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Modeling and analysis of a catastrophic oil spill and vapor cloud explosion in a confined space upon oil pipeline leaking

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Abstract
Oil spill-induced vapor cloud explosions in a confined space can cause catastrophic consequences. In this work, investigation was conducted on the catastrophic pipeline leak, oil spill, and the resulting vapor cloud explosion accident occurring in China in 2013 by modeling analysis, field surveys, and numerical simulations. The total amount of the spilled oil was up to 2044.4 m^3 due to improper disposal. The long residence time of the oil remaining in a confined space permitted the formation of explosive mixtures and caused the vapor cloud explosion. A numerical model was developed to estimate the consequence of the explosion based on volatilization testing results. The results show that the death-leading zone and the glass-breaking zone could be 18 m and 92 m, respectively, which are consistent with the field investigation. The severity of the explosion is related to the amount of the oil spill, properties of oil, and volatilization time. It is recommended that a comprehensive risk assessment be conducted to analyze the possible consequences upon oil spilling into a confined space. Prompt collection and ventilation measures should be taken immediately after the spill occurs to reduce the time for oil volatilization and prevent the mixture from reaching its explosive limit.

Keywords Pipeline leaking · Oil spill · Vapor cloud explosion · Confined space · Consequence analysis

1 Introduction

Catastrophic accidents induced by pipeline failures have been paid wide attention due to the lethal consequence, environmental impact, ecological damage, and energy loss (Cheng 2016; Naik and Kiran 2018; Hansen and Kjellander 2016). On November 22, 2013, an oil pipeline operated by Sinopec in Qingdao, China leaked, causing a great amount of oil spill into a municipal drainage. A catastrophic explosion followed, killing 62 people and injuring 136. The accident was attributed to the generation of explosive mixtures in a closed space and the vapor cloud explosion (VCE) caused by inappropriate emergency-control actions (State Administration of Work Safety of China 2014). The pipeline safety soon became a national concern.

Accidents caused by pipeline leakage have motivated the technology development to detect and locate leakages and evaluate the severity of the accidents (Wang and Ye 2010). These include the model-based, signal processing-based, and pattern recognition-based leak detection techniques. According to analysis of the performance of various techniques including pulse-echo method, acoustic technique, negative pressure wave system, support vector machine (SVM), interferometric fiber sensors, and filter diagonalization method (FDM), it was found that the acoustic reflectometry provided the most suitable method for leak detection of oil, gas, and water pipelines (Datta and Sarkar 2016). The viscoelasticity analysis of the pipe wall and its effect on detection and sizing of leaks were discussed (Lazhar et al. 2013). A parameterized transient model was established to locate multiple leaks in a pipeline based on changes in fluid flow and the operating pressure (Verde et al. 2014). Major efforts have also been made to develop techniques for leakage location in pipeline systems (Sandberg et al. 1989; Fukushima et al. 2000; Tian et al. 2016; Ge et al. 2008). Particularly, model-based leak

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detection methods have been regarded as the most appropriate and applicable for analyzing the amount of oil leakage. Relevant software has been developed for the practical application (Mylapilli et al. 2015).

When oil spill occurs, one of the factors affecting the resulting hazard is the environment where the accident happens. In an open space, the potential hazards such as pool fires, jet fires, and flash fires may happen. The terrain around the leakage point and the weather conditions also affect the consequences (Mylapilli et al. 2015). In relatively closed spaces, VCE is the most serious hazard. The severity of VCE is closely related to factors such as the chemical properties of the leaked fluid, release mode, time, and the amount of hydrocarbons involved (Koshy et al. 1995). It was found (Fingas 1997, 1998; Alkhaledi et al. 2015) that most types of oil evaporated at a logarithmic rate as a function of time, which was attributed to the overall logarithmic function of the oil components evaporating at different rates. The dense vapor dispersion under very low wind speed conditions can lead to VCE that causes serious casualties (BMIIB 2006; Johnson 2010; Hailwood et al. 2010). A large release of gasoline and the formation of vapor cloud was the main reason of the severe Jaipur accident (MoPNG 2009; Sharma et al. 2013). It was estimated that the explosion caused considerable glass breakages at distances up to 2 km. Parameters for VCE measurements and guidance for analysis of VCE accidents were proposed (CCPS 2000; NFPA 2004).

While great efforts have been made in prevention and control of VCE induced by pipeline leakage and oil spill in confined spaces, the proper methodology and consequence analysis are specific to the reality of the accident. This work investigated the root cause and consequence of the VCE occurring in Qingdao oil spill accident and the emergency response. A model was developed to quantitatively determine the amount of the spilled oil. The mechanisms resulting in the accident were discussed, and the lessons learned from the accident were imparted for improved pipeline safety.

2 Accident background

According to the investigation report on Qingdao pipeline leakage accident issued by the State Administration of Work Safety of China (2014), the whole process of the accident is schematically shown in Fig. 1, where three stages are included, i.e., oil spill-induced pipeline shutdown, reporting of the spill, and emergency response. The oil spill lasted over 1 h from its occurrence to shutdown of the valve. The accident reporting process spent 2.3 h, and the spill information was submitted to the control center of Sinopec. The emergency response process took 7.2 h from the moment when the emergency response was triggered until it was realized that more support was required for emergency maintenance. After 8.2 h of the occurrence of oil spill, the catastrophic explosion occurred.

Figure 2 shows the scene photographs of the accident. It is obvious that the explosion caused big damages to the adjacent buildings, roads, and public structures. Moreover, the explosion, combustion, and the shock wave caused injuries and deaths of workers, pedestrians, and residents. The total affected zone spread nearly 5 km.

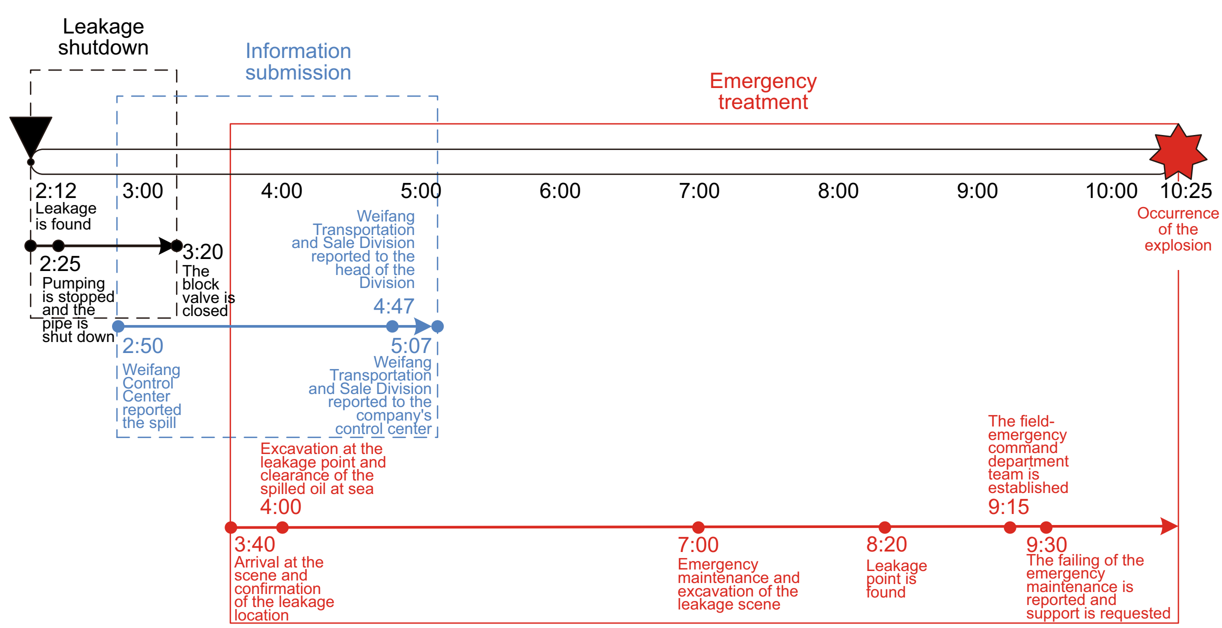

Fig. 1 Schematic diagram of the Qingdao pipeline leakage and oil spill accident, including the emergency response process

Fig. 2 Scene photographs of the explosion site **a** bird view of the location of the explosion point, **b** scene of the oil spill point after explosion, **c** scene of the nearby street, **d** scene of the drainage of the adjacent plant

3 Numerical investigation and results

3.1 The amount of spilled oil

3.1.1 Pipeline operating conditions

The oil pipeline spans from Huangdao Oil Depot to Dongying Station, with a total length of 248 km. The pipe diameter is 711 mm. The oil volume transported under the normal condition is 1308 m^3/h. The input pressures at two oil stations are 4.56 MPa and 3.63 MPa, respectively, while the output pressure is 2.78 MPa only. The discharge pressure at Huangdao station, where the oil spill occurred, is approximately 4.56 MPa. It dropped to 4.52 MPa when the oil spill occurred. The variations of the discharge pressure at Huangdao Station before and after shutting the pump off are shown in Fig. 3.

The variations of the inlet pressures of the Jiaozhou and Changyi stations, the two stations are located hundreds of kilometers away from the spill site, before and after shutting the pump off, are shown in Fig. 4. It is seen that there were slight drops of the inlet pressure at the two stations when the oil spill occurred. However, when the pump was shut off, the pressure dropped rapidly.

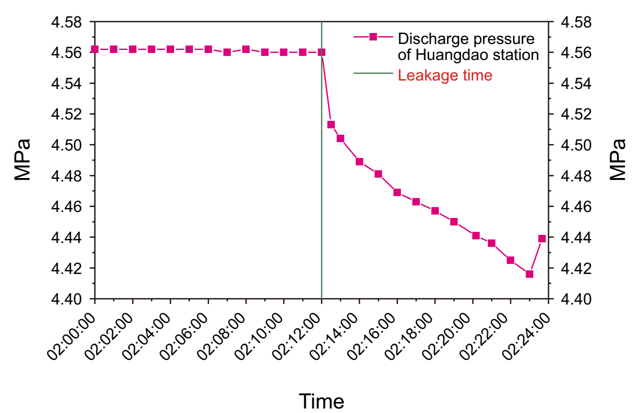

Fig. 3 Variation of the discharge pressure at Huangdao station before and after the oil spill

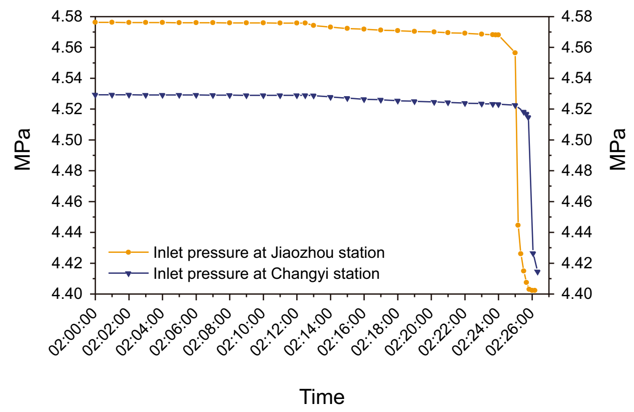

Fig. 4 Variations of the inlet pressures at Jiaozhou and Changyi stations before and after the oil spill

3.1.2 Numerical calculations

To determine numerically the amount of the spilled oil, the entire spilling process is divided into three stages, as shown in Fig. 5. It is noted that, in stage 3, although the pump was shutdown and the upstream valve was shut off, the residual oil in the pipe was still leaking until the explosion happened. Moreover, as the pipeline was constructed several decades ago, there were no flow meters installed on the pipeline. The catastrophic explosion made the pipeline leakage impossible to determine. Thus, it was not able to directly measure the size of the spill leak.

Figure 6 shows the procedure to numerically simulate the pipeline leakage in order to calculate the amount of the spilled oil. First, the size of the leaking hole in the pipe was determined. The amount of the spilled oil was then calculated based on the dimension of the hole and other parameters. According to the monitoring data including the variations of the discharge pressure at Huangdao Station and the inlet pressures at Jiaozhou and Changyi Stations before and after the oil spill, as shown in Figs. 3, 4 and 5, and the geometrical and operation parameters of the pipeline, TLNET models for the segment from Jiaozhou to Changyi and that from Huangdao to Jiaozhou were established, as shown in Figs. 7 and 8, respectively, where the former simulated the pipe flow under normal operation and the latter for the pipe flow during oil spilling. The pipe length as shown does not represent the actual length of the pipeline. The PipelineStudio software was used to derive the flow at Jiaozhou station through the model in Fig. 8. The flow at Jiaozhou station was supposed to be identical to that derived by the model in Fig. 7. In this work, it was assumed that the derived flow values could be regarded as equal when the relative error was less than 1%. The diameter of the leaking hole was obtained after a number of attempts, and it was approximately 46.7 mm.

(1) Stage 1 (2:12 am–2:25 am)

The instantaneous and accumulative amount of the spilled oil at stage 1, as shown in Fig. 8, are calculated according to the diameter of the leaking hole, and the result is shown in Fig. 9. It can be seen that the total amount of the spilled oil at stage 1 is approximately 132.76 m^3.

(2) Stage 2 (2:25 am–3:20 am)

At stage 2, the remaining oil in the pipeline continued to spill due to the low elevation of the leaking point after the pump was turned down. The relief valve at the Huangdao station was opened 15 min later. Part of the oil flowed into the relief tank until the Yang River valve was shut off. Thus, the numerical model in Fig. 8 still applied. However, the pump flow was reset to 0 and the relief valve and valve chamber were closed. The instantaneous and accumulated amount of the spilled oil at stage 2 and the oil entering the release tank are shown in Figs. 10 and 11, respectively. It is seen that the instantaneous flow at the leaking site drops rapidly after the pump is off and remains at 262 m^3/h (Fig. 10). The flow of the release valve first increases then drops rapidly and finally remains stable at 48 m^3/h (Fig. 11). The calculated accumulated amount of the spilled oil at the leaking point at stage 2 was approximately 258.87 m^3, and the total amount of oil entering the release tank was approximately 32.98 m^3.

(3) Stage 3 (3:20 am–10:25 am)

During stage 3, after the Yang River valve chamber was closed, the oil in the pipe segment from some high elevations to the Huangdao station kept spilling out, while part

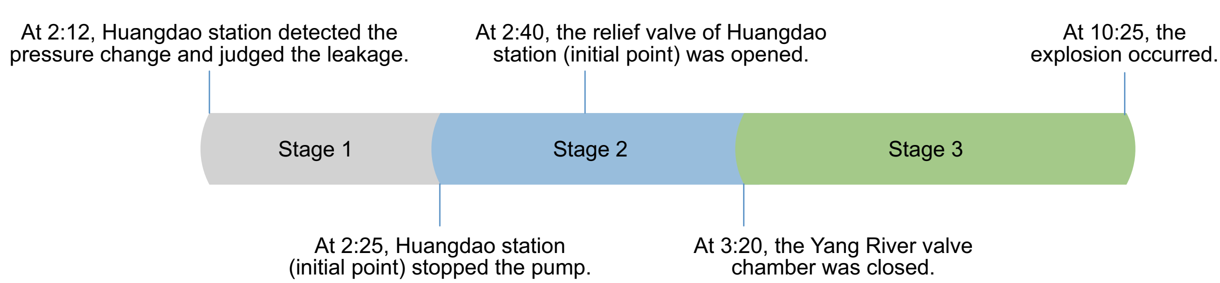

Fig. 5 Three stages of the oil spilling process

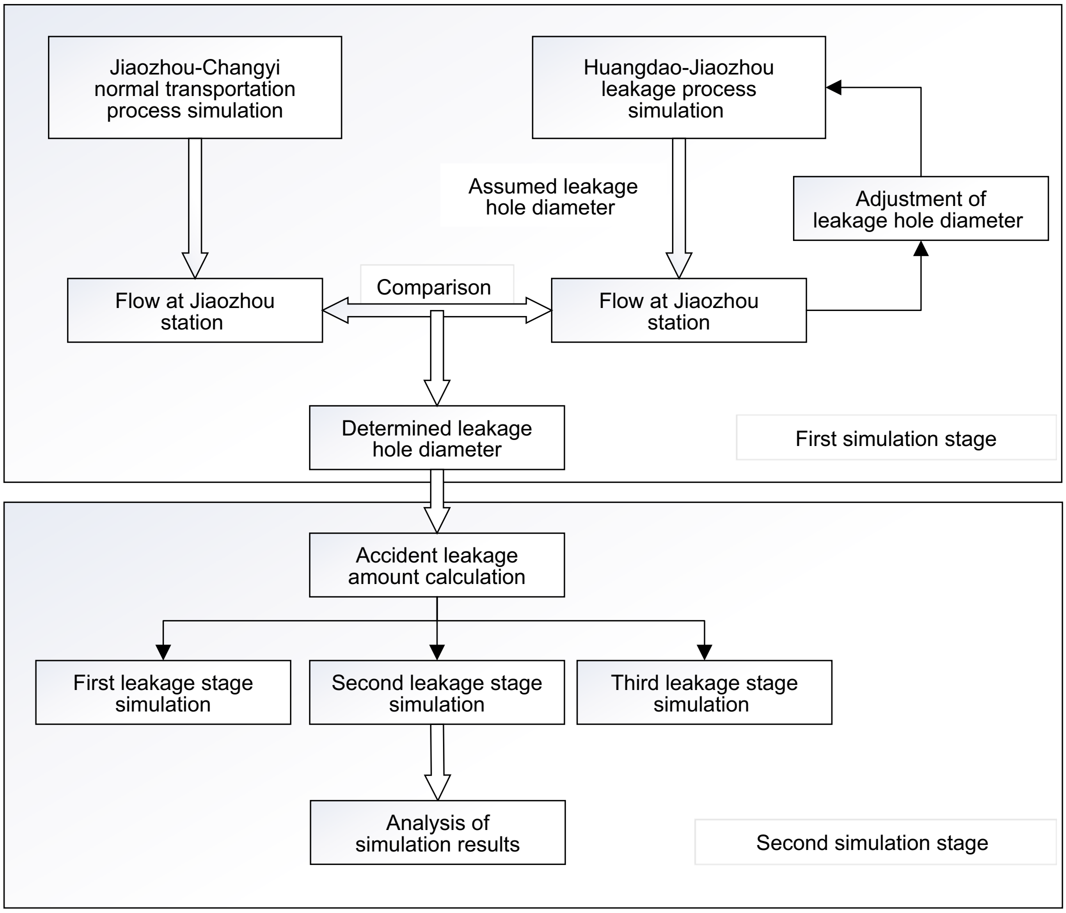

Fig. 6 Procedure for simulating the pipeline leaking and calculating the amount of spilled oil

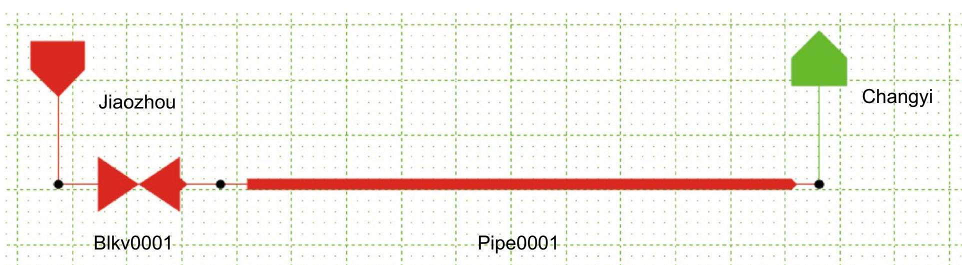

Fig. 7 TLNET model for the pipe segment from Jiaozhou to Changyi during normal operation

of the oil flowed into the release tank through the release valve. According to the measured data, the total amount of oil entering the release tank during the whole spilling period was 242.81 m^3. Thus, the amount of oil entering the release tank during stage 3 was 209.82 m^3.

According to statistics about the layout of the pipeline between Huangdao station and the high elevation, the length of the pipeline lower than the high elevation is 5.954 km, while the total length between Huangdao station and the high elevation is 10.842 km. In addition to the oil flowing into the release tank, the rest oil in the pipe segment that is higher than the leaking point in terms of the elevation was spilled out. The amount of the spilled oil during stage 3 was calculated by Eq. (1):

$$Q_S = \frac{\pi D^2}{4}(d_1 - d_2)1000 - Q_T \tag{1}$$

where Q_S is the amount of the spilled oil during stage 3 in m^3, D is the pipeline inner diameter in m (0.6968 m), d_1 is the total length between Huangdao station and the high

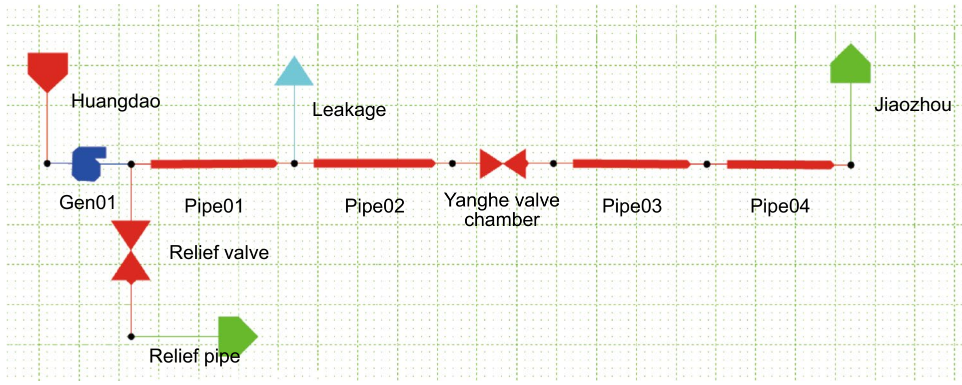

Fig. 8 TLNET model for the pipe segment from Huangdao to Jiaozhou during oil spilling

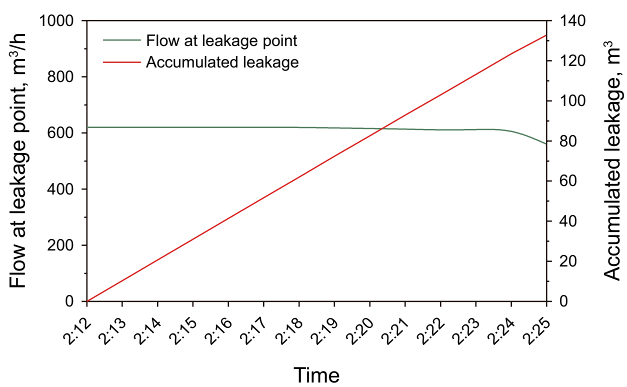

Fig. 9 Instantaneous and accumulated amount of spilled oil at stage 1

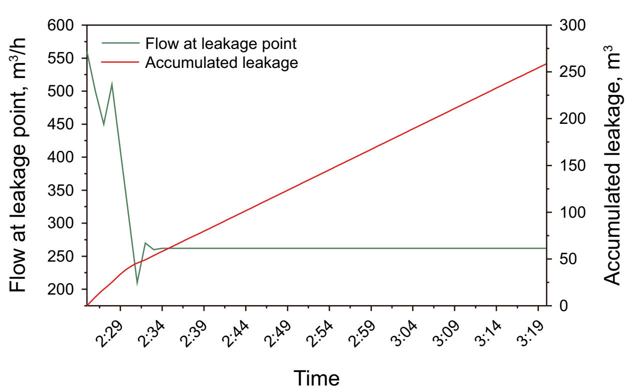

Fig. 10 Instantaneous and accumulated amount of the spilled oil at the leaking site at stage 2

elevation in km (10.842 km), d_2 is the length of the pipeline lower than the high elevation in km (5.954 km), and Q_T is the amount of oil entering the release tank during stage 3 in m^3 (209.82 m^3). Thus, Q_S is calculated to be 1652.77 m^3.

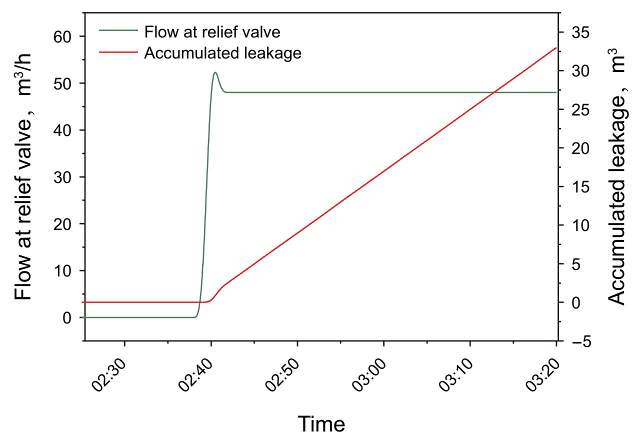

Fig. 11 Instantaneous and accumulated flow entering the release tank during stage 2

In summary, the total amount of the spilled oil in this accident is 2044.40 m^3 during 8 h of releasing until the explosion. The oil flowing into the release tank is 242.81 m^3, about 12% of the spilled amount.

3.2 Accident consequence

3.2.1 Parametric determination by modeling

The Dongying–Huangdao pipeline carries a mixed Aisipo and Hange crude oil at a ratio of 1:1. The density of the oil is 860 kg/m^3, the saturated vapor pressure is 13.1 kPa, the vapor explosion limit is 1.76%–8.55%, and the closed-up flash point is −16 °C. The oil is a light crude oil, with a discharge temperature of 27.8 °C.

The mixed crude oil transported in the pipeline is flammable. The spilled oil can easily permeate into ground and spread widely. If the oil is blocked by barriers, it could

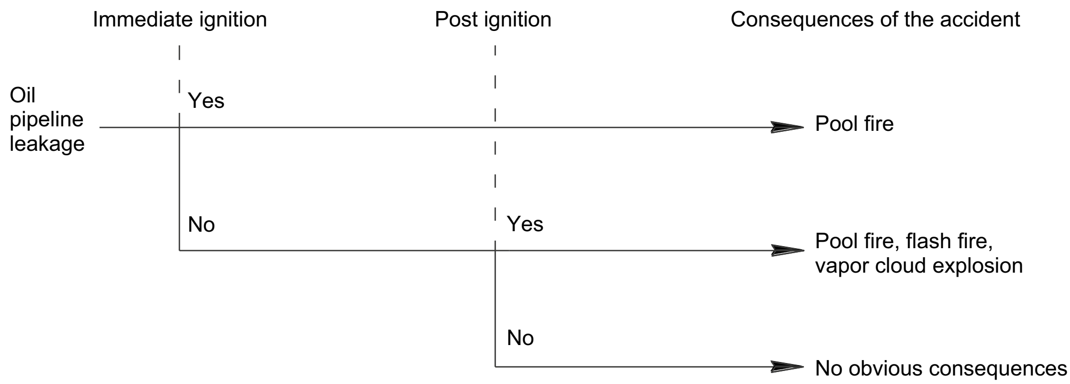

Fig. 12 Event tree of oil spill from pipelines and the resulting consequences

accumulate in a limited area (equivalent to a cofferdam) or a confined space, forming a liquid pool. If a fire source is available, the liquid pool can be ignited, leading to a pool fire. Even if it is not ignited immediately, the oil would quickly evaporate due to heating, heat transfer through soil, solar radiation, and airflow movements, generating a vapor cloud above the liquid pool. When mixed with air, the vapor cloud becomes a flammable and explosive mixture, which is the direct reason causing VCE or a flash fire. The event tree of an oil spill from pipelines and the resulting consequences are shown in Fig. 12.

According to the investigation report of the accident (State Administration of Work Safety of China 2014), the leakage point is located at the southeast corner of a drainage culvert crossing the intersection of two streets. During the oil spill, a part of oil flowed to the road surface for approximately 180 m, making the affected area approximately 1000 m^2. The rest of the oil flowed into the drainage culvert, as shown in Fig. 13a. The oil-flowing area was 18–36 m^2. The area of the single tunnel is 9 m^2, and the culvert section has two or four tunnels at different locations, as shown in Fig. 13b.

The temperatures of the area where the accident happened were 13 °C and 5 °C in the daytime and the night, respectively. After the initial oil spill, the oil flowed into the sewer in the confined space of the underground culvert. The temperature of the sewer was about 10 °C. Prior to explosion, the oil had volatilized for approximately 8 h in the confined drainage culvert. According to the volatilization simulation, the properties of the mixture are given in Table 1. It is seen that the gas mixture is within the explosion limit after 8 h of volatilization. According to the field investigation, the total volume of the underground culvert is approximately 1400 m^3. The culvert is divided into 2–4 holes by solid walls, and each hole is approximately 3 m wide and 3.3 m high. In this work, a single-hole culvert was selected for calculation by dividing into equal elements with a dimension of 3 m × 3 m × 3.3 m, as shown in Fig. 14. As

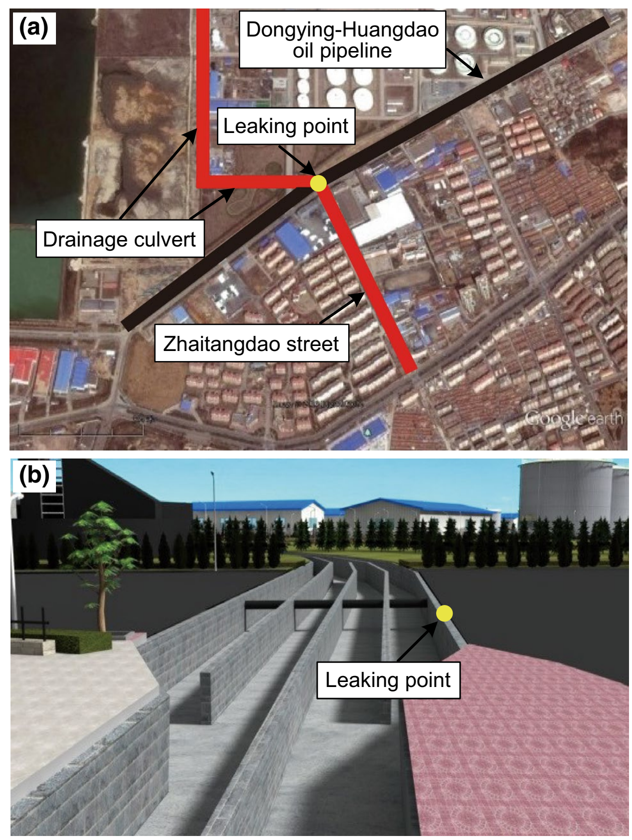

Fig. 13 **a** Flow pathway of the spilled oil from the leaked pipeline, **b** culvert at the spill point

the explosion in the culvert was caused by both chemical and physical reasons, the calculation is divided into two stages. First, the shock wave overpressure produced at point *A* at the center of the top plate above unit *i* in the chemical explosion process was calculated. Then, the shock wave overpressure transmitted to the environment during the physical explosion process was calculated, and the damage to the surrounding area was determined.

Table 1 Properties of the mixture in the sewage culvert prior to explosion based on volatilization simulation

Time	Gas mixture, %							Total organic phase	Lower explosive limit, %	Upper explosive limit, %
	Ethane	Propane	n-butane	Isobutane	n-pentane	Isopentane	C6+			
Average value after 8 h	0.027	0.389	1.679	0.434	1.137	1.208	1.811	6.685	1.48	8.14

The oil contains the mixture of Aisipo and Hange oil at a ratio of 1:1

The oil–water ratio is 20%

The amount of the spilled oil in simulation is 0.1 L, and the volume of the space is 1 L

3.2.2 Calculation of the chemical explosion

Assume that each calculation element explodes at its center. The TNT-equivalent method with shock wave overpressure test results for an explosion of 1000 kg of TNT was used. An interpolation algorithm was employed to determine the pressure induced at point A by each calculation element (Wu et al. 2002). According to the gas mixture components, the TNT equivalent of each calculation element can be calculated by Eq. (2):

$$W_{\mathrm{TNT}}=\frac{AW_{\mathrm{f}}Q_{\mathrm{f}}}{Q_{\mathrm{TNT}}} \tag{2}$$

where W_{TNT} is the TNT equivalent of the vapor cloud in kg, A is the TNT equivalent factor of the vapor cloud, which is in the range of 0.02%–14.9% (a value of 4% is generally taken), W_{f} is the total mass of fuel in the vapor cloud in kg, Q_{f} is the heat of the combustion of fluids in MJ/kg (particularly, 51.146 MJ/kg for ethane, 50.082 MJ/kg for propane, 49.665 MJ/kg for n-butane, 49.334 MJ/kg for isobutane, 48.75 MJ/kg for n-pentane and isopentane, and 48.266 MJ/kg for the C6+ component), and Q_{TNT} is the explosion heat of TNT, which is in the range of 4120–4690 kJ/kg (a value of 4500 kJ/kg is taken). The volume of each calculation element is 29.7 m^3. Assume that the explosion occurred at the upper explosive limit, and each unit vapor cloud had an equivalent TNT mass of 39.86 kg. The simulation ratio of explosion is $\alpha=0.1\sqrt[3]{W_{\mathrm{TNT}}}\approx 0.34$. The equivalent distance between point A and the benchmark explosion center can be calculated by Eq. (3):

$$R_A=\frac{R}{\alpha} \tag{3}$$

where R_A represents the equivalent distance between point A and the benchmark explosion center in m, and R is the distance between point A and the explosion center in m.

The interpolation of the shock wave overpressure of each calculation element at point A is performed according to the shock wave overpressure testing results for an explosion of 1000 kg of TNT, as given in Table 2. When the calculation element i and the adjacent two calculation elements ($i-2$, $i-1$, $i+1$, $i+2$) are considered, the shock wave overpressure at point A is calculated as 4.91 MPa. When the calculation unit i and the adjacent three calculation elements ($i-3$, $i-2$, $i-1$, $i+1$, $i+2$, $i+3$) are considered, the shock wave overpressure at point A is 5.05 MPa, representing an increase of 3% considering the adjacent two calculation elements. Elements $i-3$ and $i+3$ had a small effect on the calculation results. Elements further away from the element i has a less impact as the effect of the shock wave overpressure is inversely proportional to

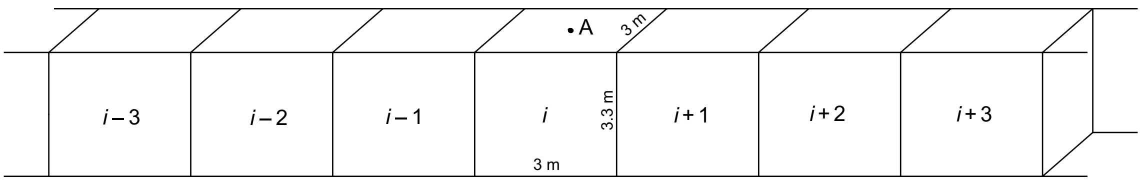

Fig. 14 Division of the calculation elements of the culvert

Table 2 Shock wave overpressure of each calculation element at point *A* in Fig. 14

Calculation unit	$i-3$	$i-2$	$i-1$	i	$i+1$	$i+2$	$i+3$
Shock wave overpressure, MPa	0.07	0.16	0.76	3.07	0.76	0.16	0.07

Table 3 Influence sphere of the shock wave overpressure upon explosion

Overpressure, MPa	Damaging effects	Range, m
0.14	Death	18
0.044	Serious casualties	31
0.017	Minor injuries	52
0.07	Domino effect (building walls crack)	24
0.007	Glass breaks	92

the third power of the distance. Thus, it can be concluded that this method is appropriate for the analysis.

3.2.3 Calculation of the physical explosion

Consider 5.05 MPa as the internal pressure of the physical explosion, the CASST-QRA^{TM} software was used to calculate the damage to the surrounding environment. The results are given in Table 3.

4 Discussion

The field investigations showed that while part of the spilled oil spread on the street for approximately 180 m, covering an area of 1000 m^2, most of the oil flowed into the drainage culvert and the ocean. It is estimated that the area of the polluted sea is approximately 3000 m^2. After explosion, the oil containment is destroyed, causing spreading of the residual oil. As a result, the maximum area of the polluted seawater is up to 17 km^2 (Wei and Lu 2015; Gao et al. 2018). At the same time, a huge amount of crude oil was lost in the accident.

Furthermore, the explosion resulted in the shock wave spreading over 5000 m along the drainage culvert, causing blowup of the paved street, cracking of adjacent buildings, and fire at the drainage estuary. These indicate that the volatile components reach the explosive limit. Most deaths caused by the explosion occurred within a range of 30 m from both sides of the drainage culvert, which conforms to the transmission distance generated by a 0.044 MPa shock wave overpressure. The deaths were caused by either the shock wave or by the debris hit. The windows of the buildings located within a range of approximately 100 m were broken, and non-solid walls were twisted, which conforms to the transmission distance of a 0.007 MPa shock wave overpressure.

Modeling and analysis of the oil pipeline leak and explosion show that the pipeline was not under a proper integrity management. For example, it took over 1.0 h to close the relief valve from realization that the pipeline leaked. The delayed response caused a massive oil spill, posing a big challenge to subsequent emergency response. Moreover, wrong decisions were made in the emergency response processes. A comprehensive risk assessment on the oil spill was not made before excavation. The staffs did not have information about the amount of oil that had been spilled and the components of the spilled oil before the repair procedure was initiated. More importantly, there were no protection and isolation measures taken nearby the area of oil spill. Flammable gas detection was not conducted in the emergency maintenance process, and no explosion-proof equipment was used.

Based on the calculated amount of the spilled oil, the oil leaking rate in stage 1 is 612.75 m^3/h, which is twice of those in stages 2 and 3. Apparently, if appropriate measures, i.e., shutting off the pump, turning on the relief valve and closing the valve chamber, were conducted in a timely manner, the time duration of stage 1 can be reduced and the amount of oil spill controlled efficiently. At the same time, the largest amount of the spilled oil was found at stage 3, which was 80.8% of the total amount of the spilled oil. Thus, although the emergency measures were taken in stage 1, attentions should be paid to collection and clearing of the spilled oil.

The spilled oil accumulating in a confined space may result in explosion of the vapor cloud once it is volatilized to reach the explosive limit. This should be fully included in the risk assessment program. The accident reporting should be immediate after the pipeline leakage is detected. The collection and clearing of spilled oil should be performed as soon as possible. The emergency response time should be shortened so that the quantity of volatile light components in the oil is reduced. Flammable gas detection measures should be carried out during the repairing stage.

Of the 61 deaths caused by the accident, there are 16 Sinopec emergency response staff members, an assistant public security guard and 45 community residents, enterprise staff members, and pedestrians. Clearly, the accident area should have been labeled a Grade 3 high-risk area according to China National Standard GB 32167 (Standardization Administration of the People's Republic of China 2015). The government planning department did not consider this area as a high-risk region and evaluate the potential risk the surrounding citizens and facilities exposed. When the pipeline was constructed in 1986, there was no dense community nearby. Therefore, the municipal and community development must consider the infrastructure that has been operating in the local area.

5 Conclusions

Models are developed to simulate, analyze, and evaluate the consequences associated with the pipeline leaking, oil spill, and the subsequent explosion occurring in Qingdao, China in 2013. Numerical simulations are performed to derive the amount of the spilled oil and determine the consequences of the explosion. The results are verified by field investigations.

The total amount of the spilled oil is up to 2044.4 m^3 due to improper disposal after the pipeline leakage. The confined space where the crude oil flows and a long residence time of the oil permit formation of explosive mixtures and cause the vapor cloud explosion. Considering the simultaneous chemical and physical explosions that occurred in the confined space, the consequences of the explosion were calculated. The death-leading zone and glass-breaking zone can reach to 18 m and 92 m, respectively.

Vapor cloud explosion will occur with a high probability once oil spill in a confined (airtight) space. The severity of the explosion is related to the amount, components of the spilled oil, and the volatilization time. To minimize the impact of such accidents, pipeline leak detection measures should be taken to reduce the amount of oil spill. Prompt collection and clearing should be carried out immediately after the spill occurs to shorten the time for volatilization of the oil. Ventilation measures should be taken to reduce the concentration of light components in the confined (airtight) space in order to prevent the mixture to reach its explosive limit.

After an oil leakage into a confined (airtight) space is detected, a comprehensive risk assessment of the oil spill accident should be made first in order to determine appropriate emergency rescue measures. The isolation and dispersal area should be determined by considering the region of influence of potential fire and explosion accidents. Moreover, a certain safety distance should be set between the pipeline and surrounding buildings (structures) in order to reduce the potential damage induced by thermal radiation and shock wave overpressure during accidents.

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