Research article

Theoretical analysis and finite element simulation of pipeline structure in liquefied soil

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ABSTRACT

A mechanical analysis model for the floating of buried pipelines in soil liquefaction areas is established in this paper. In order to improve the inherent defects of the elastic foundation beam method based on the Winkler model and increase the calculation accuracy, the Pasternak model is introduced and the interaction between soil and spring is considered. A mechanical analysis method for buried pipelines in liquefaction zone considering axial load is proposed in present paper. According to the Pasternak model and the deflection curve differential equation, the pipe bending deformation curve equation and the deformation coordination equation are derived. The analytical calculation method of the pipe mechanical response is established. A new method of the mechanical analysis of the floating of buried pipelines in the liquefaction zone is provided. The mechanical response of the pipeline under the conditions of different pipeline parameters and liquefaction zone length is analyzed. The reliability of the analysis method in this paper is verified by the comparison of finite element method (FEM). Considering that the previous researches of scholars mainly focused on straight pipes, there are few studies on the pipe structure nodes in liquefied soil. The mechanical properties of the three-way pipe structure in the soil liquefaction zone are analyzed by the finite element method (FEM). The influence of pipe diameter, wall thickness, liquefied soil density, transition zone length, buried depth, and pipeline internal pressure on the mechanical response of the pipeline is analyzed.

1. Introduction

Buried pipelines are an important part of lifeline projects and an important part of urban infrastructure construction and residents' production and life. Urban underground pipeline engineering is widely used in heat supply, oil transportation, water supply, etc., and plays an important role in urban municipal construction and development. In recent years, the long-distance pipeline projects with rapid development had become one of the important means of energy transmission. A large part of the pipelines needs to pass through areas with complex geological environment and frequent liquefaction disasters, which seriously threatens the safe operation of pipelines. Buried pipelines are often under complex site conditions, and the possibility of damage is relatively high. Moreover, accidents mostly occur underground, which is not easy to detect quickly. Once a serious accident such as a rupture occurs, it will cause huge loss of life and property. As one of the earthquakes and geological disasters in pipeline engineering, soil liquefaction poses a serious threat to pipeline safety. In 1973, soil liquefaction was defined by Yould [1] as "the increase in the water pressure in the soil pores leads to a decrease in the effective stress, and the soil changes from a solid state to a liquid state". Since then, the response of buried pipelines under earthquake liquefaction had attracted the attention of the academic community. Theoretical research, finite element analysis [2], and experimental research were successively launched. In theoretical research, in 1997, scholars based on the two assumptions that the inertial force can be ignored and the pipeline moves with the soil together, and the seismic waves can be simulated by seismic traveling waves. The analysis method of buried pipeline based on small deformation between pipe and soil was studied by Newmark et al. [3]. In 1985, the nature of the foundation soil was changed, different elastic foundation soils were set up, and a simple two-dimensional beam model was applied to simplify it to simulate underground pipelines were studied by Yeh et al. [4]. The finite difference method was applied to simulate the dynamic stress of the pipeline. It was believed that when the soil around the pipeline did not liquefy, the axial resistance of the pipeline increased. When the soil was liquefied, the buoyant force generated by the liquefied soil caused the axial stress strength of the buried pipeline decreasing. The existence of

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the resistance of the foundation soil can greatly improve the axial resistance of the pipeline was proved. In 1987, the spring mass model was applied to analyze the damage of the pipeline due to the generation of dynamic strain when the soil was liquefied, which was studied by Nishio et al. [5]. The result was that soil movement reduced the dynamic strain of the pipeline. The diameter of the pipeline was larger, the dynamic strain was smaller. This theory was also consistent with the results of later studies. In 1992, the application of damping values that were very consistent with actual working conditions, the horizontal response of buried pipelines under the liquefaction site with an entrance buried under the liquefaction site was studied by Wang et al. [6]. The analysis results showed that damping had a more significant impact on the dynamic response of buried pipelines under site liquefaction than other site parameters. Assuming that the continuous pipeline was elastic and the joint and segmented pipelines were elastic-plastic, the foundation damping was considered by Yeh et al. [7], as an extremely important influencing factor that cannot be ignored during the site liquefaction process. The accumulation and dissipation of sediments after time changes were studied by Yang et al. [8]. The distribution curve of the excess pore water pressure in the soil pores with time and depth was obtained; the calculated value was applied to evaluate the possibility of soil liquefaction and the information affecting the depth of liquefaction was given. In 2000, based on the principle of virtual work, considering the initial axial force of the pipeline and the nonlinear restraint effect of the site soil, a simplified model of the floating reaction of buried pipelines under the liquefaction site was established by Lin et al. [9]. The analysis result showed that the upward displacement of the pipeline increases with the increase of the length of the soil liquefaction zone, and the initial deformation of the pipeline would have a greater impact on its upward displacement. The simplified method for judging the elastoplastic deformation of the pipeline when the pipeline expands laterally during the site liquefaction was studied by Takada et al. [10]. A simple formula for quantitative calculation was given, which could determine the part of the curving angle when the pipeline in the liquefaction site expanded laterally. Some physical backgrounds on the liquefaction of saturated, non-cohesive soils and related phenomena were provided by Groot et al. [11]. For example, the pore pressure accumulated, dissipated and the pore pressure decreased under impact load. In 2011, considering the problem of pipeline floating, the method of eliminating pipeline sinking and pipeline floating through the treatment of foundation soil was studied by Lu et al. [12]. In terms of finite element software analysis, in 1987, the liquefaction process of the soil was studied in detail by Kiaura et al. [13]. The finite element method was applied to analyze the change of soil pore water pressure. The force of the soil on the pipeline was determined by the relationship between the pore water pressure and the elastic coefficient of the soil. The calculation results showed that the displacement of the pipeline was larger than the surrounding soil, but the acceleration response in the middle of the pipeline and the surrounding ground acceleration response were very small. The pipeline was assumed to be an elastic foundation beam by Lim et al. [14], and the influence of permanent ground deformation was fully considered, and the changes of the pipeline under the liquefaction site under seismic conditions were analyzed. The research results believed that dynamic analysis could better define pipeline characteristics. When permanent ground displacement occurred, the decrease in soil spring stiffness had a great impact on the ground. In 2003, the randomness of ground spatial distribution was studied. Vertical waves were introduced, and the model considering the application of statistics was studied by Qu et al. [15]. The results showed that the propagation speed of seismic waves affects the internal force of the pipeline. The seismic wave speed was lower, the internal force of the pipeline was greater. The large ground displacement caused by soil liquefaction under the action of an earthquake was studied by Wu et al. [16]. The response of the pipeline was analyzed. The measures of pipelines against large displacements on the ground were studied. The finite element model was established by Dunn et al. [17]. The model included a constitutive model that could predict residual liquefaction and transient liquefaction. This model was applied to study the liquefaction of buried pipelines under wave action. The pipeline under the liquefaction of the site was simplified by Bao et al. [18], and others into a straight beam model with elastic support at both ends. They considered fluid-solid coupling and pipe-soil interaction, analyzed the mechanical response of buried pipelines under seismic action, and discussed the influence of different parameters on the pipeline's floating response. In 2009, based on the pipe-soil nonlinearity, using the double-broken line model of the pipe steel model combined with the elastic foundation beam theory, the theoretical analysis method of the buried steel pipe with the total axial strain under the strike-slip fault was proposed by Wang et al. [19]. In 2011, based on the pipe-soil interaction model based on the pipe-soil coupling, the change of the ellipticity of the pipe section along the pipe axis of the large-diameter pipeline under the condition of upward buoyancy was studied by Zhu et al. [20]. The vibrating table experiment results show that with the decrease of the sinusoidal value of the pipe-fault intersection Angle, the maximum strain experienced by buried pipelines decreases linearly, and the nonlinear relationship between the relative density and the strain experienced by buried pipelines was studied by Sim W W et al. [21]. In 2014, the new tube-soil interaction equation was studied by Erami et al. [22]. In relation to different soil-structure interaction mechanisms and different damage severity, the cross-sectional and longitudinal development of pipelines respectively were studied by G. Lanzano et al. [23]. A new way was used by them to describe the pipe-soil interaction of segmented pipelines and explored the interaction of segmented pipelines under fault geological conditions. The detailed analysis of the reaction of rectangular cross-section tunnels under the liquefied site using dynamic finite element method was studied by Madabushi et al. [24]. They fully considered the influence of different seepage coefficients and believed that the tunnel design should be considered separately according to the seepage coefficient of the soil. Using the finite element software ADINA, considering the pipe-soil interaction, the establishment of a reasonable finite element analysis model for buried pipelines under the liquefaction site was studied by Chen et al. [25]. The influence of different factors under the liquefaction site on the buried pipeline was analyzed. Using a two-dimensional integral numerical model, the accumulation of residual pore pressure caused by waves near the buried pipeline and the resulting residual liquefaction were analyzed by Zhao et al. [26]. In terms of experimental research, in 1987, a reasonable experiment on the pipeline reaction in the strong topsoil when part of the sand liquefied was studied by Nisho [27]. The test results showed that when the soil was liquefied, the pipelines buried in the soil would deform, resulting in greater axial strain. The pipeline deformation at the junction of the non-liquefaction zone and the liquefaction zone was the most obvious, subjected to the greatest axial strain. The research also gives the basis for judging pipe slip. The study also gave the basis for judging pipeline slip. The mechanism of permanent lateral displacement of foundation caused by seismic liquefaction, including three series of large-scale and small-scale shaking table tests, was studied by Sasaki et al. [28]. The study found that liquefied sand exhibited a similar behavior as liquid during lateral displacement. This idea was helpful for predicting the degree of permanent displacement of liquefied ground. In 1997, the anti-floating safety factor of the pipeline was defined based on the floating mechanism of the pipeline and was studied by Kosekil [29]. In 1998, Mohri tested the anti-floating safety factor of pipelines through a shaking table test. It was believed that liquefaction made the sand into a fluid state and lost the ability to constrain the pipeline [30]. The simulation of underground pipelines with round rubber rods was studied by Bei [31]. Seismic waves to the pipe axis and the vertical pipe axis respectively were input to observe the pipeline's response to earthquakes. In 1999, the reaction of the pipeline under the liquefaction site using the shaking table model test was studied by Towhatal [32]. The buoyancy of the pipeline during the vibration of the shaking table was
monitored, and the viscous force of the liquefied sand based on the experimental conclusions was calculated. In the experiment, the buoyancy response of the gas pipeline and the damage of the ground paving under the action of ground motion and buoyancy were mainly observed by Shimamura et al. [33]. The horizontal lateral load and axial load of the pipeline caused by site displacement during liquefaction were studied by Shimamura et al. [34], using a dynamic centrifugal model test. The reaction of site liquefaction and settlement to the pipeline was studied by Fuchida et al. [35]. The purpose was to verify the effect of compaction improvement methods on reducing the displacement of the liquefaction site and the pipeline response in it. In 2003, the floating of the pipeline during sand liquefaction was simulated by Ling et al. [36], with a centrifugal model. A simplified design method for resisting liquefaction and floating of underground pipelines was proposed. The soil liquefied under the action of continuous waves, and the influence of wave height, pipe diameter, non-liquefaction conditions and immersed pipe on the pore pressure around the pipe was studied by Sumler et al. [37]. Using a combination of experiment and numerical simulation, the underground structure was studied by Chian et al. [38]. The result believed that sufficient seismic acceleration energy must be input for the floating of underground structures, and the probability of floating of the structure was positively correlated with the magnitude. The phenomenon that the normal force range of a rigid pipeline buried in fluctuating liquefied soil was several times higher than that of a pipeline in stable soil was studied by Xu et al. [39]. After the soil was liquefied, the resultant force of the horizontal normal force acting on the under-ground pipeline was increased by about an order of magnitude. Full-scale fracture test results on debonding, axial elongation, and bending properties of pipes with toroidal cracks and weak joints under sudden ground deformation were studied by Argyrou C et al. [40]. In summary, the elastic foundation beam method based on Winkler model is mostly used in the calculation of force and deformation of buried pipelines in the liquefaction zone. This method has a large application error in the soil medium with little viscosity or force transmission. When scholars analyze the response of buried pipelines in the liquefaction zone, most of the analysis objects are straight pipes. It is found that there is a lack of mechanical analysis of pipeline nodes. In view of this, based on the Pasternak model, the authors of this paper propose a method for analyzing the force of a pipe in a liquefied soil layer considering the axial load. The influence of different sizes, foundation reaction coefficients and foundation shear stiffness on the deformation characteristics of pipes in liquefied soil is discussed. This method has higher calculation accuracy than the elastic foundation beam method based on Winkler model. The calculated results are compared the finite element analysis results. The finite element software is applied to analyze the mechanical response of pipeline nodes in liquefied soil, and analyze the influence of different parameters of the pipeline and soil on the mechanical response of the pipeline.

2. The reaction of buried pipelines under soil liquefaction

A large number of earthquake damages indicate that when the soil around the buried pipeline is liquefied in a large area during the earthquake, the liquefied soil will generate upward buoyancy on the buried pipeline to make the pipeline float, which may lead to failure of the pipeline in severe cases [41, 42]. In this paper, the finite element analysis and theoretical analysis are applied to analyze the mechanical properties of buried pipelines in liquefied soil after being subjected to buoyancy, and to explore the factors that affect the mechanical response of the pipelines.

2.1. Buoyancy of the pipeline in the liquefaction zone

According to the foreign standard Seismic Design of Buried Pipelines in Indian Context [43], the formula for calculating the buoyancy \( q \) per unit length of the pipeline in the liquefaction zone can be expressed as follows

\[
q = W_i - [W_p + W_c + (P_r - \gamma_p h_p)D] 
\]

where \( W_i \) is the weight of the soil after replacing the space occupied by the pipe per unit length with soil, \( W_p \) is the weight of the pipe per unit length, \( W_c \) is the weight of the medium per unit length of the pipeline, \( P_r \) is the vertical soil pressure, \( D \) is the outer diameter of the pipe, \( \gamma_p \) is the unit water weight, \( h_p \) is the high water level above the pipe.

Assume that \( \gamma_p \) is the weight of the liquefied soil per unit, \( \gamma_c \) is the weight of the material per unit length of the pipeline (such as oil, gas, water, etc.), and \( \gamma_p \) is the weight of the unit length of the pipeline, \( t \) is the pipe wall thickness. There are

\[
egin{align*}
W_i &= \frac{\pi D^2}{4} \gamma_s \\
W_p &= \frac{\pi D^2}{4} \gamma_p - \frac{\pi (D - 2t)^2}{4} \gamma_p \\
W_c &= \frac{\pi(D - 2t)^2}{4} \gamma_c \\
q &= \frac{\pi D^2}{4} (\gamma_s - \gamma_c) - \pi Dt \gamma_p
\end{align*}
\]

2.2. Deflection and internal force analysis

2.2.1. Mechanical analysis model of pipeline

When the pipeline passes through the soil liquefaction zone, the buoyancy of the liquefied soil will cause the pipeline to bend upward. In the soil liquefaction zone, the pipeline floats in the liquefied soil. The pipes at both ends are still buried in the soil and are supported by the reaction force caused by the rebound of the ground. The soil vertical will not reach the limit state when the pipeline is not above the surface. The pipeline can be analyzed and calculated by Winkler elastic foundation beam model and Pasternak foundation model.

The pipeline along the soil liquefaction zone is symmetrical about the midpoint \( B \). The pipeline in the soil liquefaction zone receives a uniformly distributed vertical upward force \( q \) and the length of the liquefaction zone is \( L \). The pipe mechanics analysis model can be built which is shown in Figure 1.

In order to simplify the calculation, the following assumptions are made.

Assuming that the buoyancy of the soil in the liquefaction zone on the buried pipeline is evenly distributed along the length \( L \) of the liquefaction zone, and the obstructive effect of the upper soil on the pipeline is not considered (the most dangerous working condition).

Assuming that the pipe has uniform rigidity along the axial direction, the joints at the pipe-to-pipe connection are not considered, and it is regarded as a whole.

Assume that the pipe deformation and force are symmetrical about section \( B \).
Assume that point B has a maximum deflection of \( W_B \); the pipeline is of constant cross-section, and the unit length is subjected to a vertical upward force \( q \), including the buoyancy of the pipeline by the liquefied soil, the weight of the pipeline itself, and the weight of the fluid in the pipeline.

2.2.2. Pasternak foundation model

The Pasternak foundation model is based on the Winkler elastic model assuming that there is a shear interaction between the spring elements. This interaction is achieved by connecting the spring element with a vertical element that can only produce transverse shear deformation but not compressible (as shown in Figure 2) [44]. In the two-dimensional case, the model can be expressed as follows

\[
G_p \frac{d^2w(x)}{dx^2} + q(x) = kw(x)
\]

where \( q(x) \) is the reaction force of the foundation, \( k \) is the foundation reaction coefficient, \( w(x) \) is the deflection of the buried pipeline, \( G_p \) is the shear stiffness of the foundation. When \( G_p = 0 \) in Eq. (4), the model degenerates to Winkler model.

The constants describing the two-parameter model are \( k \) and \( G_p \). In this paper, the constants of the two-parameter foundation model are connected with elastic constants \( E_s \) and \( \nu_s \). The empirical formula proposed by VLAZOV et al. [45] is more representative. It can be written as

\[
G_p = \frac{E_sH}{6(1+\nu_s)}
\]

where \( E_s \) is the elastic modulus of the foundation soil, \( \nu_s \) is the Poisson’s ratio of the foundation soil, \( H \) is the thickness of the elastic layer.

YAO et al. [46] used numerical simulation technology to study the range of soil on the side of piles affected by horizontal loads. The affected area is considered to be 11 d (d is the diameter of the pile). Therefore, \( H = 11D \) (D is the outer diameter of the buried pipeline) can be approximated as the elastic layer thickness of the foundation soil. In fact, the value of \( H \) is related to soil properties.

In order to simulate the force of the soil on the pipeline, it is assumed that the displacement of the pipeline and the surrounding soil are consistent. When the maximum relative displacement between pipe and soil is reached, the interaction force between pipe and soil reaches the limit and remains constant. Three non-linear springs are applied to the pipe, including the axial direction of the pipe and the transverse and longitudinal directions parallel to the pipe section. As shown in Figure 3. The stiffness \( k \) of the soil spring can be calculated according to the recommended method of GB 50470-2008 Seismic technical code for oil and gas transmission pipeline engineering [47].

2.2.3. Analysis of the non-liquefaction zone pipeline based on Pasternak model

This section establishes the mechanical model shown in Figure 4. The \( x \)-axis is the pipeline axis of the non-liquefaction zone, and the \( u \)-axis is the right boundary of the liquefaction zone. The pipe deflection at the right boundary of the liquefaction zone is \( u_C \). \( M_C \) is the pipe bending moment at the right boundary of the liquefaction zone, \( \theta_0 \) is the pipe corner on the right boundary of the liquefaction zone, \( F_C \) is the pipe axial force.

The effect of the pipeline in the liquefaction zone on the pipeline in the non-liquefaction zone is replaced by the shear 0.5qL, bending moment \( M_C \) and axial force \( F_C \) (The pipe rotation angle at the boundary of the liquefaction zone is very small, which can be approximated as the axial force \( F_C \) parallel to the \( x \)-axis). Since the axial force \( F_C \) mainly affects the axial deformation of the pipe, the influence of the axial force on the lateral deformation of the pipe is ignored. The pipe in the non-liquefied soil layer is regarded as a semi-infinite beam on the Pasternak foundation. For the convenience of calculation, it is uniformly stipulated that the bending moment is taken as the positive tension of the fiber under the pipe, and the pipe axial force is taken as the positive tension.

It is regarded that the pipeline in the non-liquefaction zone is a beam, and the relationship between its deflection \( u \) and the load \( q_1 \) and the foundation reaction force \( p \) is

\[
EI \frac{d^4u}{dx^4} = q_1 - p
\]

where \( E \) is the elastic modulus of steel, \( I \) is the section moment of inertia of the pipe.

According to the Pasternak foundation model, Eq. (6) can be written as

\[
EI \frac{d^4u}{dx^4} + kDu = G_p D \frac{d^2u}{dx^2} + q_1
\]

where \( D \) is the outer diameter of the pipe, \( k \) is the elastic coefficient of the soil, and \( G_p \) is the shear stiffness of the foundation.

The effect of the pipeline in the liquefaction zone on the pipeline in the non-liquefaction zone is the main reason for its deformation, so the load \( q_1 \) can be approximately ignored. Eq. (7) can be simplified to
\[ EI \frac{d^4u}{dx^4} + kDu = G_0 \frac{d^2u}{dx^2} \]

The general solution of Eq. (8) is

\[ u = C_1 e^{\alpha x} + C_2 e^{-\alpha x} + C_3 e^{\beta x} + C_4 e^{-\beta x} \]

where \( \alpha = \sqrt{\frac{G_0 - \sqrt{G_0^2 - 4k}}{2EI}} \) and \( \beta = \sqrt{\frac{G_0 + \sqrt{G_0^2 - 4k}}{2EI}} \).

From the qualitative analysis, it can be seen that when \( x \to 0 \), then know \( u \to 0 \) from \( C_1 = C_3 = 0 \), so Eq. (9) becomes

\[ u = C_2 e^{-\alpha x} + C_4 e^{-\beta x} \]

From Eq. (10), we can get the expressions of any pipe section angle, bending moment \( M \) and shear force \( Q \)

\[ \theta(x) = \frac{du}{dx} = -C_2 \alpha e^{-\alpha x} - C_4 \beta e^{-\beta x} \]

\[ M(x) = -EI \frac{d^2u}{dx^2} = -C_2 EI \alpha^2 e^{-\alpha x} - C_4 EI \beta^2 e^{-\beta x} \]

\[ Q(x) = -EI \frac{d^3u}{dx^3} = C_2 EI \alpha \beta e^{-\alpha x} + C_4 EI \alpha \beta e^{-\beta x} \]

The boundary conditions at the origin are

\[ \begin{align*}
M|_{x=0} &= M_c \\
Q|_{x=0} &= 0.5qL
\end{align*} \]

Putting Eq. (14) into Eq. (10) can be solved

\[ \begin{align*}
C_2 &= \frac{0.5qL + M_c \beta}{EI \alpha \beta (\alpha - \beta)} \\
C_4 &= \frac{0.5qL + M_c \alpha}{EI \alpha \beta (\beta - \alpha)}
\end{align*} \]

The deflection \( u_c \) and corner \( \theta_c \) of section C are

\[ \begin{align*}
u_c &= \frac{0.5qL(\alpha + \beta) + M_c(\alpha^2 + \alpha \beta + \beta^2)}{EI \alpha \beta} \\
\theta_c &= \frac{0.5qL + M_c(\alpha + \beta)}{EI \alpha \beta}
\end{align*} \]

### 2.2.4. Pipeline analysis of liquefaction zone

The mechanical model is built as shown in Figure 5. The x-axis is the pipe axis when liquefaction has not occurred. The y-axis is the left boundary of the liquefaction zone. The force of the pipeline in the non-liquefaction zone on the pipeline in the liquefaction zone is replaced by a shear force of 0.5qL, a bending moment \( M_c \), and an axial force \( F_c \).

For pipelines in the liquefaction zone, the differential equation for pipeline bending is

\[ EI \frac{d^4v}{dx^4} - M + F_c (w - w_c) + 0.5qL^2 - 0.5qLx \]

The solution of Eq. (17) is

\[ v(x) = D_1 e^{\sqrt{\frac{p}{C_0}}} + D_2 e^{-\sqrt{\frac{p}{C_0}}} - \frac{q}{2F_c} x + v_c - \frac{M_c}{F_c} - \frac{qEI}{F_c^2} \]

From symmetry and boundary condition \( v_{x=0} = v_c \), we can get

\[ \begin{align*}
D_1 &= \frac{M_c - F_c}{\sqrt{p/C_0}} \\
D_2 &= \frac{M_c - F_c + qEI}{\sqrt{p/C_0}} \cdot e^{\sqrt{\frac{p}{C_0}}}
\end{align*} \]

where \( p = 1 + e^{\sqrt{\frac{p}{C_0}}} \).

The pipeline corner at the boundary of the liquefaction zone \( x = 0 \) is

\[ \theta_c = D_1 \sqrt{\frac{F_c}{p/C_0}} \left( 1 - e^{\sqrt{\frac{p}{C_0}}} \right) + \frac{qL}{2F_c} \]

From Eq. (18), we can obtain the expressions for the pipe section angle \( \theta \) and bending moment \( M \) of the liquefaction zone as follow

\[ \begin{align*}
\theta(x) &= \frac{dv}{dx} = D_1 \sqrt{\frac{F_c}{p/C_0}} e^{\sqrt{\frac{p}{C_0}}} - D_2 \sqrt{\frac{F_c}{p/C_0}} e^{-\sqrt{\frac{p}{C_0}}} - \frac{q}{2F_c} x + \frac{qL}{2F_c} \\
M(x) &= -EI \frac{d^2v}{dx^2} = -D_1 F_c e^{\sqrt{\frac{p}{C_0}}} - D_2 F_c e^{-\sqrt{\frac{p}{C_0}}} + \frac{qEI}{F_c}
\end{align*} \]

From Eq. (18), we can get the midpoint deflection \( v_b \) of the pipeline at \( x = L/2 \) as follow

\[ v_b = D_1 e^{\frac{1}{2} \sqrt{\frac{p}{C_0}}} + D_2 e^{-\frac{1}{2} \sqrt{\frac{p}{C_0}}} + \frac{qL^2}{8F_c} + v_c - \frac{M_c}{F_c} - \frac{qEI}{F_c^2} \]

#### 2.2.5. Longitudinal displacement calculation

In order to solve the unknown parameter \( F_c \) in the above model, the relationship between the longitudinal displacement of the pipeline is added. The pipeline in the liquefaction zone is taken as the research object. According to the geometric nonlinear relationship of the axial strain of the pipeline, we can get

\[ \varepsilon_x = \frac{dx}{dL} + \left( \frac{dv}{dx} \right)^2 \]

where \( \varepsilon_x \) is the axial strain of the pipe, \( \chi \) is the axial displacement of the pipe.

According to Hooke’s law, we can get the expression of pipe axial strain

\[ \varepsilon_x = \frac{F_c}{EA} \]

where \( A \) is the cross-sectional area of the pipeline.

Combining Eq. (24) and Eq. (25) we can get

\[ \frac{dx}{dL} = \frac{F_c}{EA} - \frac{1}{2} \frac{dv}{dx} \]

For the convenience of calculation, the pipe deflection curve in the liquefaction zone is approximately taken as \( v = v_b \sin \left( \frac{\pi x}{L} \right) \). From Eq. (26), we can get

![Figure 5](image-url)
2.2.6. Check of pipe strength and stiffness

It is assumed that the pipeline passing through the liquefied soil layer is a thin-walled pipeline, so there is no radial stress in the pipeline. The stress state of the pipeline can be simplified to the biaxial stress state of hoop stress and axial stress. Assuming that \( l \) is the effective length of the pipeline, the axial force caused by the geometric deformation caused by the floating is smaller, and only the elastic stage of the pipeline needs to be analyzed.

According to the axial stress, the axial stress of the pipeline is

\[
\sigma_a = \frac{F}{A} + \frac{pR}{W^2} \frac{t}{2l}
\]

(29)

where \( \sigma_a \) and \( \sigma_2 \) are the axial stress at the top and bottom of the pipe, \( F \) is the pipe axial force, \( M \) is the pipe bending moment, \( W \) is the flexural modulus of the pipe section, \( p \) is the pipe transportation pressure, \( t \) is the pipe wall thickness, \( R \) is the radius of the pipe.

According to the strength theory, the stress states can be combined to determine the reliability of the pipeline.

According to the calculated parameters, the pipeline deformation curve and internal force diagram can be determined. The pipe strain is decomposed into two components, axial strain and bending strain.

The axial strain is

\[
BC : \epsilon_a = \frac{F_l}{AE}
\]

CE : \( \epsilon_a = \frac{F_c(l - x)}{AE} \)

(31)

The bending strain of the pipeline is determined by the deformation curve of the pipeline

\[
\epsilon_b = \frac{D}{(2l)}
\]

(32)

where \( \rho \) is the radius of curvature of the pipe, \( D \) is the outer diameter of the pipe.

Assuming that the overall deformation curve of the pipeline is \( y(x) \), the calculation method of \( \rho \) is

\[
\rho = \frac{1}{\frac{y''(x)}{1 + (y'(x))^2}^{3/2}} \approx \frac{y''(x)}{1 + (y'(x))^2}
\]

(33)

Substituting Eq. (33) into Eq. (10) and Eq. (18) respectively to obtain the bending strain of the BC and CE sections

\[
BC : \epsilon_b = \frac{D}{2l} \left( C_d a^2 e^{-\sigma} + C_m b^2 e^{-\beta} \right)
\]

CE : \( \epsilon_b = \frac{D}{2l} \left( D_1 F_e e^{\sqrt{F_e}} + D_2 F_e e^{\sqrt{F_e}} - \frac{q - F_e}{F_e} \right) \)

(34)

The maximum axial strain of the pipe wall is

\[
\epsilon = \epsilon_a + \epsilon_b
\]

(35)

In actual engineering, there are working conditions such as internal pressure and temperature difference while the pipeline is deformed, and the pipeline stress is more complicated. In order to facilitate engineering applications, the axial stress caused by internal pressure and temperature can be added to the above calculation results to estimate the pipeline stress under multiple working conditions.

2.2.7. Finite element analysis

In this paper, the nonlinearity of the pipe material is considered. When the stress of the pipe is less than the yield limit, the material is in an elastic state. According to the recommendations of the country's Seismic Technical Code for Oil and Gas Transmission Pipeline Engineering [49], this paper selects the three-fold line model as the stress-strain curve of the pipeline steel [40]. The stress-strain relationship of the three-fold line material is shown in Figure 3. As the stress increases, it is divided into elastic zone, elastoplastic zone and plastic zone. Among them, \( E_1 \) is the elastic modulus in the elastic stage, and \( E_2 \) is the elastic-plastic stage modulus. \( \sigma_1 \) and \( \epsilon_1 \) are the elastic yield stress and elastic yield strain, respectively. \( \sigma_2 \) and \( \epsilon_2 \) are plastic yield stress and plastic yield strain, respectively.

Beam model and shell model are used for finite element analysis of buried pipeline [48]. The beam model is a two-dimensional model, which cannot represent the stress and strain at a certain point on a specific section of the pipe. The shell model is a three-dimensional model with thickness and section. The shell size is defined according to the length, outer diameter and inner diameter of the pipeline, which can reflect the actual stress conditions of all the nodes of the actual pipeline. Therefore, the shell model is more in line with the requirements of the research. In this section, the ground end of the earth spring is a fixed constraint, and the pipe is only constrained by the earth spring. Since the model has symmetry, in order to reduce the computational workload, the model is established as half of the actual working condition, and symmetric constraints are imposed on the symmetry surface. In the theoretical analysis, the Pasternak Foundation model was used to consider the effect of non-liquefied zone on the pipeline. In order to get the theoretical and numerical simulation closer, the soil spring model is adopted in the finite element analysis of the effect of soil on pipeline in non-liquefied zone. The stiffness of the soil spring can be determined by Figure 6. The pipeline is meshed, the mesh near the contact area between the soil spring and the pipeline is encrypted, and the mesh is finely divided, and the non-key part of the research is coarsely meshed. This mesh division method can ensure the calculation accuracy and the calculation speed is fast. The pipeline and mesh division are shown in Figure 7.
In this paper, the face to face discrete method is adopted. The outer surface of the pipeline is selected as the main surface of the contact surface, and the contact surface between soil and pipeline is selected as the slave surface of the contact surface. The contact tracking method adopts finite sliding method. The contact interface between the pipe and the surrounding body adopts a hard contact relationship, in which the tangential action sets the friction coefficient between the pipe and the stop body as 0.5.

2.3. Numerical examples

The formula for calculating pipe strain and displacement by analytical method is very complicated. In order to solve the result more quickly and conveniently, MATLAB programming is applied to iteratively solve the differential equations. Based on the analytical method of this section, the mechanical response of the pipeline floating in the soil liquefaction zone is analyzed. The calculation example parameters are shown in Table 1.

To verify the analytical method, finite element software is applied to establish a finite element model for comparative analysis. The paper takes the pipe in the non-liquefied zone as 50m to simulate the force on the distal end of the pipe. This paper does not consider the internal pressure of the pipeline. The pipe parameters are shown in Table 2. The Young's modulus of the soil in the non-liquefaction zone is \( E = 3.5 \times 10^7 \). The Poisson's ratio is 0.35. In order to increase the calculation speed, this paper takes half of the symmetrical structure analysis. Take the liquefaction center as the origin of coordinates.

In the three sets of calculation examples, the analytic method of this paper is applied to calculate the floating displacement of the pipeline. By establishing the corresponding finite element model for calculation and analysis, the pipeline floating displacement curve is obtained and compared with the analytical solutions. The method in this paper is compared with the results obtained by the Winkler method, and the pipeline floating displacement curves calculated by these three methods are obtained. The result is shown in Figure 8. As shown in Figures 9, 10, 11, and 12, the stress and strain distribution of the pipe along the top and bottom of the pipe of the comparative analysis example C. The distribution of displacement, stress and strain is compared. According to the data analysis in Figure 8, the mean value of percentage difference between Winker result and finite element result is 1.69%, and the mean value of percentage difference between Pasternak result and FEM result is 6.52% in the three calculation examples A, B and C. As can be seen from Figures 9 and 10, the maximum axial stress of the pipeline is in the center of the liquefaction zone. The percentage difference between Winker result and finite element result at the center location is 3.24%, and the percentage difference between Pasternak result and FEM result is 3.52%. Figures 11 and 12 shows that the maximum axial strain of the pipeline is in the center of the liquefaction zone. The percentage difference between Winker results and finite element results is 10.02%, and the percentage difference between Pasternak results and FEM results is 10.71%. The results show that the calculation results of the analytical method in this paper are good agreement with those calculated by Winkler method and finite element software. The Winker method is more consistent with the finite element results, because both do not take into account the shear force of the soil in the non-liquefied zone. The two-parameter elastic model makes up for the inherent shortcomings of the Winkler model in describing the continuity of actual soils, so the Pasternak model has higher calculation accuracy.

The error between Winker's results and FEM results is due to the error in the selection of spring stiffness in the non-liquefaction zone. The error between Pasternak results and Winker and FEM results is due to the consideration of foundation shear stiffness in Pasternak model.

As the model parameters are affected by many factors, it is difficult to divide different parameter values for different working conditions and soil conditions. Therefore, this paper selects the values of the parameters according to the specific working conditions, and uses this as the standard to select the larger and smaller values to study the effect of each parameter on the pipeline's force and deformation. In order to study the influence of the foundation reaction coefficient and foundation shear stiffness on the deformation and force of the pipeline, the force and deformation of the pipeline under the conditions of different foundation reaction coefficient and different foundation shear stiffness are respectively calculated.

2.3.1. Ground reaction force coefficient

Based on the calculation example C, the pipe deflection, bending moment and pipe stress and strain under different foundation reaction coefficients are analyzed. The calculation results are shown in Figures 13, 14, 15, 16, 17, and 18. Pipeline deflection, bending moment on section B, and pipe top stress and strain show a downward trend with the increase of the foundation reaction coefficient, while the pipe bottom stress and strain show an upward trend. The bending moment on the cross section B and the stress and strain at the top of the pipe show an upward trend, while the stress and strain at the bottom of the pipe show a downward trend. It can be got that with the increase of the foundation reaction coefficient, the constraint on the pipe section C is strengthened, the bending moment load is increased, the stress and strain level of the pipe bottom is improved, and the stress and strain level of the pipe bottom is reduced. The restriction of the soil on the pipe cross section C is strengthened, the bending moment on the section is reduced, and the stress and strain level of the pipe top is lowered.

When the foundation reaction coefficient is large, the calculation results of Pasternak foundation model and Winkler foundation model are similar. Because when the foundation reaction coefficient is large, the

| Examples | Pipe | Diameter D/mm | Thickness t/mm | Buried depth h/m | Liquefaction zone length L/m |
|----------|------|---------------|----------------|-----------------|-----------------------------|
| A        | X65  | 914           | 12             | 2               | 40                          |
| B        | X65  | 914           | 12             | 2               | 50                          |
| C        | X65  | 914           | 24             | 2               | 50                          |
force transmission effect of the load on the adjacent unit body is weakened, and the force and deformation behavior of the pipeline is mainly affected by the foundation reaction coefficient, the Pasternak model is approximately degraded to the Winkler model.

| Pipe material | Density (kg/m³) | Young's modulus (Pa) | Poisson's ratio | Elastic yield strength (Pa) | Elastic yield strain | Plastic yield strength (Pa) | Plastic yield strain |
|---------------|-----------------|----------------------|----------------|-----------------------------|---------------------|-----------------------------|---------------------|
| X65           | 7850            | $2.1 \times 10^{11}$| 0.3            | $4.98 \times 10^8$         | 0.0024              | $5.65 \times 10^8$         | 0.030               |

Figure 8. Deflection curve of pipeline.

Figure 9. Axial stress at the top of the pipe.

Figure 10. Axial stress at the bottom of the pipe.

Figure 11. Strain at the top of the pipe.

Figure 12. Strain at the bottom of the pipe.

Figure 13. Pipe deflection.
2.3.2. Shear stiffness of foundation

Based on example C, the paper calculates the pipe deflection, bending moment and pipe stress and strain under different foundation shear stiffness. The calculation results are shown in Figures 19, 20, 21, 22, 23, and 24. It can be seen from Figures 19, 20, 21, 22, 23, and 24 that the pipe deflection, the bending moment on the cross section B, and the stress and strain of the pipe top show an upward trend with the increase of the foundation shear stiffness. The pipe bottom stress and strain show a downward trend with the increase of the foundation shear stiffness. As the shear stiffness of the foundation increases, the bending moment on
the cross section C and the stress and strain at the top of the pipe show a downward trend, while the stress and strain at the bottom of the pipe show an upward trend. The increase in the shear stiffness of the foundation strengthens the force transmission performance between the soil springs and weakens the restriction of the soil on the pipe cross section C. The increase in shear stiffness of the foundation reduces the bending moment load of section C, reduces the stress and strain level of the pipe top, and increases the stress and strain level of the pipe bottom. The increase in the shear stiffness of the foundation reduces the restraint of the soil on the cross section C of the pipe and increases the bending moment on the cross section B. The increase in shear stiffness of the foundation improves the stress and strain level at the top of the pipe and reduces the stress and strain level at the bottom of the pipe. When the foundation shear rigidity is large, the force transmission effect of the load on the adjacent unit body is greater, which weakens the restraint effect of the soil on the pipeline. The shear stiffness of the foundation has a great influence on the deformation behavior of the pipe, which is the reason for the larger error of the elastic foundation beam method based on the Winkler model.

3. Mechanical response of buried pipeline nodes under soil liquefaction

In the previous section, this article simulated the pipeline as a straight beam on the elastic foundation and Pasternak foundation. A theoretical analysis method is applied to analyze the floating reaction of the underground pipeline caused by the liquefaction of the site soil and its influencing factors. For straight pipes, a soil spring analysis model of the floating reaction of underground pipes caused by site soil liquefaction is established. The literature [49] did not consider the pipe-soil contact, and the influencing factors were not considered comprehensively. The contact between the soil in the non-liquefied zone and the pipe-soil of the pipeline and the restraint of the liquefied soil on the pipeline were considered in the literature [24]. The finite element model of the buried liquid pipeline under liquefaction was established, but the transition between the liquefied zone and the non-liquefied zone was not considered. The objects studied in the above literature are all straight pipes,
which do not conform to actual working conditions. When the pipeline is in the liquefaction site, it is subject to the interaction between the pipe and the soil, the buoyancy caused by the liquefied soil, and the viscous force of the liquefied soil when it moves upward. The force state of the pipeline is very complex and requires a more complete model to describe. This paper uses ABAQUS finite element analysis software to establish an analysis model combining soil contact and soil spring for buried pipes under the liquefaction site. The paper considers the contact between the pipe and soil in the non-liquefied zone. The interaction between the pipeline in the liquefaction zone and the liquefied soil is simulated by a nonlinear soil spring. The paper considers the buoyancy transition zone at the junction of the liquefaction zone and the non-liquefaction zone. Taking the middle-diameter three-way pipe at the node of the pipeline structure as the research object, the floating reaction analysis of the buried pipeline in the liquefaction zone is carried out. The influence of some pipelines and soil parameters on the floating reaction of buried pipelines in the liquefaction zone is discussed.

### 3.1. Build a model

The length of the non-liquefaction zone is 40m. The length of the liquefaction zone is 20m along the positive direction of the Z axis, 30m along the negative direction of the Z axis, and 40m along the positive direction of the X axis. In this paper, the three-dimensional 4-node reduced shell element (S4R) is used as the type of pipeline mesh, which is a plastic large-strain element and can withstand in-plane loads and normal loads. The soil in the non-liquefaction zone is an eight-node linear hexahedron element (C3D8R). The vertical, horizontal and axial grounding spring elements are added to the corresponding nodes of the pipeline in the liquefaction zone. The buoyancy of the transition zone is assumed to be a linear transition. For the vertical upward force experienced by the pipe per unit length, it can be seen in Eq. (3).

Under the condition of the length of pipeline in this model, the frictional force between pipe and soil can satisfy the equilibrium state of pipeline, so no constraint is imposed on the pipeline. In this paper, the boundary constraint conditions of the soil are as follows. The upper surface of the soil is the surface free surface, and no constraint is imposed, so it is set as the free boundary. On the interface plane of liquefied zone and non-liquefied zone, no constraint is imposed in Y direction, while fixed constraint is imposed in other directions. Three directional fixed constraints are applied to the remaining surface of the soil. The analysis model is built as shown in Figure 25.

Pipe material parameters are shown in Table 2. In the calculation process, temperature changes and the influence of other factors such as external vibration are not considered temporarily. Assuming that the soil is compact sand, choose Coulomb-Moore material. The Young’s modulus of the soil in the non-liquefaction zone is $E = 3.5 \times 10^7 \, \text{Gpa}$. The Poisson’s ratio is 0.35. The density is 1800 kg/m$^3$. The friction angle is 20°. The liquefied soil density is 2000 kg/m$^3$. The pipeline depth is 2m.

### 3.2. Pipe-soil interaction

The pipe-soil interaction is realized by the pipe-soil contact setting in ABAQUS. The contact setting steps are contact control, contact group, contact surface and contact pair. The contact algorithm is determined as the penalty function method, and the contact type is surface-to-surface contact. The outer surface of the pipe is set as the main surface and the soil surface in contact with the pipe is set as the subordinate surface. The coefficient of friction is 0.18.

### 3.3. Soil spring stiffness

To obtain the buoyancy, external force and equivalent spring constant for the liquefaction analysis of underground pipelines, Takada [50] used a shaking table to conduct steady-state harmonic tests of underground pipelines. Through the combination of experimental results and theoretical analysis of elastic foundation beams, submit proposal: in the design of pipelines in liquefied soil, the equivalent spring constant can be set to 1/3000-1/1000 of the non-liquefied zone. The value in this paper is 1/2000. The spring stiffness of the soil in the non-liquefied zone is obtained.

### 3.4. Result analysis

After the finite element analysis model is established, the influence of different soil and pipeline parameters on the floating displacement and axial stress of the pipeline is analyzed. For the main pipe and the straight pipe, the deflection and stress diagrams of the pipe can be obtained by taking the distal end of the non-liquefaction zone as the origin of the coordinates.

#### 3.4.1. Influence of pipe diameter

When the pipe diameter $D$ is 0.508m, 0.610m, 0.711m and 0.820m, respectively, the influence of the pipe diameter on the floating displacement and axial stress of the buried pipeline is shown in Figures 26, 27, 28, and 29.

From Figures 26 and 27, when other factors remain unchanged, as the pipe diameter increases, the floating displacement of the pipeline decreases slightly. The pipe diameter is larger, the decreasing trend is more obvious. This is because the outer diameter of the pipe increases, although the buoyant force per unit length of the pipeline increases, the moment of inertia and stiffness of the pipeline also increase, and the bending resistance of the pipeline increases. It can be seen from Figures 28 and 29 that stress concentration occurs at the pipeline node, and the stress appears extremely at the junction of the liquefaction zone and the non-liquefaction zone. The axial stress of the non-liquefied zone...
does not change much with the increase of pipe diameter. This is because as the pipe diameter increases, the gravity of the pipeline and the buoyancy of the pipeline in the liquefaction zone increase, and the increasing in buoyancy is greater than the gravity, and the pipeline in the liquefaction zone will float more seriously. The pipes in the non-liquefaction zone have little deformation due to soil constraints, so

Figure 27. Displacement of branch pipe.

Figure 28. Axial stress of main pipe.

Figure 29. Axial stress of branch pipe.

the axial stress of the non-liquefaction zone does not increase significantly. In order to resist the buoyancy of the liquefied pipeline, the force between the soil and the pipeline increases, and the axial stress increases significantly.

3.4.2. Influence of wall thickness

When the wall thickness $\delta$ is 0.016m, 0.020m, 0.024m and 0.028m, respectively, the influence of the wall thickness on the floating displacement and axial stress of the buried pipeline is shown in Figures 30, 31, 32, and 33.

Figure 30. Displacement of main pipe.

Figure 31. Displacement of branch pipe.

Figure 32. Axial stress of main pipe.
From Figures 30 and 31, when other factors remain unchanged, as the pipe wall thickness increases, the floating displacement of the pipe in the liquefied soil gradually decreases. When the pipe wall thickness is thinner, the displacement decreases more significantly. Therefore, appropriately increasing the wall thickness of the pipeline can effectively reduce the floating displacement of the pipeline. Analyzing the reason, the wall thickness is greater, the rigidity of the pipeline is greater, and the bending resistance of the pipeline is greater. As the wall thickness increases, the gravity on the pipeline increases, but the buoyancy remains unchanged, so the floating displacement of the pipeline decreases with the increasing of the pipeline wall thickness. From Figures 32 and 33, the pipe wall thickness is greater, the axial stress in the liquefaction zone is less. This is because the increase in wall thickness increases the gravity on the pipeline, and the stronger the counteracting effect on the buoyancy.

3.4.3. Influence of buried depth

The paper calculated the buried depth $h$ of the pipeline as 1.5m, 2m, 2.5m, and 3m, respectively. The influence of the buried depth on the floating displacement and axial stress of the buried pipeline is shown in Figures 34, 35, 36, and 37.

It can be seen from Figures 34, 35, 36, and 37 that the buried depth of the pipeline is greater, the floating displacement of the pipeline is smaller. The maximum axial stress on the pipeline is also reduced, but not much. This is mainly because as the depth of the foundation increases, the stress of the overlying soil in the non-liquefied zone increases, the binding force of the liquefied soil on the pipeline increases, and the floating reaction of the pipeline weakens. In addition, there are statistics about the Kushiro-Oki earthquake in 1992 and the Hokkaido-Toho-Oki earthquake in 1994. When the buried depth is less than 2m, the underground pipelines are most damaged due to floating. It is consistent with the results of this article.
Influence of transition zone length

In the actual liquefaction site, the change from the non-liquefaction zone to the liquefaction zone is not a sudden change, but a slow change process. This will lead to incomplete liquefaction of part of the soil at the junction of the sand liquefaction area and the non-liquefaction zone.

3.4.4. Influence of transition zone length

In the actual liquefaction site, the change from the non-liquefaction zone to the liquefaction zone is not a sudden change, but a slow change process. This will lead to incomplete liquefaction of part of the soil at the junction of the sand liquefaction area and the non-liquefaction zone.
area. There is an incomplete liquefaction zone between each complete liquefaction zone and non-liquefaction zone. When the length \( l \) of the incomplete liquefaction zone is 0m, 2m, 4m and 6m, the influence of the length of the incomplete liquefaction zone on the floating displacement and axial stress of the buried pipeline is shown in Figures 38, 39, 40, and 41.

It can be seen from Figures 38 and 39 that the floating displacement of the pipeline is smaller when considering the incomplete liquefaction zone than when the incomplete liquefaction zone is not considered. As the length of the incomplete liquefaction zone increases, the floating displacement of the pipeline gradually decreases. It is because the constraining force and buoyancy of the pipeline in the incomplete liquefaction zone are between the liquefaction zone and the non-liquefaction zone. When the liquefaction length is constant and the length of the incomplete liquefaction zone increases, then the buoyancy of the pipeline decreases, and the binding force of the soil in the liquefaction zone increases. It can be seen from Figures 40 and 41 that as the length of the incomplete liquefaction zone increases, the axial stress of the pipeline has an extreme value at the junction of the liquefaction zone and the non-liquefaction zone and at the center of the liquefaction zone, and the value gradually decreases. Therefore, when the length of the liquefaction zone is constant, the existence of the incomplete liquefaction zone can be applied to slow down the floating reaction of the pipeline, and the impact of the incomplete liquefaction length on the floating of the pipeline cannot be ignored.

3.4.5. Influence of internal pressure

Long-distance gas pipelines are mostly high-pressure and large-diameter, and pipelines are greatly affected by natural gas pressure. It is necessary to study the influence of pipeline natural gas pressure on pipeline floating reaction under liquefaction environment. When the internal pressure \( P \) of the pipeline is 0Pa, \( 2 \times 10^6 \)Pa, \( 4 \times 10^6 \)Pa, \( 6 \times 10^6 \)Pa, the influence of internal pressure on the floating displacement and axial stress of the buried pipeline is shown in Figures 42, 43, 44, and 45.

It can be seen from Figures 42 and 43 that as the pressure of natural gas increases, the floating displacement of the pipeline increases slightly. The main reason is the increase in the pressure of the conveying gas in the pipeline, which causes the centrifugal force on the pipeline to increase. It can be seen from Figures 44 and 45 that as the pressure of natural gas increases, the axial stress of the pipeline increases. The main reason is that the internal pressure of the pipeline has a greater circumferential effect on the pipeline than the axial effect.

3.4.6. Influence of liquefied soil density

It is known that the different nature of the backfill directly affects the density of the soil after liquefaction, thus affecting the floating reaction of the pipeline. When the density \( \rho \) of liquefied soil is taken as 1200 kg/m\(^3\), 1500 kg/m\(^3\), 1800 kg/m\(^3\), the influence of the density of liquefied soil on...
In Figures 46, 47, 48, and 49. The deformation behavior of the pipeline is mainly affected by the foundation reaction coefficient. When the foundation shear stiffness is 0, the Pasternak model is approximately degenerated to the Winkler model, and the calculation results of the two models are similar. When the foundation shear rigidity is large, the force transmission effect of the load on the adjacent unit body is greater, which weakens the restraint effect of the soil on the pipeline. It has a great influence on the deformation behavior of the pipeline.

In this paper, the incomplete liquefaction zone is considered by establishing a pipe-soil contact-soil spring analysis model. The factors affecting the floating reaction of the buried equal diameter three-way pipeline under the liquefaction site are analyzed and the following conclusions are drawn. The corresponding recommendations for earthquake prevention and disaster mitigation of buried pipeline engineering are proposed. The top of the pipeline receives the greatest axial pressure at the junction of the liquefaction zone and the non-liquefaction zone. The pipeline receives the greatest axial tension at the center of the liquefaction zone. There is stress concentration at the three-way pipe joint. Therefore, at the junction of the liquefied zone and the non-liquefied zone, it is necessary to avoid installing joints and other pipe fittings. It is necessary to increase the thickness and strength of the pipeline at the three-way pipe joint. As the pipe diameter increases, the floating displacement of the pipe increases. The axial stress of the pipeline at the boundary and the center point of the liquefaction zone is relatively large, so the increase of the pipe diameter will increase the damage of the pipeline. Small diameter pipes should be used within the scope of the project. The larger the pipe wall thickness, the less likely it is to deform and damage. Therefore, thick pipes are preferred under the same conditions in the project. The buried depth is greater, the maximum floating displacement of the pipeline is smaller. Therefore, the deep burial of the pipeline is beneficial to the earthquake prevention and disaster reduction of the project. The length of the incomplete liquefaction zone is particularly critical to the upward buoyancy of the pipeline, and scholars should consider it when studying pipelines buried in liquefied soil. The internal pressure of the pipeline is greater, the floating displacement and axial stress of the pipeline is greater, and the internal pressure has a very obvious influence on both. Therefore, pipeline natural gas pressure is one of the influencing factors of pipeline floating reaction. The increasing in the density of the liquefied soil increases the floating displacement of the pipeline, and the axial stress of the pipeline at the boundary and the center point of the liquefaction zone increases. The quality of backfilled soil and other factors affecting the density of liquefied soil should be strictly controlled in the project.

4. Conclusions

The mechanical analysis method for buried pipelines in liquefied soil based on Pasternak model makes up for the inherent defects of the elastic foundation beam method based on Winkler model. It can consider the force transmission of the load to the adjacent unit body, and has higher calculation accuracy. For buried pipelines under the same conditions, the longer the liquefaction zone, the greater the maximum floating displacement and maximum strain of the pipeline. The thicker the pipe wall, the smaller the maximum floating displacement and maximum strain of the pipe. When the foundation reaction coefficient is large, the force transmission effect of the load on the adjacent unit body is weakened.

Figure 48. Axial stress of main pipe.

Figure 49. Axial stress of branch pipe.

It can be seen from Figures 46, 47, 48, and 49 that the density of the liquefied soil is greater, the floating reaction of the pipeline is stronger. The axial stress on the pipeline at the boundary between the liquefaction zone and the non-liquefaction zone and which on the midpoint of the liquefaction zone is greater. It is due to the increase in the density of the liquefied soil, which leads to an increase in the buoyancy of the pipeline. Considering that the factors affecting the density of liquefied soil also involve the state of the soil when liquefaction occurs, and the degree of liquefaction, it is still a complicated process that remains to be analyzed.

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In this paper, the incomplete liquefaction zone is considered by establishing a pipe-soil contact-soil spring analysis model. The factors affecting the floating reaction of the buried equal diameter three-way pipeline under the liquefaction site are analyzed and the following conclusions are drawn. The corresponding recommendations for earthquake prevention and disaster mitigation of buried pipeline engineering are proposed. The top of the pipeline receives the greatest axial pressure at the junction of the liquefaction zone and the non-liquefaction zone. The pipeline receives the greatest axial tension at the center of the liquefaction zone. There is stress concentration at the three-way pipe joint. Therefore, at the junction of the liquefied zone and the non-liquefied zone, it is necessary to avoid installing joints and other pipe fittings. It is necessary to increase the thickness and strength of the pipeline at the three-way pipe joint. As the pipe diameter increases, the floating displacement of the pipe increases. The axial stress of the pipeline at the boundary and the center point of the liquefaction zone is relatively large, so the increase of the pipe diameter will increase the damage of the pipeline. Small diameter pipes should be used within the scope of the project. The larger the pipe wall thickness, the less likely it is to deform and damage. Therefore, thick pipes are preferred under the same conditions in the project. The buried depth is greater, the maximum floating displacement of the pipeline is smaller. Therefore, the deep burial of the pipeline is beneficial to the earthquake prevention and disaster reduction of the project. The length of the incomplete liquefaction zone is particularly critical to the upward buoyancy of the pipeline, and scholars should consider it when studying pipelines buried in liquefied soil. The internal pressure of the pipeline is greater, the floating displacement and axial stress of the pipeline is greater, and the internal pressure has a very obvious influence on both. Therefore, pipeline natural gas pressure is one of the influencing factors of pipeline floating reaction. The increasing in the density of the liquefied soil increases the floating displacement of the pipeline, and the axial stress of the pipeline at the boundary and the center point of the liquefaction zone increases. The quality of backfilled soil and other factors affecting the density of liquefied soil should be strictly controlled in the project.

Declarations

Author contribution statement

Chunsheng Yang: Conceived and designed the experiments; Performed the experiments; Wrote the paper.
Shanqing Li: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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References

[1] T.L. Youd, D.M. Perkins, Mapping of liquefaction severity index, J. Geotech. 113 (11) (1987) 1274–1392.
[2] Zhaoshua Yang, Qing Ye, Zhenzhen Jia, Li He, Numerical simulation of pipeline-pavement damage caused by explosion of leakage gas in buried PE pipelines, J. Adv. Civil Eng. (2020).
[3] M.M. Newmark, Problems in wave propagation in soil and rock, in: Selected papers by Nathan M Newmark: civil engineering classics, ASCE, 2015, pp. 703–722.
[4] L.R.L. Wang, Y.H. Yeh, A refined seismic analysis and design of buried pipeline for fault movement, J. Earthquake Eng. Struct. Dyn. 13 (1) (1985) 75–96.
[5] N. Nishiz, K. Tsukamoto, A. Hamura, Model experiment on the strain in buried pipeline associated with soil liquefaction, J. Develop. Geotech. Eng. 49 (1987) 141–157.
[6] L.R.L. Wang, H. Zhang, Buried pipeline system in a liquefaction environment, in: Proc. 10 WCEE. Madrid, Spain, 1992, pp. 5529–5534.
[7] Y.H. Yeh, L.R.L. Wang, Buried pipeline in a soil liquefaction environment, J. Exp. Biol. 206 (215) (2015) 2567–2586.
[8] S.L. Yang, W.Q. Shen, Z.S. Yang, The mechanism analysis of sea floor sit solution liquefaction under wave loads, China Ocean Eng. 9 (4) (1995) 375–386.
[9] L.I.M. Yunmook, K.I.M. Taewook, K.I.M. Moon Kyum, et al., Seismic behavior of buried pipelines subjected to dip faults, J. Geotechn. Geoenviron. Eng. 129 (12) (2013) 204–214.
[10] M.B.D. Groot, M.D. Bolton, P. Foray, P. Meijers, A.C. Palmer, R. Sandven, Hongqian Lu, Hui Han, Yongqiang Zhu, Shoujian Zhu, Ground treatment of buried pipelines subjected to liquefaction, J. Geotech. Geoenviron. Eng. 129 (12) (2013) 204–214.
[11] M. Kitaura, M. Miyajima, Shuzuki, Response analysis of buried pipelines subjected to liquefaction, J. Waterway Port Coast. Ocean Eng. 132 (4) (2006) 227–243.
[12] Tie-jun Qu, Wang Qian-xin, Seismic response of underground pipelines to ground motion with spatial randomness, J. Eng. Mech. 20 (3) (2003) 120–128.
[13] X. Zhu, S. Xue, X. Tong, et al., Uplift response of large-diameter buried pipeline in liquefied soil, J. Geotech. Geoenviron. Eng. 129 (12) (2013) 204–214.
[14] S.S.C. Madabhushi, S.P.G. Madabhushi, Finite element analysis of floating of rectangular tunnels following earthquake induced liquefaction, J. Indian Geotech. J. 45 (3) (2015) 1–10.
[15] Y. Mohri, T. Kawabata, H.I. LIng, Experiments on shallowly buried pipelines using shaking table, in: Proceedings of the 10th Earthquake Engineering Symposium, Toyo, 1998, pp. 1913–1916.
[16] PuSheng North, Experimental Study on the Strain Characteristics of Underground Pipeline during liquefaction.Seismic Resistance of Underground pipeline, Academic Books and Journals Press, The United States, 1998, pp. 192–204.
[17] Towhatia, V. Vargas-Monge, R.P. Orense, et al., Shaking table tests on subgrade reaction of pipe embedded in sandy liquefied subsoil, J. Soil Dyn. Earthquake Eng. 18 (5) (1999) 347–361.
[18] K. Shimamura, M. Hamada, S. Yasuda, et al., Experimental and analytical study of the floating of buried steel pipe due to liquefaction, in: Proc. 12 WCEE. Auckland, New Zealand, 2000, p. 1385.
[19] Kanunori Shimamura, Mananori Hamada, Susumu Yasuda, Load on pipes buried in A non-liquefaction layer due to liquefaction ground displacement, in: Proc.12 WCEE. Auckland: New Zealand, 2000, 0492.
[20] Kunihiko Fuchida, Shoso Shirahishimata, Takakiti Akiyoshi, Response behavior of pipeline system subjected to subsidence of ground liquefaction, in: Proc.12 WCEE. Auckland: New Zealand, 2000, 0425.
[21] H.I. Ling, M. Asce, Y. Mohri, et al., Centrifugal modeling of seismic behavior of large-diameter pipe in liquefiable soil, J. Geotech. Geoenviron. Eng. 129 (12) (2003) 1092–1101.
[22] B.M. Sumer, C. Truelsen, J. Fredsoe, Liquefaction around pipelines under waves, J. Waterway Port Coast. Ocean Eng. 132 (4) (2006) 266–275.
[23] S.C. Chian, K. Tokimatsu, S.P.G. Madabhushi, Soil liquefaction-induced uplift of underground structures: physical and numerical modeling, J. Geotech. Geoenviron. Eng. 140 (10) (2014) 31–40.
[24] Jingbei Xu, Guohui Xu, Yuqun Ren, Zhiqun Liu, Changyun Chen, Horizontal normal force on buried rigid pipelines in fluctuating liquefied silty soil, Ocean. Coastal Sea Res. 18 (1) (2019) 1–8.
[25] Y. Mohri, T. Kawabata, H.I. LIng, Experiments on shallowly buried pipelines using shaking table, in: Proceedings of the 10th Earthquake Engineering Symposium, Toyo, 1998, pp. 1913–1916.
[26] C. Yang, S. Li Heliyon 7 (2021) e07480