Magnetic tilt angle: a simple depth estimation method for underground pipelines

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Summary

Underground pipeline detections before municipal constructions are of great significance to the modernization of urban planning and management. The main task of underground pipeline magnetic surveys is to identify anomalies contained within the total magnetic field and obtain estimations of the planimetric position and depth of the pipeline causing the anomalies. We apply a simple and fast method, magnetic tilt angle, to estimate the spatial location and depth of underground pipelines. Simulation results show that the 90° contour of the magnetic tilt angle map delineates the planimetric position of an underground pipeline whilst the depth to the pipeline is the distance between the 90° and the 0° contours. In parallel pipeline detections, the magnetic anomalies produced by the deeper pipeline are also swamped in the large anomalies produced by the shallower pipeline. Further research results show that the magnetic tilt angle can obtain the accurate estimations of the planimetric position and depth of the shallower pipeline with any ratio of the axis spacing to the total depth of parallel pipelines, but only when the ratio is greater than 1.4 can it obtain the accurate estimations of the planimetric position and depth of the deeper pipeline.

Introduction

It has great significance for the modernization of urban planning and management to understand the status quo of underground pipelines and reduce pipeline accidents caused by external forces. In recent years, ground precision magnetic surveys have attracted much attention in underground pipeline detections due to the high accuracy, flexible work mode and low cost. The main task of underground pipeline magnetic surveys is to identify anomalies contained within the total magnetic field and obtain estimates of the planimetric position and depth of the pipeline causing the anomalies.

Several methods have been developed that provide the depth to magnetic sources. Nabighian (1972) first proposed the analytic signal of magnetic anomalies and estimated the depth according to eigenvalue positions of the anomalies. Only given the type of magnetic sources can the analytic signal obtain the accurate estimate of the depth. Thompson (1982) proposed Euler deconvolution method, which can obtain the accurate estimates of the planimetric position and depth with the given structural index of target bodies. However, the structural index related to the type of magnetic sources is usually unknown and the same magnetic source has different structural indexes at different depths. The wrong structural indexes can lead to large inversion errors. In order to solve this problem, many scholars have improved the above-mentioned methods (Keating et al., 2004; Salem et al., 2005; Zhou et al., 2016). These improved methods do not need the prior information of structural indexes of target magnetic bodies, but the calculation is complex and the accuracy is low.

In this paper, we apply a simple and fast method, magnetic tilt angle, to obtain estimates of the planimetric position and depth of underground pipelines. The magnetic tilt angle is a normalized derivative based on the ratio of the vertical and horizontal of the magnetic field. This method provides an intuitive means of understanding the variation in planimetric position and depth of underground pipelines. It main advantage of the magnetic tilt angle is the additional attribute of responding equally as well to shallow and to deep pipelines and is, therefore, able to resolve the presence of subtle deeper pipelines which are often swamped in the large responses of shallower pipelines in parallel pipeline detections. However, the magnetic tilt angle method has a drawback is that it is valid only for magnetic anomalies that has been reduced-to-the-pole.

Method

The tilt angle first described by Miller and Singh (1994) and defined as

$$\theta = \tan^{-1}\left(\frac{\frac{\partial U}{\partial z}}{\sqrt{\left(\frac{\partial U}{\partial x}\right)^2+\left(\frac{\partial U}{\partial y}\right)^2}}\right) \tag{1}$$

where $\frac{\partial U}{\partial x}, \frac{\partial U}{\partial y}, \frac{\partial U}{\partial z}$

are first-order derivatives of the magnetic field U in the x, y, and z directions. Due to the nature of the arctan trigonometric function, all tilt amplitudes are restricted to values between -90° and +90° regardless of the amplitude of the vertical or the absolute value of the total horizontal gradient.

The general expressions given by Li (2012) for the vertical and horizontal derivatives of the magnetic field over an infinite horizontal cylinder are

$$\left.\begin{aligned}\frac{\partial U}{\partial z} &= \frac{\mu_0 S\left\{M_z\left(\Delta z^2-\Delta x^2\right)+2M_x\Delta x\Delta z\right\}}{2\pi\left(\Delta x^2+\Delta z^2\right)^2}\\ \frac{\partial U}{\partial x} &= \frac{\mu_0 S\left\{M_x\left(\Delta x^2-\Delta z^2\right)+2M_z\Delta x\Delta z\right\}}{2\pi\left(\Delta x^2+\Delta z^2\right)^2}\\ \frac{\partial U}{\partial y} &= 0\end{aligned}\right\} \tag{2}$$

where μ_0 is the permeability of vacuum, S is the cross-section area of the cylinder, M_x=$M_s$cosi_s, M_z=$M_s$sini_s, M_s is the effective magnetization, i_s the effective magnetic inclination, Δx and Δz are the distances from the current measurement point to the cylinder. Setting m_s=SM_s to be the effective magnetic moment per unit length, we get

$$\left.\begin{aligned}\frac{\partial U}{\partial z}&=\frac{\mu_0 m_s}{2\pi}\frac{1}{\left(\Delta x^2+\Delta z^2\right)^2}\left[\left(\Delta z^2-\Delta x^2\right)\sin i_s+2\Delta x\Delta z\cos i_s\right]\\ \frac{\partial U}{\partial x}&=-\frac{\mu_0 m_s}{2\pi}\frac{1}{\left(\Delta x^2+\Delta z^2\right)^2}\left[\left(\Delta z^2-\Delta x^2\right)\cos i_s+2\Delta x\Delta z\sin i_s\right]\end{aligned}\right\}(3)$$

If the cylinder was vertically magnetized (i.e., i_s=90°), then Equation 3 reduces to

$$\left.\begin{aligned}\frac{\partial U}{\partial z}&=\frac{\mu_0 m_s\left(\Delta z^2-\Delta x^2\right)}{2\pi\left(\Delta x^2+\Delta z^2\right)^2}\\ \frac{\partial U}{\partial x}&=\frac{-\mu_0 m_s\bullet}{2\pi\left(\Delta x^2+\Delta z^2\right)^2}\end{aligned}\right\} \qquad (4)$$

Substituting Equation (4) into Equation (1), we get

$$\theta=\tan^{-1}\left(\frac{\Delta z^2-\Delta x^2}{\left|2\Delta x\Delta z\right|}\right) \qquad (5)$$

The 90° value (Δx=0) of the magnetic tilt angle delineates the planimetric position of the cylinder whilst the depth to the cylinder is the distance between the 90° and the 0° values (Δx=Δz).

Examples

When the length is much longer than the buried depth for an underground pipeline, it can be regarded as an infinite horizontal cylinder. Figure 1 shows the magnetic anomaly observation system of an underground pipeline. The anomalies were calculated as an east-west profile across a north-south striking pipeline. The national standard CJJ 61-2003, "Technical specification for detecting and surveying underground pipelines and cable in city", stipulates that the planimetric position and buried depth errors of underground pipeline detections shall not exceed 0.1h and 0.15h respectively (h is the buried depth of the underground pipeline. When h<100cm, replace h with 100cm).

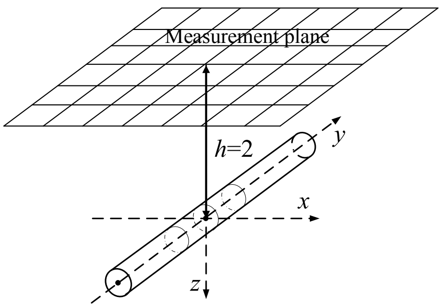


Figure 1: The magnetic anomaly observation system of an underground pipeline. The center of the pipeline location at (0,0,2). The length, external diameter and wall thickness of the pipeline were 50m, 0.3m and 0.01m. The susceptibility of the pipeline was 10SI unite. The geomagnetic intensity, inclination and declination were 55000nT, 90°, and 0°.

The horizontal derivative is zero over the pipeline as indicated in Figure 2(a). The vertical derivative peak over the pipeline as indicated in Figure 2(b). Neither of them could provied information about the depth of the pipeline. In Figure 2(c) and (d), the 90° value (Δx=0) of the magnetic tilt angle delineates the planimetric position of the pipeline as (0,0) whilst the depth to the pipeline is the distance between the 90° and the 0° values (Δx=Δz), which is 2m. Both the planimetric position and buried depth errors are 0, satisfying the detection precision.

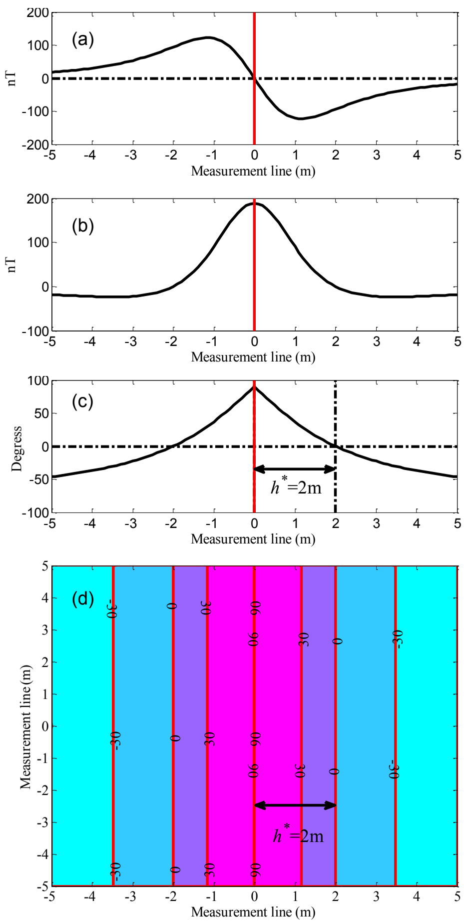


Figure 2: (a) (b) Profiles of the horizontal and vertical derivatives of the magnetic field produced by the pipeline in Figure 1. (c) The profile of the magnetic tilt angle θ of the data from Figure 2(a) and (b). Red solid lines show the true planimetric position of the pipeline in Figure 1. Black dashed lines are values of the magnetic tilt angle for 0° and 90°. (d) The magnetic tilt angle map.

Figure 3 shows the magnetic anomaly observation system of parallel pipelines.

It can be seen from Figure 4(a) and (b) that the magnetic anomalies produced by the deeper pipeline are swamped in the large anomalies produced by the shallower pipeline. In Figure 4(c) and (d), the 90° values (Δx=0) of the magnetic tilt angle delineate the planimetric positions of the parallel pipelines in figure 3 as (-2,0) and (1,0) whilst the depths to the parallel pipelines are the distance between the 90° and the 0° values (Δx=Δz), which are 1m and 3.1m respectively. Both the planimetric position and buried depth errors of the shallower pipeline are 0, satisfying the detection precision. The buried depth error of the deeper pipeline is 0.1, satisfying the detection precision (less than 0.15h), but the planimetric position error of the deeper pipeline is 1, not satisfying the detection precision (greater than 0.1h).

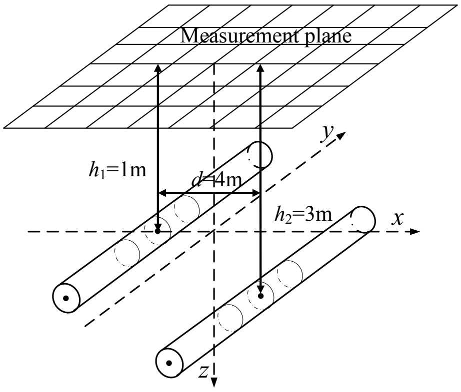


Figure 3: The magnetic anomaly observation system of parallel pipelines. Centers of the parallel pipelines location at (-2,0,1) and (2,0,3). Other parameter values are equal to those of the pipeline in Figure 1.

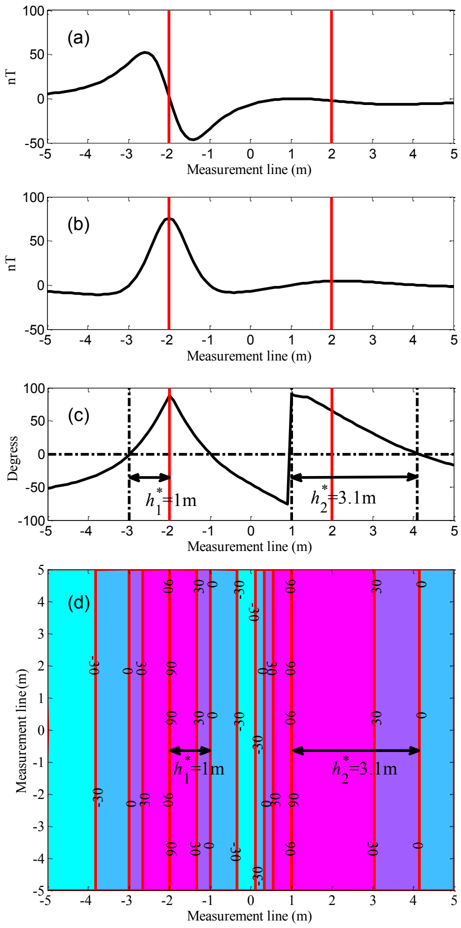
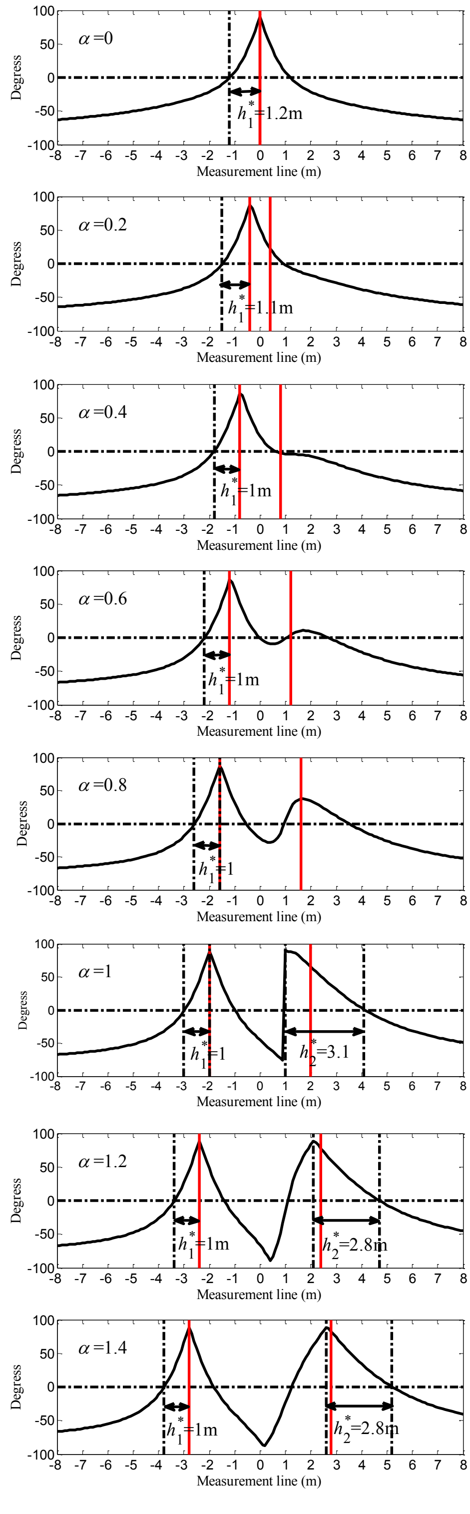


Figure 4: (a) (b) Profiles of the horizontal and vertical derivatives of the magnetic field produced by the parallel pipelines in Figure 3. (c) The profile of the magnetic tilt angle θ of the data from Figure 4(a) and (b). Red solid lines show the true planimetric position of the parallel pipelines in Figure 3. Black dashed lines are values of the magnetic tilt angle for 0° and 90°. (d) The magnetic tilt angle map.

The total depth of the parallel pipelines in Figure 3 is defined as h=h_2+h_1. The ratio α of the axis spacing d to the total depth h is defined as

$$\alpha = \frac{d}{h} \tag{6}$$

We keep the depths of the parallel pipelines in Figure 3 unchanged and increase the ratio α from 0 to 1.6 at an interval of 0.2. Profiles of the magnetic tilt angle θ of each ratio α are shown in Figure 5. Research results show that the magnetic tilt angle can obtain the accurate estimations of the planimetric position and depth of the shallower pipeline with any ratio α, but only when the ratio α is greater than 1.4 can it obtain the accurate estimations of the planimetric position and depth of the deeper pipeline.



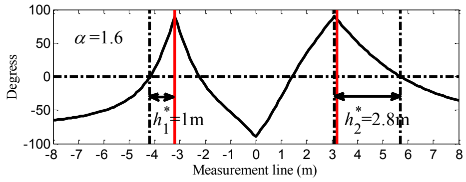


Figure 5: Profiles of the magnetic tilt angle θ of each ratio α. Red solid lines show the true planimetric position of the parallel pipelines with different ratios α in Figure 3. Black dashed lines are values of the magnetic tilt angle θ for 0° and 90°.

Conclusions

We apply a simple and fast method, magnetic tilt angle, to obtain estimations of the planimetric position and depth of underground pipelines. Simulation results show that the 90° contour of the magnetic tilt angle map delineates the planimetric position of an underground pipeline whilst the depth to the pipeline is the distance between the 90° and the 0° contours. In parallel pipeline detections, the magnetic anomalies produced by the deeper pipeline are also swamped in the large anomalies produced by the shallower pipeline. Further research results show that the magnetic tilt angle can obtain the accurate estimations of the planimetric position and depth of the shallower pipeline with any ratio of the axis spacing to the total depth of parallel pipelines, but only when the ratio is greater than 1.4 can it obtain the accurate estimations of the planimetric position and depth of the deeper pipeline. However, the magnetic tilt angle method has a drawback is that it is valid only for magnetic anomalies that has been reduced-to-the-pole.

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