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STRENGTH FAILURE OF A NATURAL GAS STATION PIPE SYSTEM UNDER FOUNDATION SETTLEMENT AND COUNTERMEASURES

Summary

The foundation settlement is one of the potential hazards that causes stress concentration in natural gas station pipes and their bending deformation. This paper deals with the on-site foundation settlement of a natural gas station. A set of three-level early warning schemes was proposed for the foundation settlement in the natural gas station. In addition, a countermeasure method was also proposed. Results show that the stress is concentrated at the bend of the gate-shaped pipe and the connection between the gate-shaped pipe and the main pipe. The gate-shaped pipe exhibits inclined deformation. The method of installing a concrete floor under the pipe can effectively reduce stress concentration at the connection between the gate-shaped pipe and the main pipe. If pipe piers are used for support, the stress and displacement of the pipe can be reduced to a certain extent, but the impact is limited, and the effect is slightly better when both ends and the middle of the pipe are supported.

Key words: *natural gas station; foundation settlement; pipe system; countermeasures*

1. Introduction

Natural gas is a low-carbon fossil fuel energy source that plays an important role in achieving the goal of green energy transformation [1]. The natural gas stations play an important role in the long-distance transfer of natural gas and are the reliable guarantee for the safe and stable operation of the pipeline network. At present, the total length of natural gas pipelines in China has reached about 11×10^4 km [2], and the original terrain for the construction of natural gas stations is mostly in complex environments, such as hills and mountains. The construction of new natural gas stations inevitably involves excavation and backfilling of soil and rock, resulting in varying degrees of foundation settlement hazards. Uneven settlement of the foundation can easily cause additional stress concentration in buried pipelines and their bending deformation. Once the ultimate stress of the material is exceeded, it can lead to excessive deformation or even rupture of the pipeline, resulting in natural gas leakage and even causing natural gas explosion accidents [3]. Therefore, it is of great significance for the operation and maintenance of natural gas stations to study the pipeline stress caused by the foundation settlement and the related countermeasures.

Many scholars have conducted extensive research on pipelines with foundation settlement. Fadee et al. [4] investigated the interaction between the pipeline and the reverse fault, and the buckling behaviour of the buried pipeline was analysed. Sarvanis et al. [5] proposed a novel analytical method for the strain calculation of pipelines under permanent ground displacement, such as fault actions and settlement. Zha et al. [6] established an XFEM-based model of pre-cracked PE pipe under foundation settlement to investigate the fracture behaviour of the pipe, the results showed that the existence of cracks would greatly reduce the mechanical performance of the pipe. Tafreshi et al. [7] and Babagiray et al. [8] studied the protection effect of expanded-polystyrene (EPS) blocks on buried flexible pipelines. Results of experiments showed that EPS can reduce the pressure of settlement on pipelines and absorb impact energy. The FDM-DEM coupling method of corrugated pipe subjected to ground settlement was investigated by Gu et al. [9]. A pipeline-soil integrated model was established for four different types of pipelines by Liu et al. [10], and the ground settlement displacement at the limit state of each pipeline was obtained. Although there are many studies on buried pipelines under soil settlement, few researchers have focused on pipeline systems under natural gas station settlement. Zhu et al. [11] established a pipeline model to analyse the stress distribution of buried pipelines under station foundation settlement and compared numerical results with measurement results. Xu et al. [12] measured the stress on pipelines for compressor stations using the indentation strain method and analysed the position where strength failure might occur. Yuan et al. [13] studied the stress situation of process pipelines in natural gas stations. At present, there are few studies on pipeline mechanics being conducted on natural gas stations. This situation leads to a lack of pipeline prediction data in the presence of settlement at natural gas stations. There are significant differences between the research results on the settlement of buried pipelines in the existing literature. Therefore, these results cannot effectively give the safety assessment of pipelines during the settlement process of natural gas stations.

This paper presents the mechanical behaviour of pipelines under natural gas station settlement and compares them with the actual station conditions. The results are used as predictive data for online detection of natural gas station settlement in the future. In addition, several countermeasures to reduce the impact of station settlement on pipeline systems are proposed, and the differences between countermeasures are analysed using numerical analysis. These results provide a basis for pipeline design, construction, and safety assessment, and a basis for the selection of settlement monitoring points in natural gas stations.

2. Numerical model

2.1 Project overview

The covering layer inside the station is composed of clay and other materials. The thickness of the silty clay is unevenly distributed, and the underlying bedrock has a large fluctuation in burial depth. The overall uniformity of the station foundation is poor. There is farmland waterlogging on the north and east sides of the station (Figure 1). The inlet valve group area is located on the northeast side of the natural gas station, adjacent to farmland. The high humidity of the foundation can easily induce settlement of the station, which has a significant impact on the safety of pipeline operation inside the station. In addition, some equipment and pipelines are located in high fill areas with poor foundation stability. After long-term operation, they are prone to local non-uniform foundation settlement, which may cause pipeline deformation and damage, posing certain safety hazards.

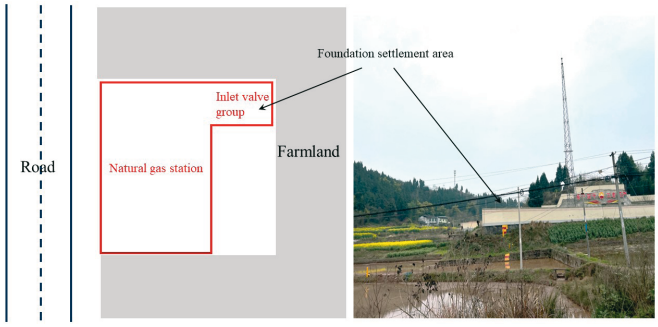


Fig. 1 Geomorphic overview of the station

Figure 2 shows the measured surface settlement of the inlet valve group area at the station. The field investigation revealed the following:

(1) There is significant uneven settlement on the surface, with a settlement range as shown in Figure 2 (a). The settlement boundary is irregular, and the maximum settlement position is located near the gate-shaped pipe in the figure.

(2) There was no additional load on the surface of the settlement area; therefore, it was determined that the cause of settlement was natural settlement. The outer side of the surrounding wall in this area is farmland with a large amount of accumulated water, which may cause settlement within the strata due to water erosion. Therefore, the settlement soil exerts a tensile force on the upper soil of the stratum (near the surface) acting in the underground direction. Since there is no pipeline protection structure inside the strata after excavation, Figure 2 (b), this results in the settlement of buried pipelines.

(3) The settlement in the area where the main pipe is located is relatively small. The main deformations of the two types of pipelines shown in Figure 2b are concentrated in the gate-shaped pipe, and their relative positions are inclined. The upper section of the gate-shaped pipe deviates from the horizontal plane.



Fig. 2 Field investigation of settlement area

2.2 Finite element model

In this study, the finite element model of the process pipeline in the natural gas was established. The pipeline system consists of the main pipe and the gate-shaped pipe. The yield stress of pipeline material is 448.5 MPa. The soil material, i.e., clay, is described through an elastic-perfectly plastic Mohr–Coulomb constitutive model. The basic parameters of pipelines and the surrounding soil are shown in Tables 1 and 2, and the geometric dimensions of the

model are shown in Figure 3. The shell elements and solid elements are used for the pipelines and the surrounding soil, respectively [14]. There are at least sixteen shell elements in the circumferential direction of the pipeline, and the size of the shell elements in the axial direction (x direction) is 0.05 m. In addition, the soil mesh around the pipeline is refined.

The top surface of the model is an unconstrained free surface, and the side surface is a normal constraint [15]. The bottom surface of non-settlement area is fixed constraint. The cause of settlement deformation is natural settlement, where the stratum is subjected to vertical tension from the underlying soil. In numerical simulation, the analysis is divided into two steps: gravity loading is applied on the whole model and internal pressure of the pipe is applied on the inside surface of the pipeline first; then, the fixed settlement displacement is applied on the bottom plane of the soil [16], as shown in Figure 3.

In the finite element model, some pipeline attachments were simplified. Although the valve group was not shown in the model, a mass element was set at the valve position during modelling to simulate the effect of the valve on the pipeline stress [17]. In addition, the confinement of the pipeline by the surrounding soil uses the nonlinear pipe-soil coupling frictional contact [18] and simulates the interaction between all buried pipes and the soil by setting the friction coefficient value to 0.3 [18-19]. In this study, the explicit dynamic analysis is used to simulate the quasi-static condition of the settlement problem. This analysis method prevents the occurrence of convergence problems. The analysis is computationally efficient for the analysis associated with large deformation and a high degree of nonlinearity [21].

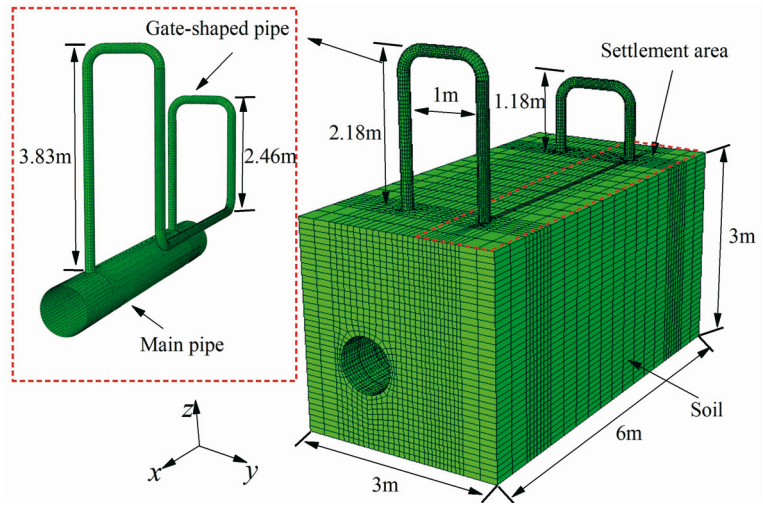


Fig. 3 Finite element model

Table 1 Pipeline parameters

Pipeline	Outer diameter (mm)	Thickness (mm)	Density (kg/m^3)	Elastic modulus (GPa)	Poisson`s ratio
Main pipe	800	10	7850	207	0.3
Gate-shaped pipe	160	10	7850	207	0.3

Table 2 Soil parameters

Density (kg/m^3)	Elastic modulus (MPa)	Poisson`s ratio	Friction angle (°)	Cohesion (kPa)
1946	20	0.3	21.2	27

2.3 Comparison of results

Figure 4 shows a comparison of the deformation of the pipe group before and after settlement. After the settlement, the whole gate-shaped pipe tilts to the positive y direction, and there is a slight inward trend of the gate-shaped pipes on both sides. Compared with the

field investigation shown in Figure 2 (b), the finite element method results are consistent with those of the field investigation.

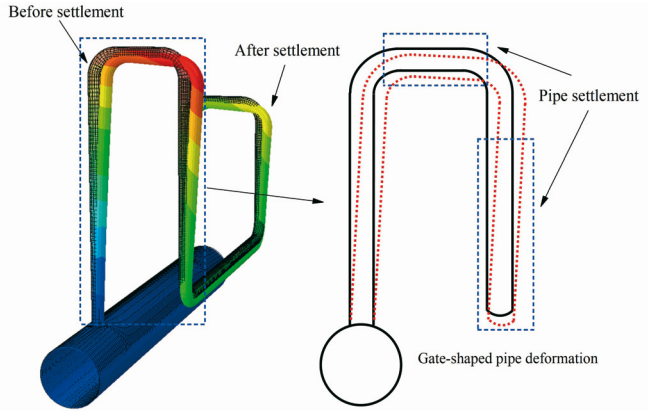
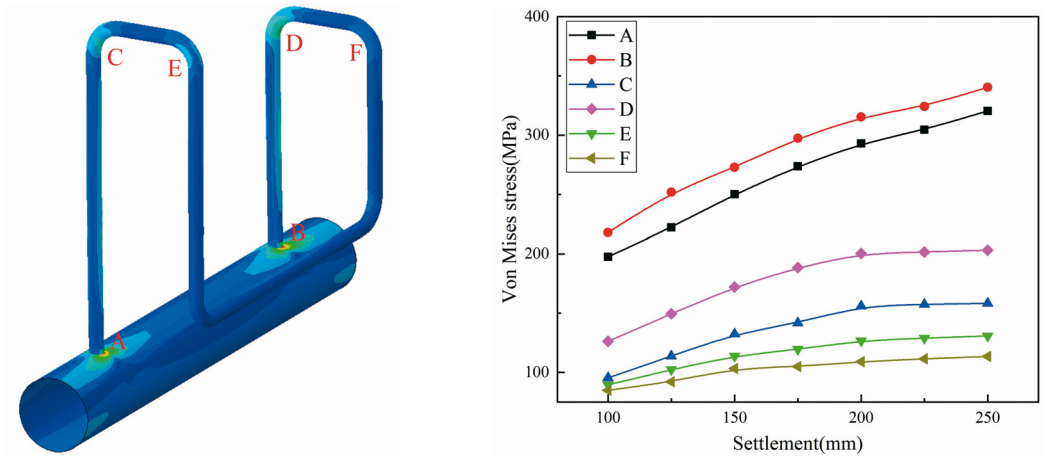


Fig. 4 Comparison between simulation and measurement

3. Analysis of results

3.1 Settlement

The main pipeline has high stiffness and does not deform significantly after settlement, while the gate-shaped pipe has low stiffness, resulting in more significant overall deformation. Figure 5 (a) shows that the stress concentration areas are A~F regions. A and B regions are the connections between gate-shaped pipeline and the main pipe, which have higher stress and show stiffness changes and structural nonlinearity. The stress distribution of C and E is different from that of D and F because the vertical length (*z* direction) of the gate-shaped pipe at E and F is different, resulting in different degrees of stiffness. The gate-shaped pipe at C and E has a larger frame, longer vertical length, higher centre of gravity, and obvious displacement deformation, while the gate-shaped pipe at D and F has a smaller vertical length and slightly lower centre of gravity. Combining the deformation and total displacement trends in Figures 4, CE and DF pipe sections exhibit horizontal displacement and vertical displacement (settlement displacement), while AC and BE pipe sections generally exhibit horizontal displacement, and the vertical pipe sections at E and F generally exhibit vertical displacement and a small degree of horizontal displacement.



(a) The von Mises stress distribution (b) The von Mises stress of measure points

Fig. 5 The von Mises stress of the pipeline system with different settlements

Figures 5 (b) and 6 show the stress and axial strain curves, respectively. Due to the bending moment and large displacement of the CE section, the stress concentration at point C

is higher than at point E. The same applies to points D and F. During the settlement process, due to the small length of the BD section, stress transmission is more pronounced, resulting in a higher stress at point D than at point F.

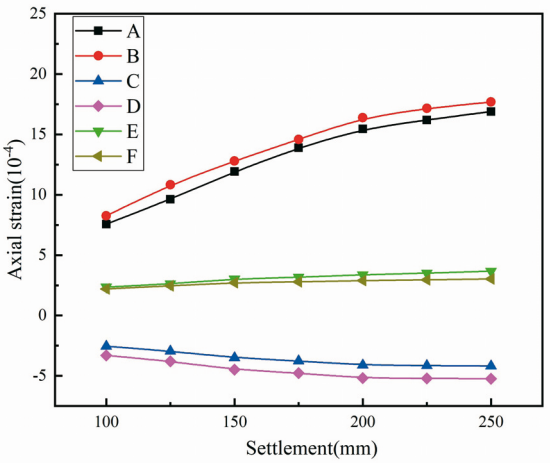
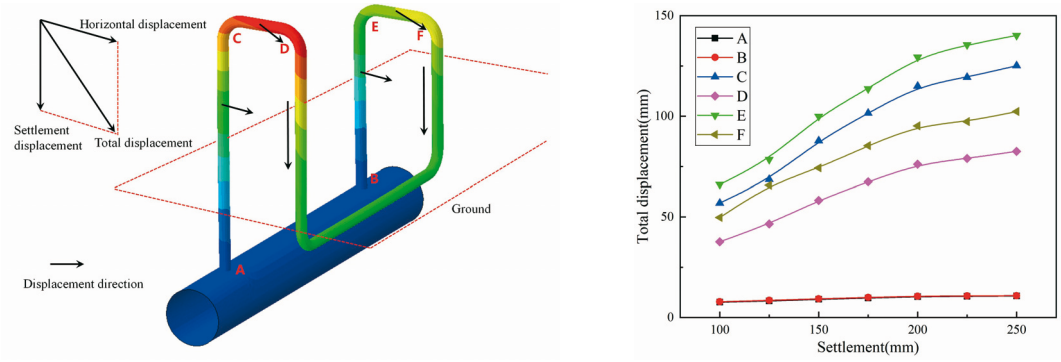


Fig. 6 Axial strain of the pipeline system with different settlements

The settlement of the natural gas station will change the stress distribution of the pipeline system in the station and cause the stress concentration. Therefore, it is necessary to monitor pipeline systems with potential settlement hazards. Based on the above analysis, the recommended stress monitoring points are A, B, C, and D, and the recommended displacement monitoring points are C, D, E, and F.



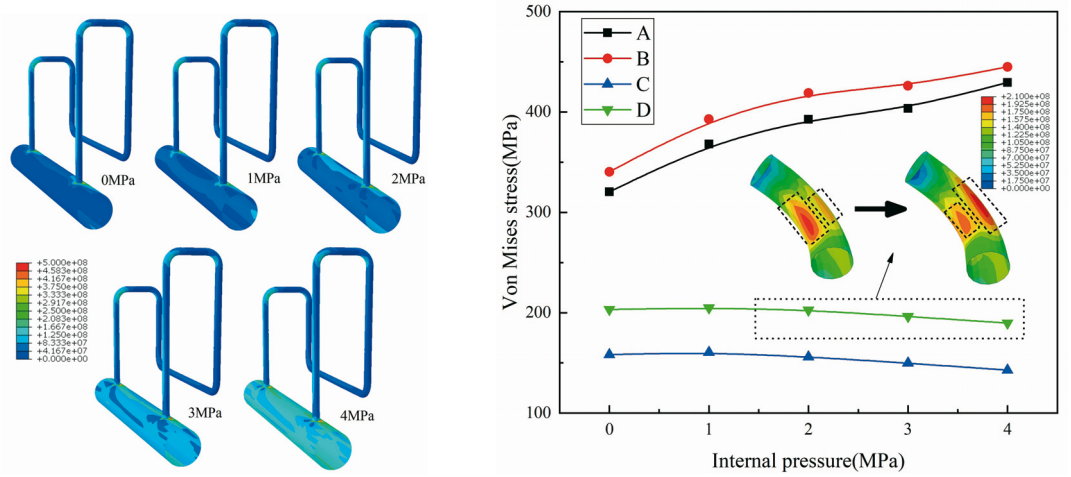
(a) Diagram of displacement direction (b) Total displacement

Fig. 7 Total displacement of the pipeline system with different settlements

3.2 Internal pressure

The stress of the pipeline increases with the increase in internal pressures, as shown in Figure 8. Internal pressure will change the original stress state of the pipeline and increase the stress of the whole pipeline. Figure 8 (b) shows that as the internal pressure increases, the stress distribution at points C and D of the pipeline changes. A high-stress area will be generated on the side of the pipeline and its range will gradually increase, while the original high-stress area on the inner side will gradually decrease. This causes the maximum stress at points C and D to gradually decrease and reach a new balance.

The total displacement of the pipeline system with different internal pressures is shown in Figure 9. The internal pressure will increase the stiffness of the pipes, so the deformation of the pipes decreases, but the overall deformation is relatively small. Taking point E as an example, the displacement of the pipeline with internal pressure of 4 MPa is reduced only by 4 % compared to the pipeline without pressure.



(a) Stress distribution (b) The von Mises stress of measure points

Fig. 8 The von Mises stress of the pipeline system with different internal pressures

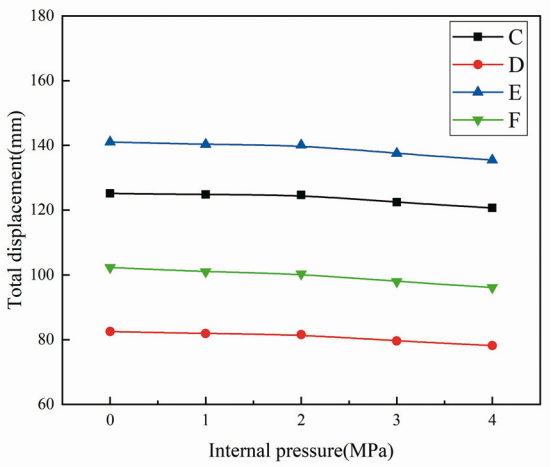


Fig. 9 Total displacement of the pipeline system with different internal pressures

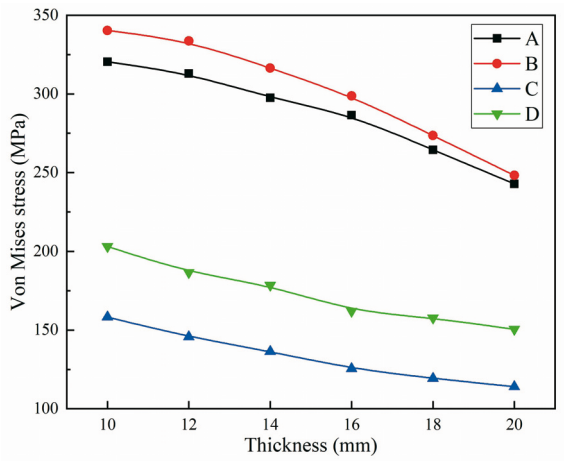


Fig. 10 Pipe stress with different thicknesses

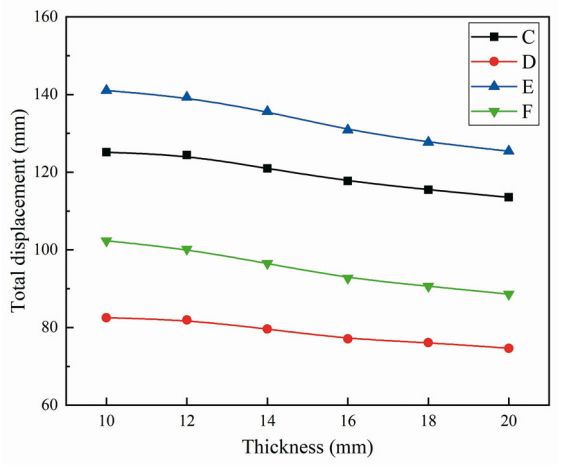


Fig. 11 Pipe displacement with different thicknesses

3.3 Thickness

The von Mises stress and total displacement of the pipeline system are shown in Figure 10 and Figure 11, when settlement is 250 mm and the thickness of pipes ranging from 10 mm to 20 mm. As the wall thickness increases, which has a significant impact on the stress at

points A and B. This can be attributed to the fact that pipes with thicker walls have greater stiffness, and they can improve their ability to resist soil deformation. Thus, the stress concentration degree of the pipeline at points A and B sharply decreases. However, the effect of the thickness of the pipes on the displacement is relatively small.

4. Pipeline warning threshold

At present, there is no warning standard for natural gas station settlement. Therefore, in this study, a three-level warning scheme for natural gas station settlement based on finite element analysis is proposed. Adopting stress-based pipeline strength design criteria, the stress at which the pipeline fails is taken as the yield strength, which is 485 MPa, and the safety factor for its allowable stress is taken as 0.9, which is 436 MPa [20]. The first-level warning, second-level warning, and third-level warning have allowable stress values of 60 %, 80 %, and 100 %, respectively. Based on the monitoring and alarm systems, the third-level warning threshold is configured for each measuring point of the monitoring equipment to achieve alarm function.

Table 3 shows the warning threshold of the station based on the finite element analysis results. It shows the three levels of the warning threshold of ground settlement and the calculated stress and total displacement of monitoring points A~F when point B of the pipeline reaches the allowable stress (for the selection of monitoring points, the reader can refer to section 3.1). When the monitoring point reaches the level 1 warning threshold, it is necessary to consider whether the station pipeline is in a safe operating state, and the pipeline should be rigorously monitored. When the monitoring point reaches the level 2 warning threshold, the settlement control of the natural gas station should be carried out. This alarm standard and its application are of great significance for the safety evaluation and operation maintenance of natural gas stations with settlement hazards.

Table 3 Natural gas station settlement warning threshold

Warning point	Warning threshold					
	1		2		3	
Ground settlement(mm)	91.79		139.38		164.17	
Measure point	Stress (MPa)	Total displacement (mm)	Stress (MPa)	Total displacement (mm)	Stress (MPa)	Total displacement (mm)
A	236.84	\	329.73	\	415.50	\
B	261.6	\	348.8	\	436	\
C	123.07	80.00	159.08	128.59	174.67	157.52
D	107.75	91.42	132.13	143.83	148.00	182.81
E	\	53.05	\	84.69	\	105.37
F	\	68.09	\	104.76	\	134.60

5. Countermeasures

By analysing the stress distribution and pipeline displacement in the investigated natural gas station, it is determined that the stress concentration is caused by the effect of soil settlement on the deformation of the pipeline system. On the one hand, the settlement of station causes the buried pipeline to be pulled, resulting in uneven bending moments on the pipeline. On the other hand, there is no protective device installed below the pipeline. The stiffness of the gate-shaped pipe is relatively low, so the gate-shaped pipe is prone to a higher degree of deformation than the main pipe. It is necessary to adopt protective devices to

prevent pipeline failure in the station. This section discusses the effect of two different types of protective measures to be taken on the station pipelines.

5.1 Concrete floor

A reinforced concrete floor of a certain thickness is set up in the process area of the natural gas station, forming a unified structure with the foundation of the process area; thus, the load of newly built equipment and pipelines is evenly distributed on the bottom floor. As the stiffness of the reinforced concrete foundation floor is much greater than that of the soil, it can prevent uneven settlement of the process area, as shown in Figure 12. Assuming that the reinforced concrete foundation floor is parallel with the main pipe and of the same size as the settlement zone, the material density is 2000 kg/m^3, the elastic modulus is 20 GPa, and Poisson's ratio is 0.3.

Figure 12 shows that the stress concentration area is still in the A~F area. When the settlement is small, the stress concentration areas of points A and B are on the outside of the gate-shaped pipe, which is different from the situation without a concrete floor (compare with Figure 5 (a) in section 3.1). When the settlement increases, the stress concentration areas of points A and B are consistent with the situation without a concrete floor. When the settlement is 100 mm, the stress at points A and B decreases by 75% and 71%, respectively, compared to Figure 5 (b), due to the resistance of the concrete floor to soil settlement. The stress changes at the other points are very small, and there is a partial increase compared to Figure 5 (b) at points D and F. When the settlement increases, the stress in each area increases, but the rate of change is significantly smaller compared to the pipeline without a concrete floor, and the changes at points C~F are relatively small. Figure 13 shows the total displacement in each area of the pipeline. The displacement has significantly decreased. In summary, the concrete foundation floor mainly reduces stress concentration at points A and B, with little impact on other areas.

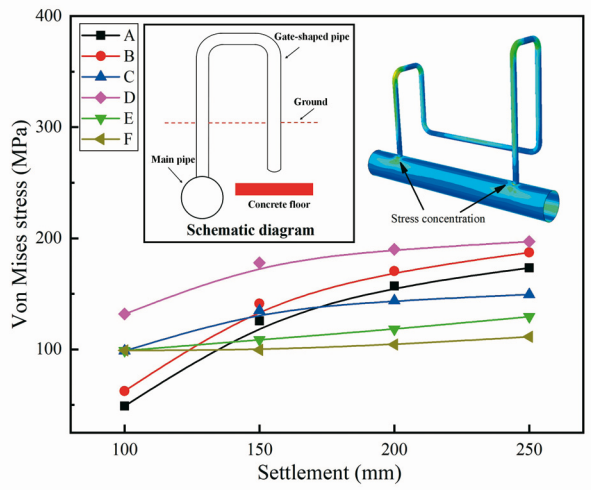


Fig. 12 Pipe stress with a concrete foundation floor

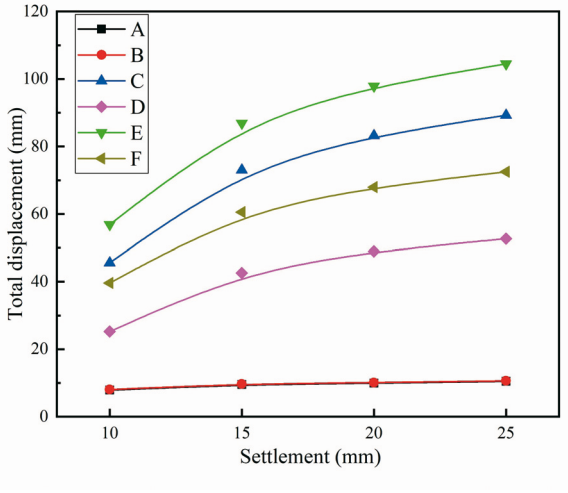
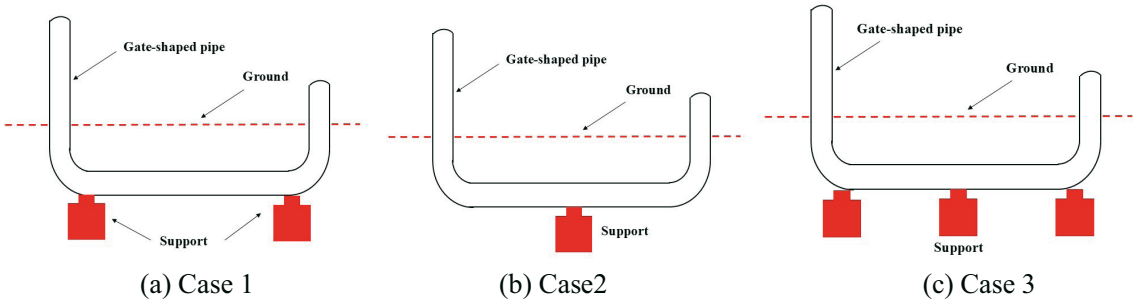


Fig. 13 Pipe displacement with a concrete foundation floor

5.2 Pier support

The method of adding pipe piers to gate-shaped pipe sections can reduce the tensile force of buried pipelines on above-the-ground pipelines. At the same time, due to the high stiffness of pipe piers, the displacement of the strata in this area can be reduced to a certain extent. Consider the three methods for adding pipe piers shown in Figure 14.



(a) Case 1 (b) Case2 (c) Case 3

Fig. 14 Diagram of pipe pier supports

As a supporting facility for pipelines, foundation piers can withstand various loads during the pipeline operation [12]. Consider using a concrete material for the pipe pier, with material parameters as described in section 5.1, and a pipe pier size of 600 mm × 600 mm.

Figures 15 and 16 show the stress and displacement with different support methods in the A~F region when the settlement is 25 cm. One can see that using supports at both ends (Case 1) or in the middle (Case 2) has a relatively small impact on the stress and displacement of the pipeline. The reason is that the support size of the pipe pier is limited, and its stiffness has a modest effect during settlement. During settlement, the pipe pier will be dragged and displaced at the same time, so the pipe pier only affects the stress and deformation of the pipeline to a certain extent. Compared to the method of case 2, the method of case 1 has a relatively better effect. If the method of case 1 is used, the bottom of the gate-shaped pipe will be like a simply supported beam, and the bending moment at the bottom will be highlighted. If the method of case 2 is used, the tensile force of the buried gate-shaped pipe exerted on the exposed gate-shaped pipe cannot be affected by the pipe pier, which is less effective. Therefore, it is possible to consider using the method of case 3 to support the pipeline to reduce stress and displacement.

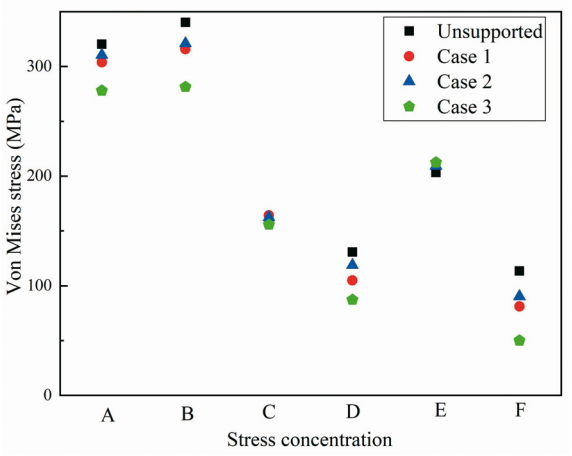


Fig. 15 Stress of a pipeline with pier supports

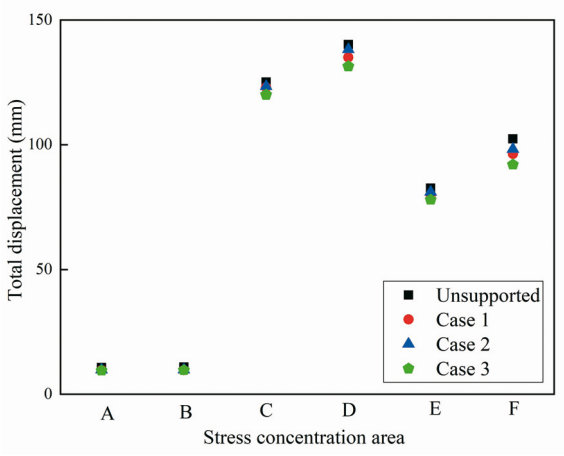


Fig. 16 Displacement of a pipeline with pier supports

6. Conclusions

A gas station pipeline under soil settlement was studied. The position where the strength failure may occur and effect of operating parameters were analysed. The countermeasure method is also proposed for the case with large stress. The following conclusions can be made:

(1) There are six stress concentration areas in the pipeline system of the inlet valve group at the station under settlement, which are concentrated at the bend of the gate-shaped pipe and the connection between the gate-shaped pipe and the main pipe. The gate-shaped

pipe has inclined deformation. The points A and B have higher stress, followed by C and D, while E and F have lower stress. The internal pressure will increase the pipeline stress but reduce the pipeline deformation, and the thicker pipelines can significantly increase the stiffness and reduce deformation.

(2) Based on the results of finite element numerical simulation, the layout of monitoring points was optimized, and a three-level warning scheme for the settlement pipelines in the natural gas station was proposed. The scheme includes four stress monitoring points and displacement monitoring points, and the alarm function is achieved through a three-level early warning threshold configuration.

(3) When the settlement is too large, it is necessary to treat the station pipeline, and the methods that can be adopted are adding the concrete foundation floor or the pipe pier support. The method of installing a concrete floor under the pipeline can effectively reduce stress concentration at the connection between the gate-shaped pipe and the main pipe, but this method is costly and involves a large excavation area during treatment. If pipe piers are used for support, the stress and displacement of the pipeline can be reduced to a certain extent, but the impact is limited, and the effect is slightly better when both ends, and the middle of the pipeline are supported.

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