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Stress Analysis of Buried Pipeline in Soil Liquefaction Environment

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Abstract: *The Sichuan-East Gas Pipeline uses a 1016mm large-diameter pipeline. The geographical conditions and soil conditions along the project are complex, and the pipeline is prone to float up, which affects the safe operation of the pipeline. Taking this project as an example, this paper analyzes the force law of the buried pipeline when the soil liquefaction causes the pipe section to float. Through the ABAQUS finite element simulation, the force and displacement of the pipeline after floating, the influence of parameters such as the length of liquefaction zone, soil density, pipe diameter, wall thickness, buried depth, and pipeline operating pressure on the force and displacement of the pipeline are analyzed. A five-element cubic nonlinear fitting equation was established, and the nonlinear fitting was performed using ORIGIN, and the calculation formula of the limit floating length of the pipeline was obtained and verified. Through the study of the force and displacement of buried pipelines in liquefied soil, the occurrence of pipeline floating accidents can be effectively predicted and prevented, and the safe operation of pipelines can be guaranteed.*

Keywords: *soil liquefaction; pipeline floating; failure analysis; numerical simulation*

1. Introduction

1.1. Research background

Due to the complexity of the areas spanned by the pipeline, mostly mountainous areas or water network areas, soil liquefaction is one of the main types of geological disasters suffered by the Sichuan-East Gas Pipeline Project. The pipeline floating in the liquefied soil is more serious. The pipeline floating poses a serious threat to the safe operation of buried pipelines. In severe cases, the pipeline will break and cause more secondary disasters. Therefore, the analysis and study of the force and displacement laws of the buried pipeline of the Sichuan-East Gas Transmission Project when the pipe section floats due to soil liquefaction is of great significance for predicting and preventing the occurrence of pipeline floating accidents and ensuring the safe operation of the pipeline.

1.2. Literature review

The floating failure of buried natural gas pipeline under liquefaction of the site involves complex pipe-soil interaction, and many factors will affect the floating reaction of the pipeline.

In 1973, Youd T.L. [1] carried out the definition of the concept of soil liquefaction, which initiated many scholars' research on the floating reaction of pipelines under site liquefaction. In 1985, Yeh, Y.H. and L.R.L.Wang [2] changed the properties of the foundation soil, set up different elastic foundation soils, used a simple two-dimensional beam model to simulate the underground pipeline, and applied the finite difference method to simulate the dynamic stress of the pipeline.

In 1997, Koseki [3] defined the anti-floating safety factor of pipelines by paying attention to the floating mechanism of pipelines. In 2000, K. Shimamura and others [4] monitored the floating reaction of buried gas pipelines. In 2003, Ling et al. [5] used a centrifugal model experiment to simulate the floating state of the pipeline after sand liquefaction, and thus proposed a simplified calculation method for the anti-liquefaction buoyancy of buried pipelines. In 2014, Mohammad Hossein Erami et al. [6] proposed a new pipe-soil interaction equation, introduced a new way to describe the pipe-soil

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interaction of segmented pipelines, and explored the interaction of segmented pipelines under fault geological conditions.

In 2017, aiming at the floating situation of the shallow buried pipeline in the liquefaction under the sloping sand soil, Liu Jingwen [7] used a centrifugal model test to obtain the interaction between the pipeline and the soil, and established a mechanical model for the liquefaction and floating pipeline. In next year, Zhang Yanan [8] established a pipe-soil contact analysis model under soil liquefaction environment based on the finite element software ADINA. The model takes into account factors such as soil spring and thermal-mechanical coupling, and thus analyzes mechanical problems such as the strain stress of the pipeline.

In summary, there have been many results in finite element analysis and experimental research on natural gas pipelines under soil liquefaction, and many theoretical results have been able to provide early warning effects for the deformation and failure of the pipeline floating under soil liquefaction environment. However, the pipe-soil model under soil liquefaction environment is very complicated, and the finite element method is also difficult to fully and reasonably consider all influencing factors. At present, some quantitative fitting formulas often have certain limitations and are often not applicable to the Sichuan-East Gas Pipeline. The empirical formula obtained by scholars based on the quantitative analysis of multiple influencing factors is difficult to use in engineering practice. At present, no empirical formula can be found for the maximum floating displacement of the 1016mm pipe diameter of the Sichuan-East Gas Transmission Trunk Line. In addition, there is a big gap between the experimental model and the actual site engineering. The experimental research can only study the mechanical phenomena of the pipeline, and there are fewer influencing factors that can be considered. Moreover, the test conditions are difficult to determine, and the test results cannot be completely consistent with the finite element analysis results, and the accuracy of the test results cannot be guaranteed.

2. Manuscript Preparation

This section is divided into five parts: basic parameters, loads and analysis steps, pipe-soil interaction, boundary conditions, and grid division. The establishment of the model and the value of each parameter that ABAQUS used for simulation are introduced in this section.

2.1. Basic parameters

The Sichuan-East Gas Transmission uses buried pipelines of X70 and ϕ1016, the simulated wall thickness is 17.5mm, the material density of X70 is 7850kg/m3; the buried depth of the pipeline is 1.5m, the soil is clay, and the soil density is 2000kg/m3. The coefficient of friction between pipe and soil is set to 0.2, the liquefaction zone and the non-liquefaction zone are symmetrically distributed, and the length of the liquefaction zone is 80m. The physical model is shown in Figure 1. The soil in the liquefaction zone is simulated by an equivalent soil spring model.

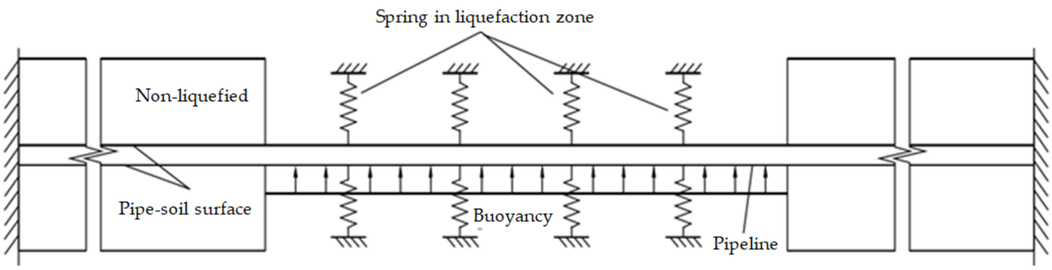

Figure 1: Physical model.

In this finite element simulation, two material properties need to be set.

(1) Material properties of the pipeline

The pipe model of the pipeline is X70, and the characteristic parameters of the X70 pipe are shown in Table 1:

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Table 1: Pipeline parameters.

Pipe model	Density (kg/m3)	Modulus of elasticity (GPa)	Poisson's ratio	Yield strength (MPa)
X70	7850	210	0.3	485

According to the Ramberg-Osgood constitutive model, the true stress-plastic strain relationship of the X70 pipe is obtained, as shown in Table 2. The data has been converted and will be input to the ABAQUS.

Table 2: The true stress and plastic strain of the pipe.

Real stress (MPa)	485	500	520	540	565	590	615
Plastic strain (10-3)	0	0.357	3.74	9.16	17.06	27.12	44.52

(2) Material properties of soil

In this paper, the Moore Coulomb model is used to describe the properties of the soil. The coefficients are shown in Table 3.

Table 3: Soil properties.

Poisson's ratio	Saturated bulk density of soil (kN/m3)	Modulus of elasticity (MPa)	Expansion angle (°)	Friction angle in soil (°)	Cohesion (KPa)
0.25	18	15	0	30	8

2.2. Load step and Analysis

After the force analysis of the buried natural gas pipeline in the liquefaction zone, it can be seen that the overall load received includes: the gravity of the pipeline, the pressure transmitted by the natural gas inside the pipeline to the pipeline, the buoyancy of the pipeline in the liquefied soil, and earth pressure that hinders the movement of the pipeline. The calculation result of the soil spring is 5.022×106 N/m2. Take 1/2000 of the value of the soil spring in the liquefied environment.

2.3. Pipe-soil interaction

In ABAQUS, the nonlinear contact of pipe-soil is defined by setting the normal and tangential behavior of pipe-soil contact. The contact between pipe and soil adopts "surface-surface" contact. Because the rigidity of the pipe is much greater than that of the soil, the outer surface of the pipe is used as the main contact surface, and the surface of the soil contacting the pipe is taken as the slave surface. In the contact attribute setting, the normal behavior is defined as "hard contact"; the tangential behavior is defined as "penalty", and the friction coefficient is set to 0.2. The soil-spring model is adopted for the pipe-soil interaction in the liquefaction zone.

2.4. Boundary conditions

The normal displacement angle of the upper and lower surfaces of the soil is set to 0; the normal displacement angle of the two side surfaces of the soil is set to 0; the displacement angle of the end cross section of the buried pipeline along the axial direction of the pipeline is set to 0. Because the mid-span cross-section of the pipeline is a symmetrical plane, it is setted as symmetry constraint (ZSYMM).

2.5. Meshing

The soil mesh is selected as a hexahedral structured mesh, and the element type is C3D8R. The mesh of the pipeline is divided into a quadrilateral mesh, and the element type is selected as S4R. Since the force of the model is concentrated in the pipe-soil con-tact part of the pipe and the soil, the meshing of this part needs to be more dense. The result of mesh is shown in Figure 2.

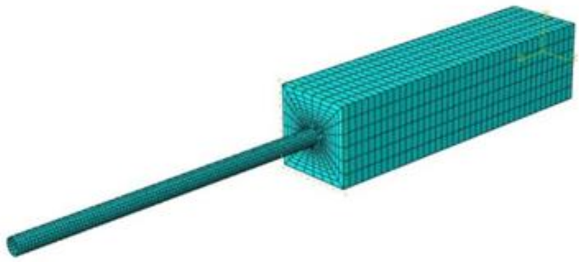
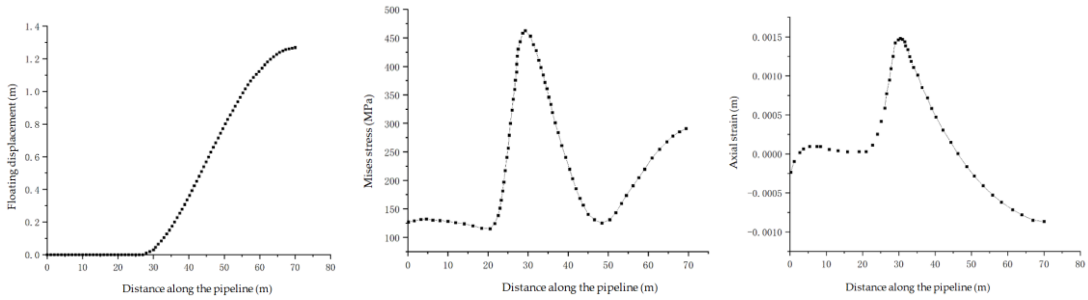


Figure 2: Mesh division.

3. Results

According to the results of the finite element calculation, the pipeline stress concentration zone mainly includes two places, one is the junction of the liquefaction zone and the non-liquefaction zone, and the other is the middle of the pipeline in the liquefaction zone. The change trend of strain and stress is basically the same. Both stress and strain have maximum values near the junction of the liquefaction zone and the non-liquefaction zone and in the middle of the liquefaction zone. The junction is the most concentrated area of the entire pipeline.



(a) (b) (c)

Figure 3: Finite element calculation results: (a) The relationship between the distance along the pipeline and the floating displacement; (b) The relationship between the distance along the pipeline and the Mises stress; (c) The relationship be-tween the distance along the pipe and the axial strain.

The maximum displacement of the pipeline appears in the middle of the liquefaction zone, and the maximum vertical displacement is 1.26m. The buoyancy of the pipe-line in the vertical direction is much greater than the soil restraint force in the horizontal direction. At the same time, because the transport medium is natural gas, the weight of natural gas is ignored, resulting in the combined force of buoyancy and lift being much greater than gravity, so the pipeline as a whole shows a vertical upward bending deformation. At this time, the maximum Mises stress experienced by the pipeline is 437MPa, which has not exceeded the yield strength of the pipeline. If judged according to the stress failure criterion, there is no failure of the pipeline at this time. The maximum strain of the pipeline is 0.28%. If judged according to the strain failure criterion, the pipeline is in a safe state at this time.

4. Discussion

In this section, according to the results of the section four, the influencing factors of the stress on the floating pipeline are analyzed. After that, the relevant content of the maximum floating displacement of the pipeline was studied.

4.1. Influencing factors

According to the theoretical analysis of the uplift of liquefied soil, the main factors affecting the stress of the pipeline in liquefaction environment are: the length of the liquefaction zone, the density of the liquefied soil, the pipe diameter, the buried depth, the wall thickness and the operating pressure of the pipeline. This part will discuss the influence of various factors to guide engineering practice.

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The length of the liquefaction zones are setting as 20m, 40m, 50m, 60m, 80m, and 100m. Multiple sets of simulation analysis are performed to obtain the stress and deformation of the pipes with different liquefaction zone lengths. It can be seen from the result that the length of the liquefaction zone will have significant impact on the force and deformation of the floating pipeline. As the length of the pipeline in the liquefaction zone increases, the floating reaction of the pipeline is significantly strengthened. This is mainly because as the length of the pipe section in the liquefaction zone increases, the buoyancy also increases significantly, and the pipe will therefore bear greater floating displacement, axial strain and concentrated stress. Therefore, it is easy to cause the deformation or even failure of the pipeline if the length of the liquefaction zone is too long.

The density of liquefied soil is taken as 1800kg/m3, 1900kg/m3, 2000kg/m3, 2100kg/m3, 2200kg/m3. According to these values, multiple sets of simulation analysis are performed to obtain the stress and deformation of the pipeline under different soil densities. The floating reaction of the pipeline will be pronounced as the density of the liquefied soil increases. The Mises stress and axial strain of the pipeline increase with the increase of the density of the liquefied soil, and the maximum appears at the junction of the liquefied section and the non-liquefied section. Based on the Archimedes buoyancy principle, the buoyancy of the pipeline is equal to the product of the volume of the pipeline and the density of the liquefied soil. Therefore, as the density increases, the buoyancy reaction increases significantly. As a result, when soil in the area where the pipeline passes is easily liquefied, attention should be paid to the density of the liquefied soil.

Then we analyze the finite element model by changing the pipe diameter. The pipe diameters are respectively 800mm, 1016mm and 1200mm. As the pipe diameter increases, the Mises stress and axial strain experienced by the pipe also increase. However, as the pipe diameter increases, the floating displacement of the pipe decreases slightly. This is because as the pipe diameter increases, the overall strength of the pipe also increases, and the ability to resist deformation has been strengthened.

The finite element model is analyzed by taking different pipe wall thicknesses. The pipe wall thickness is 12.5mm, 15.0mm, 17.5mm, 20.0mm and 22.5mm respectively. The greater the pipe wall thickness, the smaller the floating displacement of the pipe, and the Mises stress and axial strain on the pipe are also significantly reduced. This is mainly because when the thickness of the pipeline increases, the weight of the pipeline also increases significantly, effectively weakening the upward trend. The increase in wall thickness also increases the stiffness of the pipeline, and the ability to resist bending deformation will be greatly enhanced.

By setting different buried depths, the influence of buried depths on pipeline float-ing in the liquefaction zone is analyzed. The buried depths are respectively taken as 1.0m, 1.5m, 2.0m, 2.5m, and 3.0m. As the buried depth of the pipeline increases, the floating displacement of the pipeline will decrease. The Mises stress and axial strain of the pipeline will decrease, but the change is relatively small. This is mainly because the deeper the buried depth, the greater the pressure of the overlying soil on the pipeline, and the more obvious the restraint effect of the soil on the pipeline, thereby reducing the possibility of failure.

The influence of pipeline operating pressure on pipeline floating in the liquefaction zone is analyzed by setting different pipeline internal pressures. The pressure inside the pipeline will affect the overall mechanical properties of the pipeline. The higher operating pressure, the more significant the upward floating of the pipeline.

The maximum Mises stress and axial strain of the pipeline both increase with the increase of the operating pressure of the pipeline, and the maximum Mises stress and the maximum axial strain appear in the middle of the pipeline in the liquefaction zone. Therefore, in the engineering practice, the influence of factors such as temperature or flow rate should be avoided to cause drastic changes in the internal pressure of the pipeline. When the pipeline rises due to soil liquefaction, it is possible to consider reducing the operating pressure to reduce the risk of pipeline failure.

4.2. Calculation of maximum floating displacement

The calculation method of the maximum floating length is shown in Figure 4 (a). When the curve of the relationship between the floating length of the pipeline and the maximum Mises stress intersects the yield strength of the pipeline (485MPa) line, it in-dicates that the maximum Mises stress experienced by the pipeline under this floating length has reached the yield strength. Therefore, the maximum floating length of the pipeline is 90.4m.So the maximum floating displacement of the pipeline is 90.4m.

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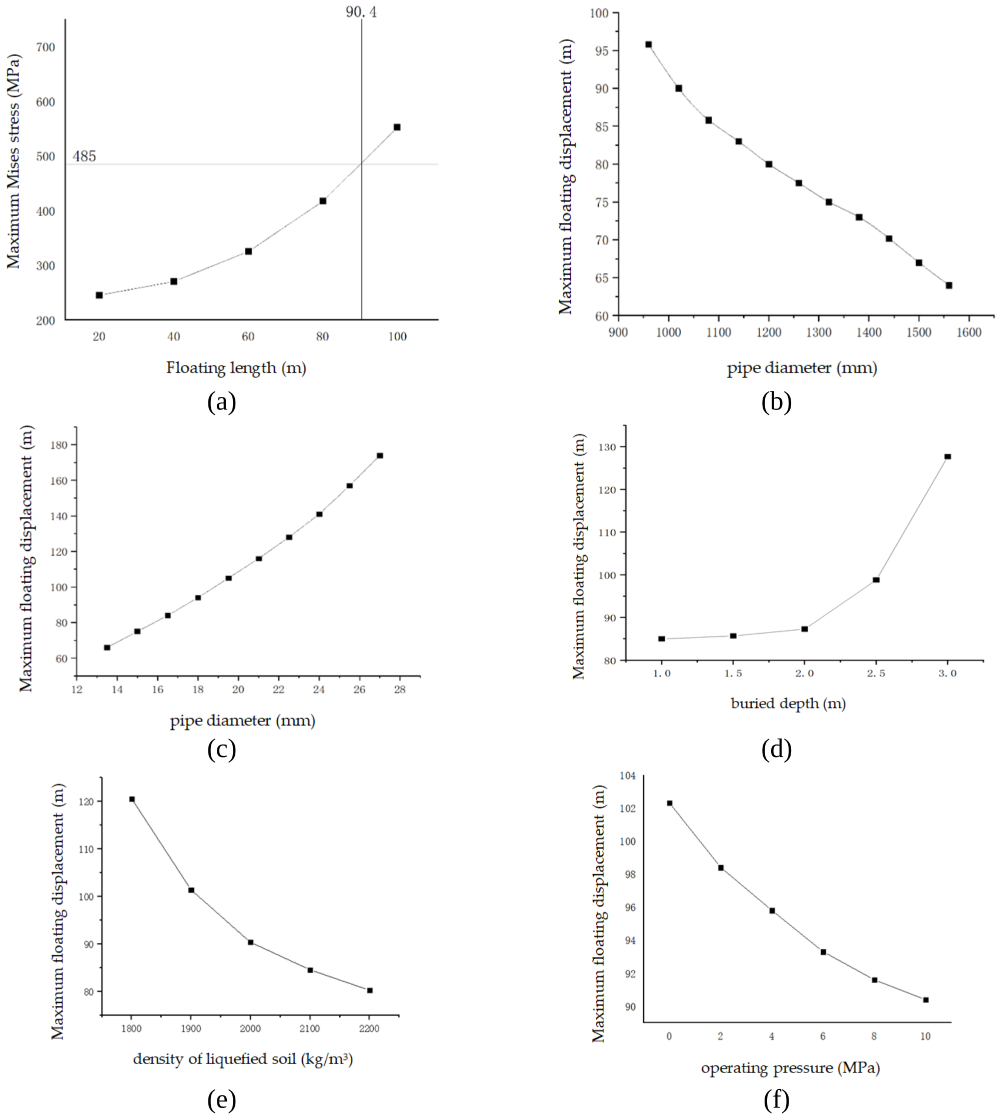

Figure 4: Curve of relationship between maximum floating displacement and others: (a) Floating length and maximum Mises stress curve; (b) Curve of relationship between maximum floating displacement and pipe diameter; (c) Curve of relationship between maximum floating displacement and wall thickness; (d) Curve of relationship between maximum floating displacement and buried depth; (e) Curve of relationship between maximum floating displacement and density of liquefied soil; (f) Curve of relationship between maximum floating displacement and operating pressure.

The relationship between the maximum floating displacement and pipeline diameter, wall thickness, buried depth, liquefied soil density and pipeline operating pressure is shown in Figures 4 (b) to (f). The larger the diameter of the pipeline, the smaller the maximum floating displacement, the more likely the pipeline will fail. The maximum floating length increases with the increase in buried depth. The greater wall thickness, the greater maximum floating displacement. This is mainly because wall thickness increases the weight of the pipeline and increases the ability of the pipeline to resist bending. As the density of the liquefied soil increases, the maximum floating displacement of the pipeline in the liquefaction zone is also significantly reduced, mainly because the increase in the density of the liquefied soil causes the buoyancy to increase. The operating pressure of the pipeline increases, and the maximum floating displacement decreases. This is mainly because the stress concentration of the pipeline will increase after a large deformation of the pipeline.

4.3. Fitting of pipeline failure maximum floating displacement formula

4.3.1. Parameter setting and equation construction

The maximum floating displacement of the buried pipe is related to the wall thickness, the buried depth, the diameter and the operating pressure. Therefore, in this part, the calculation equation of the maximum floating displacement is constructed. The ORINGIN and the method of undetermined coefficients are used to solve the equations.

There is no formula for calculating the maximum floating displacement of buried pipelines. However, according to theoretical analysis, the maximum floating displacement of pipelines is mainly affected by the characteristics of the pipeline and soil. Therefore, the following cubic nonlinear fitting equation is constructed.

$$\begin{cases} L_{lim} = f(\delta) \times f(\hbar) \times f(D) \times f(P) \times f(\rho) + A_{21} \\ f(\delta) = A_1\delta^3 + A_2\delta^2 + A_3\delta + A_4 \\ f(\hbar) = A_5\hbar^3 + A_6\hbar^2 + A_7\hbar + A_8 \\ f(D) = A_9D^3 + A_{10}D^2 + A_{11}D + A_{12} \\ f(P) = A_{13}P^3 + A_{14}P^2 + A_{15}P + A_{16} \\ f(\rho) = A_{17}\rho^3 + A_{18}\rho^2 + A_{19}\rho + A_{20} \end{cases} \tag{1}$$

In formula 1, δ is wall thickness, h is buried depth, D is diameter, P is operating pressure, ρ is density of liquefied soil.

4.3.2. Formula fitting and accuracy analysis

Establish the above equation model in ORINGIN, input the initial value and each group of original data, use the nonlinear fitting module to perform multivariate high-order nonlinear regression analysis, and calculate the best value of 21 undetermined parameters. In order to ensure accuracy, the undetermined coefficients are kept to 3 decimal places. The calculated values are shown in Table 4.

Table 4: The value of the undetermined coefficient.

coefficient	Value	coefficient	Value	coefficient	Value	coefficient	Value
A_1	0.045	A_2	-98.639	A_3	7.204	A_4	-1.698
A_5	-1.449	A_6	9.732	A_7	-2.162	A_8	1.542
A_9	0.015	A_{10}	0.142	A_{11}	12.291	A_{12}	-341.350
A_{13}	-0.051	A_{14}	-0.021	A_{15}	0.013	A_{16}	1.160
A_{17}	89.639	A_{18}	74.632	A_{19}	15.625	A_{20}	905.600
A_{21}	-755.236						

This article uses correlation coefficient sum of squares (R2), residual sum of squares (SSE), and mean square error (MSE) to measure the fitting accuracy. The fitting accuracy is shown in Table 5, and the regression curve is shown in Figure 5.

Table 5: Fitting accuracy of formula.

Index item	R2	SSE	MSE
Calculated	0.9983	20.20818	0.9365

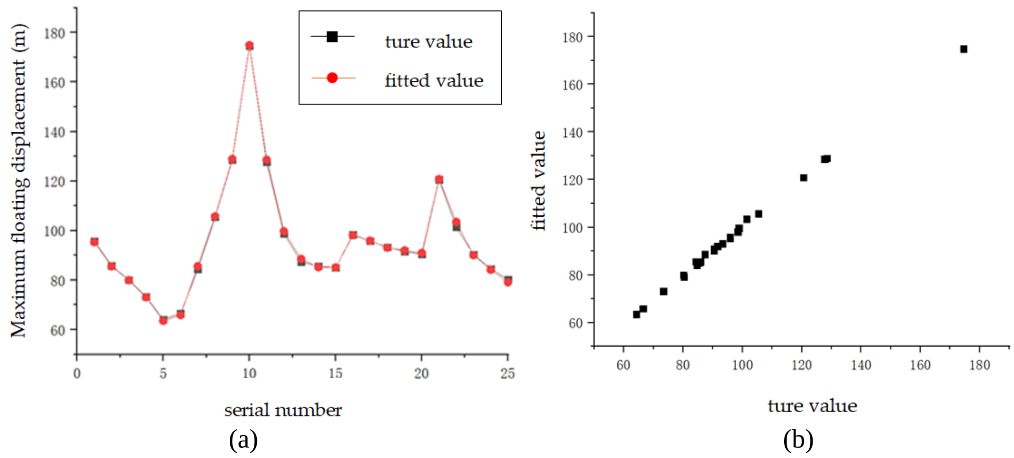

Figure 5: Regression curve: (a) Scattered point distribution chart; (b) Target range.

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It can be seen from Figure 5 that the regression fitting accuracy of the five-element cubic non-linear polynomial used in this article is very high. Therefore the floating failure (maximum floating displacement) formula of the buried pipeline of the Sichuan-East Gas Transmission Project is obtained, as shown in formula 2.

$$\begin{cases} L_{lim} = f(\delta) \times f(\hbar) \times f(D) \times f(P) \times f(\rho) - 755.236 \\ f(\delta) = 0.045\delta^3 - 98.639\delta^2 + 7.204\delta - 1.698 \\ f(\hbar) = -144.9\hbar^3 + 9.732\hbar^2 - 2.162\hbar + 1.542 \\ f(D) = 0.015D^3 + 0.142D^2 + 12.291D - 341.350 \\ f(P) = -0.051P^3 - 0.021P^2 + 0.013P + 1.160 \\ f(\rho) = 89.639\rho^3 + 74.632\rho^2 + 15.625\rho + 905.600 \end{cases} \tag{2}$$

There is no relevant standards and literature about maximum floating displacement calculating. Therefore we combined with the actual situation of the project, five sets of parameters (data points used in the non-fitting formula) are randomly selected, and the ABAQUS is used to model and calculate the maximum floating displacement. Compare the calculation result of the fitting formula with the result of the software simulation. The value and calculation result are shown in Table 6.

Table 6: Fitting formula validity check calculation table.

Serial number	Internal pressure (MPa)	Buried depth (m)	Wall thickness (mm)	Liquefied soil density (kg/m3)	Pipe diameter (mm)	Finite element value (m)	Fitting calculation (m)	absolute error	relatively error
1	10	1.2	17.5	2000	1080	85.81	84.64	-1.17	1.36%
2	10	1.5	16.5	2000	1016	81.23	83.16	1.93	-2.38%
3	5.0	1.5	19.5	1800	1016	111.28	103.73	-7.55	6.78%
4	2.5	1.5	17.5	2000	1016	102.36	103.53	1.17	-1.14%
5	7.5	1.5	17.5	2000	1016	86.85	87.91	1.06	-1.22%

It can be found from Table 6 that the calculated value of the fitting formula at the non-fitting data point is very similar to the finite element analysis value. The minimum error is -1.14%, and the maximum error is only 6.78%, indicating that the fitting formula has high accuracy and good applicability, can effectively reflect the relationship between the maximum floating displacement and various environmental parameters, and has great engineering application value.

5. Conclusions

This paper takes the buried pipeline of the Sichuan-East Gas Transmission as the research object, analyzes the stress of the buried pipeline in the environment of soil liq-uefaction. After studying the deformation of the pipeline and the forces that pipeline suffers under the soil liquefaction environment, the following results are obtained:

(1) Through the finite element simulation with ABAQUS, the force and displacement of the pipeline after the uplift has been analyzed, and the influence factors such as the length of liquefaction zone, the density of soil, diameter, the wall thickness, the buried depth and the operating pressure of pipeline have been analyzed. As the length of the liquefaction zone increases, the floating reaction of the pipeline is significantly strengthened. The greater the density of the liquefied soil, the more significant the floating reaction of the pipeline. As the pipe diameter increases, the Mises stress and axial strain experienced by the pipe also increase, and the floating displacement of the pipe decreases slightly. The greater the pipe wall thickness, the smaller the floating displacement of the pipe, and the Mises stress and axial strain on the pipe are also significantly reduced;

(2) The relationship between the maximum floating displacement and pipeline diameter, wall thickness, buried depth, density of liquefied soil and pipeline operating pressure is obtained. The larger the diameter of the pipeline, the smaller the maximum floating displacement, and the easier the pipeline will fail; the maximum floating displacement increases with the increase in buried depth; the greater the wall thickness, the greater the maximum floating displacement; the greater the density of liquefied soil, the smaller the maximum floating displacement; as the operating pressure of the pipeline increases, the maximum floating displacement will decrease;

(3) A six-element cubic nonlinear fitting equation was established, and the nonlinear fitting was performed using ORIGIN, and the calculation formula for the maximum floating displacement of the

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pipeline was obtained. Both the accuracy index and the validity check prove that the fitting formula is accurate, has good applicability, and has great engineering application value.

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