Force properties of longitudinal interaction of the underground pipeline with soil

Sabida Ismoilova\textsuperscript{2}, Pavel Loginov\textsuperscript{2}, Saidjon Khamidov\textsuperscript{1}, Nodirbek Akbarov\textsuperscript{2} and Jakhongir Kumakov\textsuperscript{3}

\textsuperscript{1}TIILME, Department of Theoretical and Structural Mechanics, 100000 Tashkent, Uzbekistan
\textsuperscript{2}Institute of Mechanics and Seismic Stability of Structures of Academy of Sciences of the Republic of Uzbekistan, 100187 Tashkent, Uzbekistan
\textsuperscript{3}Tashkent Institute of Architecture and Construction, 100011 Tashkent, Uzbekistan

E-mail: lopavi88@mail.ru

Abstract. The reliability of underground trunk pipelines, in most cases, is estimated based on their strength. When determining the strength of underground pipelines under seismic effects, it is necessary to take into account the forces of pipe-soil longitudinal interaction (the friction force) in calculations. Currently, linear relationships are used to describe the longitudinal interaction forces, where the interaction force is determined depending on the value of the pipe displacement relative to soil. The dependences of the interaction forces on the seismic stress state of soil are not taken into account at all. The paper shows that the interaction forces on the contact surface of an underground pipeline with soil are complex in nature and depend on the wave parameters in soil and in the pipeline itself. Based on the numerical results of solving one-dimensional unsteady-state coupled wave problems for the interacting system “underground pipeline-soil”, the pattern of changes in interaction forces on the pipeline-soil contact surface are determined. It was found that an account for static and dynamic soil pressure normal to the contact surface leads to quantitatively different results than when only static pressure is considered. It is shown that when solving the reliability problems of underground trunk pipelines under seismic effects, first it is necessary to take into account the dynamic stress-strain state of soil in the vicinity of the pipeline.

1. Introduction
Underground trunk pipelines, as the systems conveying liquid and gas substances, are an important type of underground structures. As noted in [1–4], ensuring the strength and reliability of underground and underwater pipelines during seismic impacts is of paramount importance and is an urgent problem, since the consequences of underground transportation pipelines destruction can lead to great economic and environmental damage [1]. Therefore, research work is increasingly devoted to ensuring reliable operation of underground pipelines and their strength under the impact of dynamic, including seismic, loads [1-10].

In [5–10], the issues of experimental and theoretical determination of interaction forces of an underground pipeline with surrounding soil were considered. However, the interaction models in the applied problems of seismic safety of underground pipelines were not discussed. The research devoted to the study of the properties of interaction forces, observed under seismic wave propagation in the
“underground pipeline-soil” system, is practically non-existent.

The aim of this study is to determine the patterns of changes in longitudinal interaction forces of underground pipeline with soil under dynamic (seismic) impacts on the "pipeline-soil" system and their properties depending on the stress state of soil.

2. Methods

An underground pipeline surrounded by a soil medium is considered in the paper. Not considering the free (daily) soil surface, the problem can be reduced to a one-dimensional problem [11].

Then the process of wave propagation from the cross section of the pipeline and soil \( x = 0 \) ( \( x \) - the axis of the pipeline) is described by the equations

\[
\rho \frac{\partial v}{\partial t} - \frac{\partial \sigma}{\partial x} + \kappa \cdot \sigma_i = 0, \tag{1}
\]

\[
\frac{\partial \sigma}{\partial x} - \frac{\partial \epsilon}{\partial t} = 0, \tag{2}
\]

\[
\frac{\partial \epsilon}{\partial t} + \mu \epsilon = \frac{\partial \sigma}{E_i \partial t} + \mu_i \frac{\sigma_i}{E_{si}}, \tag{3}
\]

\[
\sigma_i = \frac{4D_H^2 - D_B^2}{4D_H^2} \tau, \tag{4}
\]

\[
\mu_i = \frac{E_B \cdot E_{si}}{(E_D - E_{si}) \eta_i} \tag{5}
\]

where \( i = 1, 2 \) (at \( i = 1 \) all parameters refer to the pipeline, and at \( i = 2 \) - to soil); \( \rho \) - initial density; \( v \) - particle velocity; \( \sigma \) - longitudinal stress; \( \epsilon \) - longitudinal strain; \( \kappa = \text{sgn}(v) \), \( v = v_1 - v_2 \) (at \( v > 0 \), \( \kappa = +1 \), and at \( v < 0 \), \( \kappa = -1 \), at \( v = 0 \), \( \kappa = 0 \); \( \sigma_i \) - reduced force of interaction; \( \tau \) - the force of interaction of the pipeline with soil; \( E_D \) - modulus of dynamic strain; \( E_{si} \) - modulus of static strain; \( \mu \) - volume viscosity parameter; \( \eta \) - coefficient of volume viscosity; \( D_H \) - outer diameter; \( D_B \) - inner diameter; \( t \) - time.

According to equations (1) - (5), the soil medium around the pipeline, in fact, is considered as a cylindrical layer with outer diameter \( D_{H2} \) and inner diameter \( D_{B2} \). The boundary conditions are

\[
\sigma_i = \sigma_{max} \sin \left( \pi t / T \right), \quad 0 \leq t \leq \theta, \tag{6}
\]

\[
\sigma_i = 0, \quad t > \theta, \tag{7}
\]

\[
\sigma_i = \epsilon_i = v_i = 0 \quad \text{at} \quad x = c_i t, \tag{8}
\]

where \( \sigma_{max} \) is the amplitude of the load generating the wave in the pipeline and soil; \( \theta \) is the load duration; \( c_i \) is the velocity of longitudinal wave propagating in the pipeline \( (i = 1) \) and soil \( (i = 2) \).

The system of equations (1) - (3) with (4), (5) and boundary conditions (6) - (8) and zero initial conditions is solved numerically by the finite difference method using the method of characteristics. The substantiation of the solution method and the reliability of the algorithm and program for solving equations (1) - (3) are given in [11].

It should be noted that the longitudinal stresses \( \sigma_i \) for the pipeline were determined and analyzed in [11], from equations (1) - (3). The pattern of changes in interaction forces were not considered and
discussed in [11].

Here, from the solution of the problem under consideration, we determine the force properties of interaction of the pipeline with soil, depending on the stresses in soil. For this, consider in detail the case of the simplest determination of the interaction force based on the law [12]

\[
\tau = K_x(\sigma_N, I_S) \cdot u \quad \text{at} \quad 0 \leq u \leq u_* , \quad du / dt > 0 , \quad (9)
\]

\[
\tau = K^R_x(\sigma_N, I_S) \cdot u \quad \text{at} \quad 0 \leq u \leq u_* , \quad du / dt \leq 0 , \quad (10)
\]

\[
\tau = f \cdot \sigma_N \quad \text{at} \quad u > u_* , \quad (11)
\]

\[
K_x(\sigma_N, I_S) = K^*_x(\sigma_N) \cdot \exp[\beta(1 - I_S)] , \quad (12)
\]

\[
K^*_x(\sigma_N) = K_N \sigma_N , \quad (13)
\]

\[
K^R_x(\sigma_N, I_S) = K^*_x(\sigma_N)e^\beta , \quad (14)
\]

where \( K_x \) is the interaction function; \( u = u_2 - u_1 \) - relative displacement (\( u_2 \) - the absolute displacement of the soil particles, \( u_1 \) - the absolute displacement of the pipeline particles); \( u_* \) - critical value of relative displacement; \( f \) - coefficient of internal friction of soil; \( \sigma_N \) - soil pressure normal to the outer surface of the pipeline; \( I_S = u / u_* \) - a parameter characterizing structural destruction of the soil contact layer when the pipeline is displaced relative to soil; \( \beta \) - dimensionless coefficient characterizing the intensity of structural destruction of the contact layer of soil; \( K^*_x \) - variable coefficient of interaction of the pipeline with soil; \( K_N \) - the coefficient of rigidity of soil particles contact with the pipeline.

As seen from equation (3), the laws of soil and pipeline strain are taken as linearly viscoelastic ones (a standard viscoelastic body), since under seismic loads the soil medium is assumed to be strained elastically considering its viscous properties. For generality, the pipeline material is also considered as a linearly viscoelastic body. At \( E_D \rightarrow E_S \), equation (3) turns to Hooke’s linear law.

In equation (9), \( \sigma_N \) is determined from the relation

\[
\sigma_N = \sigma^S_N + \sigma^D_N , \quad (15)
\]

where \( \sigma^S_N \) is the static normal stress to the outer surface of the pipeline, determined by the pipeline depth [11]; \( \sigma^D_N \) is the dynamic normal stress, determined from the formula

\[
\sigma^D_N = K_\sigma \sigma_2 , \quad (16)
\]

where \( K_\sigma \) is the lateral pressure coefficient of soil; \( \sigma_2 \) - longitudinal stress in soil, determined from numerical solution of equations (1) - (3) for the soil medium.

The value of displacement of soil particles and the pipeline is determined from \( u_i = \int_0^t v_i dr , \) where \( v_i \) is the velocity of soil particles (\( i = 2 \)) and the pipeline (\( i = 1 \)), also determined from numerical solutions of the system of equations (1) - (3) for the pipeline and soil medium, respectively.

Numerical solution of the problem under consideration is carried out on a computer. The rationale for the algorithm and program for numerical solution and their reliability are given in [11].
3. Results and discussion

In [11], longitudinal stresses in the pipeline were determined from numerical solutions of one-dimensional unsteady-state coupled wave problems (1) - (3), for the underground pipeline and the soil medium surrounding the pipeline. It was found that, depending on the laws of change in the interaction forces of the underground pipeline with soil, the amplitude of longitudinal stresses in the pipe manifold exceeds (by 30-40 times) the amplitude of stresses in soil. In [11], this result is explained by the properties of interaction forces. However, these properties were not discussed in [11].

In [11], it was noted that the interaction forces of an underground pipeline with surrounding soil mainly depend on physical and mechanical characteristics of soils. Indeed, at longitudinal (shear) interaction of the underground pipeline with soil, due to significant difference in stiffness (strength) characteristics of the pipe and soil (metal, polymer pipes), the soil is first destroyed. At the same time, the process of soil destruction around the pipeline presents a rather complicated nonlinear process [12, 13]. This nonlinear process, as shown in [14], manifests itself even under weak seismic wave propagation in soil. The impact of the process of nonlinear strain of soils occurring under weak longitudinal wave propagation in soil was also investigated in [12–13, 15]. It was shown in [15] that at underground pipeline-soil interaction under seismic wave propagation in soil with amplitude of 0.5 MPa, a soil layer around the pipeline destroyed. In [15], this soil layer was called the contact layer of soil. The process of strain of the contact layer of soil, as shown in [15], differs significantly from the process of soil strain outside this layer. At longitudinal interaction of the underground pipeline with soil, a shear displacement of the pipe relative to soil occurs. The soil around the pipeline undergoes shear strains. Moreover, the values of this strain can reach such values at which the contact layer of soil destroys. As a result, this contact layer of the soil undergoes all stages of strain from elastic to plastic and to the fracturing [15].

The determination of the elastic, plastic, viscous properties of soils under dynamic loading at amplitude of 0.5 MPa was considered in [16, 17]. It was shown in [18] that such nonlinear properties under strain were also manifested in fibrous composite materials. Methods for determining the nonlinear properties of soils under strain to a failure were also considered in [17, 19].

Thus, in [11–17] it was shown that the process of soil strain under dynamic (seismic) loads is a nonlinear one. This process significantly affects the mechanism of stress state formation in an underground pipeline [11, 12-15].

At present, in determining the longitudinal (seismic) stress in an underground pipeline, the calculations are based on the theory developed by Shunzo Okamoto [20]. In this theory, it is accepted that when a pipeline interacts with soil under the action of a seismic wave, the soil strains only elastically. As the experimental and theoretical results of [11-19] show, when an underground pipeline interacts with soil, under the action of seismic loads, the soil around the pipeline is strained not only elastically. The stress state of the underground pipeline is significantly affected by stresses in soil generated from the seismic wave propagation in it.

However, in [11,13,15], when determining longitudinal stresses in an underground pipeline, the patterns of changes in the interaction forces between the pipeline and soil were not considered. Based on the obtained numerical solutions of equations (1) - (3), consider the patterns of change in the interaction forces of an underground pipeline with soil under the impact of dynamic loads created according to the law (6).

To carry out numerical calculations on a computer, the initial data are accepted, for the pipeline:

\[
D_{H1} = 0.2 \text{ m}; \quad D_{B1} = 0.18 \text{ m}; \quad \rho_{01} = 7800 \text{ kg/m}^3; \quad \mu_1 = 10^4 \text{ s}^{-1}; \quad c_1 = 5000 \text{ m/s}; \quad E_{S1} = 2 \times 10^5 \text{ MPa};
\]

\[
E_{D1} = 1.02E_{S1}; \quad L = 1000 \text{ m} – \text{the pipeline length};
\]

for soil:

\[
D_{H2} = 1 \text{ m} \text{ (the pipeline depth in soil)}; \quad D_{B2} = D_{H1}; \quad \rho_{02} = 1800 \text{ kg/m}^3; \quad c_2 = 1000 \text{ m/s}; \quad E_{S2} = 50 \text{ MPa}; \quad E_{D2} = 2E_{S1}; \quad K_\sigma = 0.3;
\]

Load parameters:
$T = 0.01 \ s; \ \theta = 5 \ s; \ \sigma_{\text{max}} = 0.5 \ \text{MPa}.$

At $u_s \to \infty (u_s = 1000 \ m)$ the process of the pipeline-soil interaction occurs only according to the law (9).

Consider the results of calculations. The change in shear stress over time is shown in figure 1. Curves 1–3 refer to pipeline sections $x = 5, 10, 15 \ m$, respectively. Figure 2 shows the changes in relative displacement corresponding to figure 1 on the same sections of the pipeline (curves 1-3).

**Figure 1.** Change in interaction force of the pipeline with soil over time.

**Figure 2.** Change in relative displacement over time in different sections of the pipeline.
Changes in the relative velocity for this option of calculations are shown in figure 3. Here, curve 0 is the pipeline cross-section velocity at \( x = 5 \text{ m} \). As can be seen, the pipeline cross-section velocity varies according to the load (6).

Figure 3 shows that the wave front in the pipeline propagates faster than in soil and reaches the pipeline sections earlier than the wave front in soil. Therefore, the values of the relative velocity before the wave arrival in soil at these sections of the pipeline are negative. After the wave front arrival to these sections, the relative velocity values begin to increase (points A, B and C in figure 3). As a result, the values of shear stress and relative velocity (points A, B, C in figures 1 and 2) are similarly but more smoothly changed. Since the soil stiffness is much less than the pipeline stiffness, the velocity of the soil particles at these sections is greater than the velocity of the pipeline sections. As a result, the relative velocity changes the sign (figure 3), and the signs of the relative displacement and shear stress change accordingly.

In the case of a negative sign of shear stress, it is directed counter the motion of the pipeline cross section and presents a resistance force (a passive force). The energy is wasted to overcome this resistance force by a wave, and the longitudinal stresses in the pipeline decrease. With an increase in the velocity of soil particles in all sections of the pipeline, the relative displacement value increases and the sign of the shear stress becomes positive. This means that the shear stress turns from a passive resistance force into an active force. The vector direction of this force coincides with the pipeline section motion. This leads to an increase in longitudinal stress in the pipeline [11]. As shown in [11], the value of longitudinal stresses in this case increases manifold. The reason for the increase in longitudinal stress in the pipeline is the transformation of interaction force from a passive force into an active one.

The corresponding diagram of the interaction force change on relative displacement is shown in figure 4. Here, curves 1-3 refer to the same sections as the curves in figures 1-3. In all sections of the pipeline at \( u = 0, \tau = 0 \). Further, at the beginning of the interaction process, the values of both \( \tau \) and \( u \) are negative. Further, the sign of \( \tau \) changes and \( \tau \) and \( u \) begin to grow. When the pipeline starts the reverse motion from points A, B and C, respectively (Fig. 4), the interaction force begins to decrease and the whole process repeats. The trajectory \( \tau(u) \) in figure 4 is similar to elastic-plastic
strain of soil. This means that the interaction law (9) - (11) indirectly describes the process of strain of the soil contact layer.

Figure 4. Diagrams of changes in the interaction force of an underground pipeline with soil.

The interaction processes, shown in figures 1-4, are repeated at each contact point of the outer surface of the pipeline with soil. These patterns of change in the interaction force $\tau$ are the true cause of formation of significant longitudinal stresses in the pipeline.

The calculation results show that an account for $\sigma_N^D$ in relation (15) is the main reason for the increase in the pipeline longitudinal stresses. With an increase in $\sigma_N$ with account for $\sigma_N^D$, the values of the active interaction force, according to equations (9) - (14), increase. This leads to an increase in longitudinal stress value. In order to account for $\sigma_N^D$, it is necessary to solve equations (1) - (3) for the soil medium.

In [20], the ignoring of $\sigma_N^D$ leads to significant errors in determining longitudinal stresses in an underground pipeline.

The calculation results also show that the load action (6) in the initial section of the pipeline does not significantly affect the values of the interaction force. In the absence of this load (6) in the initial section of the pipeline $x=0$, the results in figures 1-4 practically do not change. Accordingly, the longitudinal stress values in the underground pipeline do not change. The main reason for the formation and increase of longitudinal stress in the pipeline is the interaction force and its transformation from a passive force to an active one. Therefore, the main factors in ensuring the reliability, strength and stability of underground pipelines built for various purposes, under dynamic (seismic) impacts, are the wave processes in soil and the stress-strain state of soil.

This condition must be taken into account when developing the methods for calculating the strength, stability and reliability of underground pipelines on seismic effects.

4. Conclusions
1. Based on the results of numerical solutions to the problem of the underground pipeline-soil interaction, the mechanisms for the formation of interaction forces on the "pipeline-soil" contact
surface are determined.

2. The reason for the transformation of the interaction force from a passive resistance force to an active force of motion is shown. Moreover, its values significantly depend on the stress-strain state of the soil medium surrounding the pipeline.

3. It is recommended in developing engineering methods for determining the strength, stability and reliability of underground pipelines under the impact of dynamic (seismic) loads, to take into account first the dynamic stress-strain state of the soil medium surrounding the pipeline.

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