EFFECT OF SOIL SITE CONDITION ON THE DEFORMATION RESPONSE OF PRESSURE PIPELINES CROSSING FAULT

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Abstract

The oil and gas pipeline, water supply pipeline, heat supply pipe and other pressure pipelines are important lifeline engineering, they are at high risk of being damaged by earthquakes when crossing active faults. In order to further ensure the seismic safety of oil & gas pipeline, when the pipeline passes through the fault, it is required to have wide trench, shallow buried depth, and backfill loose sand instead of local soil. The effect of backfilled loose sand is discussed with the improved shell Finite Element Model. Based on the force balance analysis on pipeline moving in shallow soil layer, the method of modifying the soil spring model is proposed. When the trench is backfilled with loose sand, the deformation response of the pipeline mainly depends on the sand rather than the local soil. According to the results of Finite Element Analysis, the seismic measures of backfilling loose sand and widening pipe trench can reduce the deformation response of the pipeline. But the effectiveness of anti-seismic measure will be gradually failed with the gradual compaction of backfilled loose sand, and the deformation response of the pipeline will gradually approach the pipeline deformation responses without seismic measures. The results show that the trench slope is the main factor affecting the strain response of the pipe, the slope of the trench should be less than tan(45°-Φ/2), and the bottom width of the trench should be greater than the horizontal displacement of the fault.

Keywords: Buried pipeline, Seismic response, Site condition, Fault crossing

1. Introduction

Long-distance oil & gas, water supply and other pressure pipelines usually have to cross the seismic activity faults. The results of many earthquake disaster investigations show that the impact of the earthquake on the buried pipeline from light to heavy is the ground vibration, sand liquefaction and active fault, in another word, the dislocation of the earthquake fault caused the most serious damage to the gas pipeline. Scholars have carried out a lot of research work on the pipeline crossing seismically active faults, including the buckling characteristics of steel pipe, pipe-soil interaction, FEM model's boundary conditions, the failure criteria of steel pipe, etc. The seismic analysis method of pipeline under fault movement includes the theoretical analysis method and the numerical analysis method. The early theoretical method ignored the bending stiffness of pipe and the lateral pressure of surrounding soil, the fault displacement was assumed to be completely absorbed by the axial deformation of pipeline[1]. Later, the improved cable-model theory and beam-model theory were suggested [2,3,4]. It is worth noting that the theoretical analysis method can be used when the fault displacement is small and the pipeline is under tensile deformation. The above theoretical calculation methods are no longer available for the pipeline under large fault displacement. It is necessary to use the finite element model [5,6,7]. The finite element method could also be roughly divided into two categories: beam element method and shell element method. Because the pipe is a kind of shell structures, it is easy to produce large buckling phenomenon in its cross section under compressive load, so it is difficult to be analyzed with beam element method. Therefore, scholars generally use shell element method to simulate the response of buried pipelines under fault movement [8,9]. Under the fault movement, soil springs in three directions are generally used to simulate the soil-pipe interaction, including the soil spring in pipe axial direction, the horizontal lateral soil springs and the vertical soil spring[10].

In order to further ensure the seismic safety of oil & gas pipeline, when the pipeline passes through the fault, it is required to have wide trench, shallow buried depth, and backfill loose sand instead of local soil. The plane strain model has been used to analyze the influence of pipe trench size on pipe-soil interaction[11], but the model can not fully reflect the shape of the actual pipe and soil 3D deformation. Some scholars use nonlinear finite element method to establish a cross fault analysis model considering the backfill loose sand in the pipe trench [12], but this kind of FEM model is relatively complex. For the sake of simplicity, The 3-direction soil -spring elements are commonly used in the FEM model to consider the pipe-soil interaction, it is based on the premise that the soil properties outside the pipeline are the same in the infinite range. Therefore, the soil spring is supposed to be modified for the case that the pipe trench backfilled with loose sand in this paper.

2. Analysis of a pipe moving in trench

The theoretical study of pipe-soil interaction evolved from the model of pile-soil interaction. The p-y curve of pile-soil interaction model can be used to deduce the lateral earth pressure. The p-y curve was first proposed by McClelland and Focht in the relationship between the measured reaction force and the lateral deformation of the test pile [13]. It has developed relatively mature in the calculation theory of soil resistance. The soil around the pipe is similar to the soil around the pile, which may have two failure modes: passive wedge failure mode and flow failure mode [14]. These two failure modes correspond to the conditions of shallow and deep buried pipelines respectively. For pipelines crossing faults, they are generally shallow buried and belong to passive wedge failure mode. As shown in Fig.1, The soil deformation area around the pipeline can be roughly divided into active area, passive area and gravity balance area. As the main bearing body of the pipeline movement process, the passive area is driven by the pipeline to move forward and upward together. Because the active area loses the restriction of the pipeline, it slides downward under the action of self weight. The soil movement in the active area and the passive area has shear failure with the soil body in the gravity balance area, and finally two fracture surfaces are formed.

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Fig. 1 – Force analysis of a pipe moving in the trench

The soil in the upper left part of the pipeline is simplified as the active area, the soil in the upper right part is simplified as the passive area. The horizontal soil pressure acting on the pipeline F_{p1} can be obtained through the force balance along the direction:

$$F_{p1} = F_{n1}\cos\alpha + F_{s1}\sin\alpha + F_{s1}\sin\beta - F_{n2}\cos\beta \tag{1}$$

Where, α=45°+Φ/2, β=45°−Φ/2 ;

Φ : Internal friction angle of fill-back soil;

F_n : Supporting force of soil under the sliding surface;

F_s : Friction force under the sliding surface;

According to Eq. (1), the horizontal soil pressure acting on the pipeline is obtained as follows:

$$F_{p1} = \frac{\gamma}{2}\left(H + \frac{D}{2}sin\alpha\right)^2 (tan^2\alpha - tan^2\beta) \tag{2}$$

Where, γ is the density of soil, H is the buried depth, and D is the diameter of pipe.This formula ignored the cohesion of soil, describe the movement of pipeline in the trench, and the surrounding soil has broken, so its calculation result is smaller than that of the code formula.

The above theoretical derivation shows that the smaller the internal friction angle of the backfill, the smaller the passive area of the lateral movement of the pipeline, the smaller the lateral earth pressure on the pipeline, and the easier the pipeline moves in the trench, which can reduce the strain produced by the pipeline.

3. Effect of backfilled loose sand in the trench

3.1 Soil spring model in general

Under the fault movement, there exists interaction between oil and gas pipeline and surrounding soil. The interaction between the pipes and soil is generally simulated using the soil spring model, including the axial soil spring, the horizontal soil spring, and the vertical soil spring. The vertical soil spring is divided into vertical upward soil spring and vertical downward soil spring, as shown in Fig. 2. The parameters of these soil springs are determined by the diameter of the pipe, the buried depth, and the type of site soil, the soil density, the soil cohesive force and the internal friction angle, referred to ASCE guide [10].

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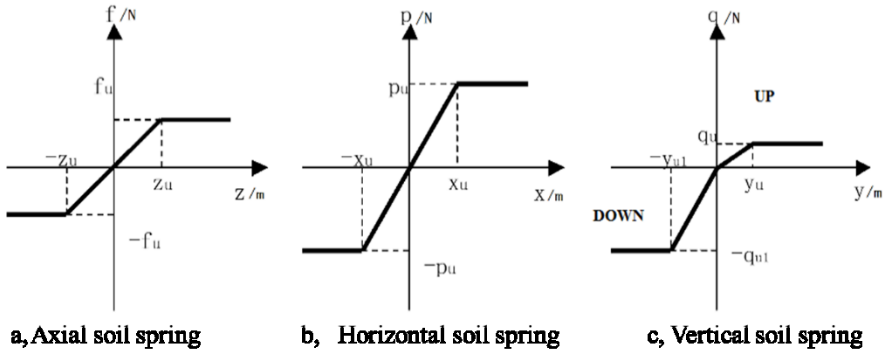

Fig. 2 – Soil spring models characterizing the pipe-soil interaction

3.2 Soil spring model for the backfilled loose sand

The typical trench section for a pipeline crossing fault is shown in Fig. 3. For the convenience of laying and welding, the widening allowance (*w*)at the bottom of the trench is generally not less than 0.5m. Following the fault displacement, the pipeline movement in the trench could be divided into three stages: (a) the pipeline moves in the backfilled loose sand; (b) from the beginning of touching the trench slope to the time when it is completely subject to the original site soil pressure; (C) completely subject to the lateral pressure of the original site soil. In this paper, the upward sliding of the pipeline along the trench slope is not considered temporarily, and the bottom width of trench only affects the horizontal transverse soil spring.

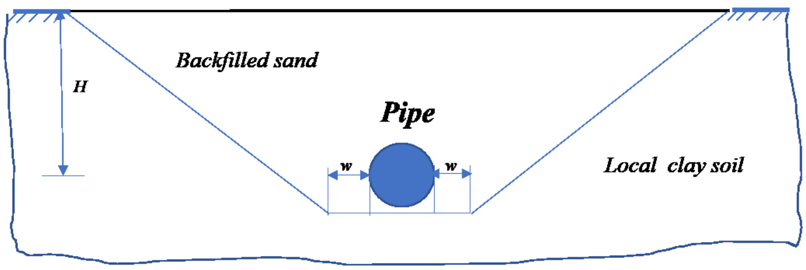

Fig. 3 – Typical trench for a pipeline crossing fault

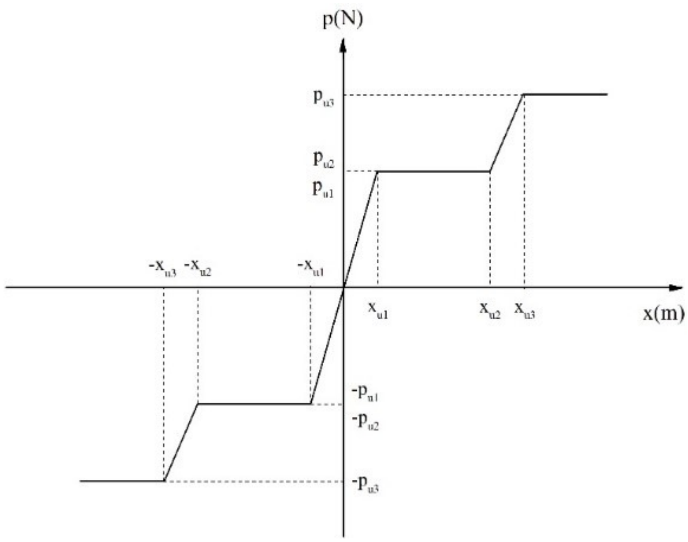

Fig. 4 – Horizontal soil spring for the pipe buried in a backfilled-sand trench

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The horizontal Soil spring for the pipe buried in a backfilled-sand trench could be defined as shown in Fig.4. In the Fig.4, $P_{u1} = P_{sand}$, $X_{u1} = X_{sand}$; $P_{U2} = P_{sand}$, $X_{u2} = X_{sand} + w$; $P_{U3} = P_{clay}$, $X_{U3} = X_{sand} + w + X_{clay}$. In this paper, the upward sliding of the pipeline along the trench slope is not considered temporarily, and the bottom width of trench only affects the horizontal transverse soil spring.

As an example, for a gas pipeline crossing the strike slip fault , the pipe is made of steel X80 with the diameter of 1.016m, the buried depth is 1.2 m, and the crossing angle is 90°. For comparison, two study cases are considered, one is the trench backfilled with local clay soil, the other is the trench backfilled with loose sand. The parameters of loose sand are listed in Table 1. The bottomn width of trench is 0.5 m. As shown in Fig. 5, the maximum axial tensile strains of two cases are not too different when the fault displacement is small, but with the increase of the fault displacemnt, the pipeline strain can be greatly reduced by backfilled loose sand and designing a wider trench.

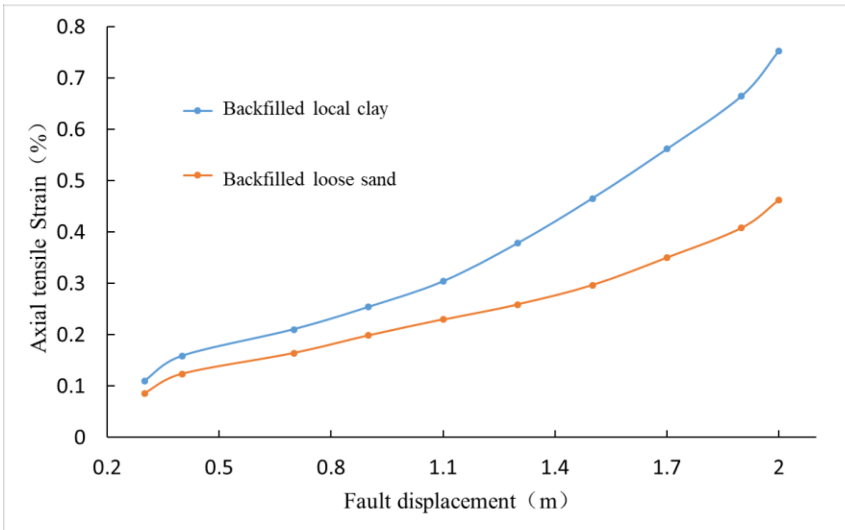

Fig. 5 –Axial tensile strain of the pipe with the fualt displacement

3.3 Effect of sand compaction on deformation response of pipeline

With the passage of time after pipeline laying, the backfilled loose sand will gradually become nore and more dense. It will affect the deformation response of the pipeline, including the change of internal friction angle, density and friction coefficient of backfilled loose sand. As shown in Table 1, loose sand becomes more dense, sand particles are closely occluded with each other, so the internal friction angle becomes larger. FEM results of axial tensile strain of pipeline with fault displacement are shown in Fig. 6.

Table 1 – Soil parameter of sand compaction

Case	**Backfilled Soil Type**	**Internal friction angle (°)**	**Density (kg/m³)**	**Friction coefficient**
Case 1	Loose sand	20	1.6×10^3	0.4
Case 2	Sand 1	25	1.7×10^3	0.5
Case 3	Sand 2	30	1.8×10^3	0.6
Case 4	Sand 3	35	1.9×10^3	0.65
Case 5	Dense sand	40	1.95×10^3	0.675

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As shown in Figure 6, the backfilled sand becomes gradually dense, the deformation response of the pipeline is gradually close to the strain response of the pipeline without seismic measures. That is to say, with the passage of time, the seismic measures for backfilling loose sand will gradually fail. This also shows the reason why the calculation of the lateral soil spring is based on the site soil parameters buried in the pipeline, rather than the loose sand parameters.

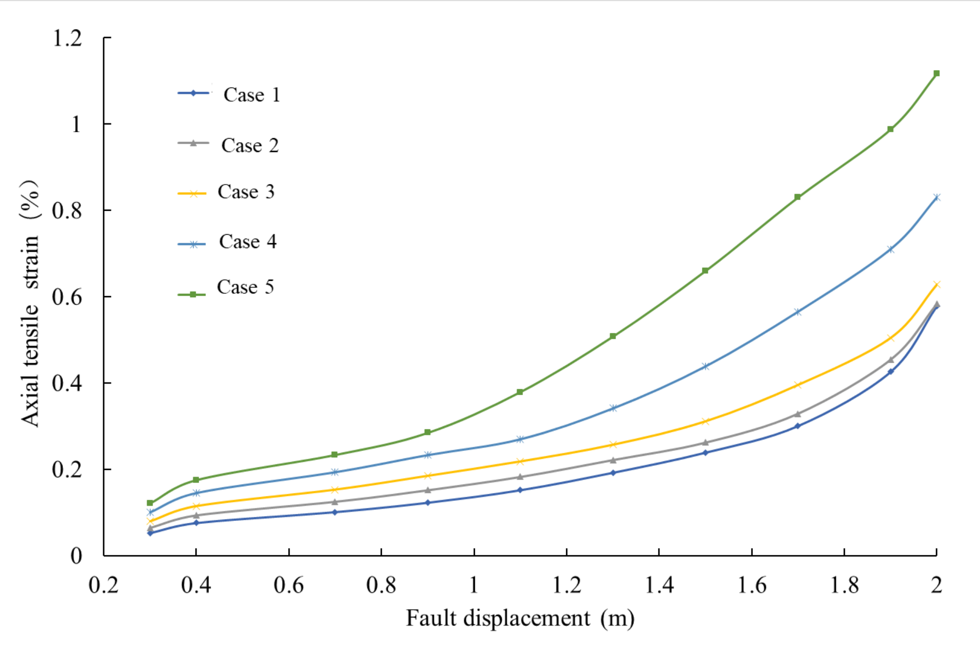

Fig. 6 –Effect of sand compaction on the strain response of pipeline

4. Conclusion and discussion

Based on the force balance analysis on pipeline moving in shallow soil layer, the method of modifying the soil spring model is proposed. When the trench is backfilled with loose sand, the deformation response of the pipeline mainly depends on the sand rather than the local soil. According to the results of Finite Element Analysis, the seismic measures of backfilling loose sand and widening pipe trench can reduce the deformation response of the pipeline. The slope of the trench wall is better to be less than tan(45°-Φ/2). When the pipeline moves to the trench wall, the stress analysis becomes complex and needs further study. The bottom width of trench should be greater than the horizontal displacement of the fault. It should be noted that the seismic measures for backfilling loose sand will gradually fail with the passage of time.

5. Acknowledgements

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