经开展了相关研究并取得了相应的研究成果，为本项目的开展打下了理论基础；此外，申请人所在单位及企业合作单位具有完备的硬件设施，可以有效保障该申请项目的顺利开展。

申请项目的主持人具有正高级职称，在国外知名高校取得博士学位并在多所知名高校开

展博士后研究，于2019年入选国家级人才计划青年项目；项目主持人具有较高的学术水平并长期活跃在科学研究前沿，目前已在Geophysics等国际知名勘探地球物理领域期刊发表数十篇高水平科研文章，其中在最小二乘逆时偏移和全波形反演领域的研究成果得到了国际勘探地球物理学界的广泛关注。申请项目的研究团队共25人，其中包括高级职称4人，中级职称2人，博士研究生及本科生共计19人，申请研究团队规模适中，结构合理。申请团队成员前期就申请项目相关的研究内容已经开展了预研研究并取得了较好的学术成果，为该申报项目的顺利开展实施打下了扎实的基础。

申请项目的预期研究工作主要包含三个方面：（1）起伏地表粘弹各向异性波场高精度模拟，（2）各向异性介质多参数全波形反演，（3）粘弹各项异性介质纵横波偏移成像。目前，项目申请人及其研究团队在上述三个研究方向均做了扎实的预研研究并取得了较好的学术成果，为上述三项研究内容的开展奠定了坚实的理论基础。申请项目依托单位及企业合作单位完备的硬件设施及实验设备为上述三项研究内容的开展奠定了硬件基础，能够确保上述研究顺利开展。此外，企业合作单位的野外观测数据为本项目的最终测试提供了测试平台。申请项目主持人已承担或参与了多个国家自然科学基金面上项目和科技部重点研发项目课题，具备丰富的项目管理经验，可以确保项目的顺利开展实施。

申请项目预算资金总额为270万，其中包含设备费35万，业务费122.2万，劳务费112.8万。预算总额及各项预算均有严格的测算依据，清楚了；相关预算紧扣申报项目所涉及的研究内容，预算合理。

<5>项目拟发展与多波多分量地震采集技术配套的粘弹各向异性介质波场模拟、全波形地震成像和多参数同步反演理论及核心技术，推动新一代地震采集技术的落地应用，提升油气勘探的精度和效率。研究涉及的多参数半全局反演、多波信息全波形反演、地质信息约束反演是提高地震反演稳定性的创新方案。项目依托中国石油大学(北京)的油气资源与探测国家重点实验室和中国石油天然气集团有限公司物探重点实验室，实验室拥有200亿次/秒运算速度的服务器和多套地震数据处理和建模软件，能满足项目研究的计算需求。申请人曾在海外学习工作多年，是“青年千人计划”入选者，发表高级别学术论文多篇，主持过国家级项目，具有较高的学术水平。团队成员在地震波成像、反演方向积累了丰硕的研究成果，与多所国外著名高校保持的合作关系能为项目开展提供技术支持。预期成果能提高我国油气勘探理论的创新水平，推动勘探地球物理学科发展和技术进步。预算说明书与项目的研究内容和目标适应，有明确的分类和详细的计算过程，经费预算合理。

修改意见：

地球科学部

2023年11月26日