Underground pipeline reliability under longitudinal impact load

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Abstract. The paper presents the results of numerical solution obtained by the modified finite difference method according to the Wilkins scheme, to a two-dimensional unsteady-state problem of the plane shock wave propagation in an underground elastic pipeline, interacting with surrounding soil. Soil is considered to be an undeformable body moving relative to the pipeline at a given velocity. The value of the friction force depends on radial stress in the pipeline, determined by numerical solution to the problem. Changes in longitudinal and radial stresses over time and pipeline length, of velocity and displacements for fixed sections of the pipeline are obtained. Two times increase in values of longitudinal and radial stresses was detected in the case of active Coulomb friction at the pipeline-soil contact. The increase in stress values occurs due to the friction force acting in the direction of wave propagation. At significant values of the friction force on the outer surface of the pipeline, the hypothesis of flat sections is fulfilled for all its sections. This result justifies the consideration of similar problems of underground pipelines earthquake resistance in a one-dimensional statement. The results also make it possible to identify the mechanisms of the stress state formation in an underground pipeline interacting with soil, which can be used in seismic resistance calculation of underground trunk pipelines.

1. Introduction

The use of underground pipelines as a means of transporting various gas and fluid substances requires ensuring their reliable operation. The researchers pay a great attention to these issues [1-10]. Earthquake is essentially dangerous for the reliability of underground pipelines. In [1], the principal forces acting on underground pipelines during earthquakes were revealed in detail. Methods for determining the soil response to the underground pipeline motion were considered. The results of various tests of pipeline-soil interaction were compared. In [2], the performance of underground pipelines subjected to constant strike–slip movements was studied. For the pipelines having an infinite and finite length, the influence of the boundary conditions on the pipeline strain was shown. In [3], using the finite element model of beam-type components for the pipeline and nonlinear springs for soil, the ability of the considered model of “pipeline-soil” system to withstand the reverse fault motion was studied. The safety of underground steel pipelines conveying natural gas was addressed in [4]. The formation of local buckling in gas-conveying pipelines during earthquakes was studied in [5]. Experimental studies in a centrifuge of the effect of an earthquake on buried pipelines were conducted.
in [6,7]. Issues of seismic risk on the functioning of underground and underwater pipelines for various purposes were considered in [8-12].

2. Statement of problem

The dynamics of underground pipelines, taking into account the rheological properties of soil, have been studied mainly in a one-dimensional statement [13,14]. Models of pipe–soil interaction were experimentally studied in [15], the substantiation and method for considering complex rheological properties of soils were presented in [16–20]. Methods for experimental determination of mechanical characteristics of soils were considered in [21]. The issues of soil contact layer formation and its destruction under longitudinal motion of a pipeline were considered in [22,23]. Continuing the research conducted in [23], we consider here a two-dimensional unsteady-state wave problem for an underground pipeline. In cases of impact loads acting along the pipeline axis and neglecting the effect of the soil medium surface, the problem can be reduced to an axisymmetric problem. In this case, the equations of motion of the pipeline in a cylindrical coordinate system $r, z, \varphi$ have the form

$$
\rho \frac{dU_z}{dt} = \frac{\partial \sigma_{zz}}{\partial z} + \frac{\partial \tau_{rz}}{\partial r} + \frac{\tau_{rz}}{r}, \quad \rho \frac{dU_r}{dt} = \frac{\partial \sigma_{rr}}{\partial r} + \frac{\partial \tau_{rz}}{\partial z} + \frac{\sigma_{rr} - \sigma_{\varphi\varphi}}{r},
$$

where $z$ is the axis of pipeline; $r$ is the radial coordinate. Here, the components of the stress tensor are related to the corresponding components of stress deviator by relations that have the form

$$
\sigma_{zz} = S_{zz} - P, \quad \sigma_{rr} = S_{rr} - P, \quad \sigma_{\varphi\varphi} = S_{\varphi\varphi} - P, \quad \tau_{rz} = S_{rz}.
$$

The continuity equation takes the form

$$
\frac{\partial U_z}{\partial z} + \frac{\partial U_r}{\partial r} + \frac{U_z}{r} = \frac{\dot{V}}{V},
$$

where $V = \rho_0/\rho$ is the relative volume; $\dot{V} = dV/dt$; $\rho_0$ is the initial density of the medium.

The Cauchy relation in the case under consideration has the form:

$$
\dot{e}_{zz} = \partial U_z/\partial z, \quad \dot{e}_{rr} = \partial U_r/\partial r, \quad \dot{e}_{\varphi\varphi} = U_r/r, \quad \dot{e}_{rz} = \left(\partial U_r/\partial z + \partial U_z/\partial r\right)/2.
$$

Next, using the relations for the equation of state of the pipeline in the form of an elastic law of strain

$$
\frac{d\sigma_{zz}}{dt} = -K \frac{\dot{V}}{V}, \quad \frac{d\sigma_{rr}}{dt} = 2G \left(\dot{e}_{zz} - \frac{1}{3} \frac{\dot{V}}{V}\right), \quad \frac{d\sigma_{\varphi\varphi}}{dt} = 2G \left(\dot{e}_{\varphi\varphi} - \frac{1}{3} \frac{\dot{V}}{V}\right), \quad \frac{d\tau_{rz}}{dt} = G \dot{e}_{rz},
$$

the complete system of equations (1)-(5) for axisymmetric motion of the pipeline in soil is obtained.

First of all, of interest is the study of the effect of ground motion on the parameters of the waves propagating in the pipeline under Coulomb interaction with soil. Soil is considered to be an undeformable medium and moving at a certain velocity $U_{ext}$. Consider the process of longitudinal wave propagation in a pipeline buried in soil. A semi-infinite elastic pipeline with an outer radius $R_0$ interacts with rough soil, which moves at velocity $U_{ext}$. Note that the effect of soil motion on the pipeline behavior begins only under lateral expansion of the pipe. Therefore, we are dealing with a pipeline, pressed by soil without pressure. Let the initial section of the pipeline $z = 0$ be affected by a load which varies according to the law.
\[ \sigma_{zz} = \sigma_{\text{max}} \quad \text{at} \quad 0 < t \leq T, \quad \sigma_{zz} = 0 \quad \text{at} \quad t > T; \]
\[ \tau_{zz} = 0 \quad \text{at} \quad t > 0. \tag{6} \]

Naturally, before the load application, the pipeline in question is considered to be at rest and stress-free. From the moment of loading (6), a longitudinal wave propagates in a pipe along the axis of symmetry. Behind the wave front, longitudinal, radial and hoop stresses arise in the pipe, respectively, and due to the existence of external soil, a friction force appears on the side surface of the pipe, acting against the direction of relative velocity. The dynamics of the pipeline is studied for dry friction. Hence, for the boundary conditions on the side surface of the pipe \( r = R_0 \), we have the relations:
\[ \tau = \kappa \cdot f \cdot \left| \sigma_n \right| (z, R_0, t) \quad \text{and} \quad U_z (z, R_0, t) = 0, \tag{7} \]
where the shear stress (the friction force) arises from the amplitude of radial stresses determined in solution; \( \kappa = \text{Sign} \left( U_{\text{ext}} - U_z (z, R_0, t) \right) \), at \( U_{\text{ext}} = U_z (z, R_0, t) \) at \( \kappa = \pm 1 \). Note that in the case of a pipe separation from soil the stresses at the lateral boundary are taken as equal to zero. Thus, the equations of the pipeline dynamics with boundary conditions correspond to the system of equations (1)-(7).

3. Method of solution
When solving dynamic problems of an underground pipeline interaction with soil, a complex mathematical problem arises of integrating, in the general case, a nonlinear system of equations of motion, continuity and strain, both for a rigid body and for soil. The analytical methods used to integrate this system of equations have some drawbacks, as they greatly simplify the real situation.

The use of more complex equations of state instead of (5), which take into account the complex properties of the medium and soil motion, makes it difficult to obtain analytical solutions to the problem. To numerically solve the problem posed here, a set of programs was developed using the Wilkins scheme [24], which can be used as a reliable and effective tool for studying wave processes in an underground pipeline and surrounding soil. Therefore, the problem under consideration is solved by the finite difference method using the Wilkins scheme for two-dimensional axisymmetric problems. The finite-difference relations of the considered equations are available in [24].

4. Results and their analysis
For the steel pipe we accept the following data of the material: \( \rho_0 = 7800 \, \text{kg} \cdot \text{m}^{-3} \); \( E = 2.1 \cdot 10^5 \, \text{MPa} \); \( \nu = 0.3 \); \( R_0 = 0.2 \, \text{m} \) and \( \sigma_{\text{max}} = 11.163 \, \text{MPa} \). The values of the coefficient of friction, soil velocity and duration of acting load varied in a series of calculations. Calculations were made with varying amplitude of load, the outer radius and the mechanical characteristics of a pipe.

Consider some calculation results. Figures 1 and 2 show the changes in longitudinal stresses and particle velocity over time at fixed points in the pipeline at \( U_{\text{ext}} = 0.5 \, \text{m} \cdot \text{s}^{-1} \); coefficient of friction \( f = 0.2 \); \( T = 1 \, \text{ms} \). Curves 1-4 correspond to sections \( z = 0 \); 0.4 m; 1.2 m and 2 m along the axis of the pipeline. As seen from figure 1, the values of longitudinal stresses in the pipeline sections, with increasing distance from the end, increase and reach a maximum. Then, the maximum values of stresses over time remain almost unchanged. The increase in stress with distance is explained by the fact that the shear stress arising on the side surface of the pipe acts in the direction of wave propagation in the pipe. It should be noted here that the motion of surrounding soil, when the pipe is at rest, caused by the absence of normal pressure does not affect the stress state of the pipeline.

Changes in the pipe cross-section velocity over time for this calculation option are shown in figure 2. The pipe cross-section velocities increase in the pipe cross sections with the distance from the front end and with time. The increase in the pipe cross sections velocity occurs until reaching the specified velocity of soil motion. Then, the pipe moves with soil as a whole system.

At other values of soil velocity \( U_{\text{ext}} \), the longitudinal stress in the pipeline increases. After reaching the limit value of velocity, the stress growth stops, and the stress remains constant in all
sections of the pipeline at the reached maximum values. A similar pattern is observed for the distribution diagrams of stresses and cross-sectional velocity along the pipeline length for a fixed point in time (figures 3 and 4). Curves 1-4 in figures 3 and 4 correspond to \( t=5R_0/c_1 \), \( 10R_0/c_1 \), \( 15R_0/c_1 \) and \( 25R_0/c_1 \), where \( c_1 \) is the propagation velocity of longitudinal waves in the pipeline.

From the results given in figures 3-4, it follows that after reaching the limit value of the pipe section velocities, a plane wave propagates in the pipe without account for normal lateral stresses in soil. In figures 3 and 4, shock wave fronts are also visible. The numerical finite difference method used here is an approximate method. Therefore, the fronts of shock waves cannot be obtained as vertical in numerical solutions. The so-called "jumps" in stress and velocity are absent. This result is well known [24].

The pattern of change in time of shear stresses arising on the outer surface of the pipeline is shown in figure 5. The stress distributions along the pipe length at various points in time are shown in figure 6. Curves 1-3 in figure 5 correspond to sections \( x=0.4; 1.2 \) and \( 2 \)m, respectively. On the contact surface, shear stress occurs with the appearance of radial stresses behind the wave front due to soil incompressibility. As seen from figure 5, with distance, the friction force, being an active force, increases, and in fixed sections of the pipe behind the wave front remains practically constant until a certain point in time (curves 1-2). Later, under joint motion of the pipe and soil, the shear stresses tend to zero. In numerical calculations, the values of velocity of pipeline sections (particle velocities on the outer surface of the pipeline) do not always exactly coincide with the value of \( U_{ext} \). A slight deviation (of the order of \( 10^{-22} \)) in values of section velocity of the pipeline and soil leads to the values of \( \pm 1 \) of function \( \text{Sign}(U_{ext} - U(z,R_0,t)) \). As a result, at each step of calculation, the shear stress direction...
changes. Therefore, the oscillation results observed in figures 5 and 6 are obtained. This also implies the inaccuracy of the numerical method.

Figure 5. Change in time of friction forces arising on the side surface of the pipeline.

Figure 6. Friction forces distribution on the side surface along the pipeline length.

Figure 7 shows the change in radial stresses over time in fixed sections of the pipeline. Curves 1-4 in this figure correspond to the same points in figure 1. As expected, the radial stresses of the pipeline change in quality similar to the changes in longitudinal stresses (figure 1). In quantity they differ coefficient of proportionality equal to the coefficient of lateral pressure. Here, an increase in values of radial stresses occurs up to a certain time, i.e. up to aligning the pipe sections velocity with soil velocity. According to the calculation results, the maximum values of longitudinal (figure 1), radial (figure 7) and hoop stresses in the option under consideration are approximately doubled compared to the set stress in the initial section of the pipe.

Figure 7. Change in radial stresses over time in fixed sections of the pipe.

Figure 8. Change in longitudinal displacements of pipe sections over time.

Figure 8 shows the changes in longitudinal displacements of the same sections of the pipeline in time. A linear change in displacements in pipeline sections shows that the hypothesis of flat sections in this case is fulfilled. The fulfillment of the hypothesis of flat sections at significant shear stresses (1.5 MPa) on the outer surface of the pipeline justifies the one-dimensional statement of similar problems of seismic resistance of underground pipelines, considered in [13,14].

5. Discussion

The results of the above numerical calculations show that the increase in longitudinal stresses in underground pipelines occurs due to soil displacement relative to the pipeline. The greater the relative displacement of soil, the greater the longitudinal stress. Soil displacement during real earthquakes is formed as a result of soil strain, which differs along the pipeline length. The assumption that the soil is an undeformable body is a limiting case when the particle displacement along the entire length of the
pipeline is the same. Such a simplification of the problem was necessary to identify the mechanism of the stress state formation in the underground pipeline.

The solution to the problem considered here, taking into account the strain characteristics of soil surrounding the pipeline and taking into account the free surface of soil, will lead to significant difficulties. Obtaining a solution to this problem will undoubtedly clarify the results obtained here, but this is a matter for the future.

In the case considered here, the friction force on the contact surface of an underground pipeline with soil arises due to radial stresses in the pipeline (figure 7). The value of radial stresses in this case reach $\sigma_r = 5\pm10$ MPa. An account for strain characteristics of soil will correct the obtained values of radial stresses. Therefore, the statement of the problem considered here on pipeline-soil interaction system is a simplified one. However, the considered statement of the problem and its solution allows revealing the mechanisms of a stress state formation in an underground pipeline when surrounding soil moves with a certain velocity in the pipe axial direction, and the hypothesis of flat sections for the pipeline is fulfilled at significant values of the friction forces on its outer surface.

6. Conclusion
A two-dimensional non-stationary problem of longitudinal plane wave propagation in an underground pipeline is set, the front of which is perpendicular to the pipeline axis, taking into account soil motion as an undeformable body. An algorithm and software for numerical solution to the problem using the finite difference method according to the Wilkins scheme are developed. Based on the obtained numerical solutions, the changes in longitudinal and radial stresses in the pipeline are determined. Two times increase in longitudinal stresses along the pipeline length was detected due to the active Coulomb friction force between the pipeline and soil. Validation of the hypothesis of flat sections fulfillment for the pipeline is obtained at significant values of the friction force on pipe outer surface – soil contact.

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