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Seismodynamics of Underground Pipelines during Visco-Elastic-Plastic Interaction with Soil

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ABSTRACT: The paper presents an analysis of the dynamic response of an underground pipe under the action of a longitudinal wave in the soil propagating along the pipe. It is assumed that the elastic pipe has a finite length and the viscoelastic-plastic model of the interaction of the pipe-ground system is considered. The influence of the hardening coefficient and boundary conditions on the absolute and relative displacement, as well as the stress of the underground pipeline, is investigated. Each specific case is brought up to numerical values, dangerous points of the occurrence of maximum normal stresses under the influence of seismic loads on the underground pipeline are determined. Various regularities of the change in displacement and stress in the sections of steel pipelines in time and coordinate were established under the action of a traveling sine wave, in particular, it was shown that the resulting absolute maximum stress values when taking into account the nonlinear interaction of the pipeline with the soil are always less than with linear interaction.

KEY WORDS: viscosity, ductility, pipeline, hardening coefficient, elasticity, stress.Introduction

I.INTRODUCTION

The behavior of underground structures during seismic impact is largely determined by the nature of the soil conditions, and when conducting seismodynamic calculations, the degree to which the results obtained correspond to the actual process substantially depends on how much the selected model of interaction between the structure and the soil corresponds to the real nature of the interaction.

Further studies [1–7] indicated that dynamic amplification plays a minor role in the response of continuous buried pipelines. Therefore, axial strains and curvatures of a buried pipeline at the passage of a seismic wave can be determined according to the static response of the pipe [8]. In [9] O’Rourke and El Hmadi developed a procedure to estimate the maximum axial strain for long straight of buried continuous pipes subjected to seismic propagation along the longitudinal axis. They concluded that if slippage between the pipe and the surrounding soil does not occur, the pipe strain is similar to the ground strain, according to the Newmark approach. On the contrary, if slippage occurs, the Newmark method provides very conservative values of the pipe axial strain. Others authors [10-15] studied seismic response of buried pipes schematizing the pipe as a beam on dynamic elastic foundation and the soil modeled as a bed of springs according to the Winkler model BDWF—Beam on Dynamic Winkler Foundation.

Nevertheless, the above-mentioned procedures consider infinite length pipelines and hence fail to account for their effective lengths and any construction works constraint conditions. In [9] O’Rourke et al. developed analytical relations for finite length pipe subjected to various combinations of end conditions i.e., free end, pinned, or spring end using the concept of pipe development length. De Martino et al. [16] and Corrado et al. [17] developed a pipe soil interaction model considering finite length pipe. By assuming a linear elastic soil and neglecting slippage at the pipe-soil interface, the model analyzes the dynamic behavior of a finite length pipeline taking into account the boundary conditions at its ends and the inertia forces FLBDWF—Finite Length Beam on Dynamic Winkler Foundation. The pipeline was assumed to be continuous; that is, any variations between the characteristics of the pipe and those of the joints were assumed negligible.

According to the FLBDWF approach, in this paper numerical simulations are carried out to assess the pipe dynamic response, showing that the maximum pipe strain strongly depends on the length and constraint conditions. Results obtained considering free- and pinned- end conditions are compared with values inferred from models assuming infinite length pipe and/or neglecting the inertial terms. For free-end pipes, the obtained results agree with the

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values inferred from the above-mentioned models only for long pipes, whereas for short lengths the maximum pipe strain significantly reduces. For pinned ends, neglecting pipe inertia and considering infinite length pipe underestimates the axial strain, particularly for short pipes.

In [18-19], a study was made of the influence of the elastic-plastic properties of the interaction on the seismic vibrations of an underground pipeline system, the design scheme of which was chosen with a finite number of degrees of freedom.

The formulation and solution of any engineering problem is always associated with the idealization of real processes and phenomena, since it is impossible to take into account all factors that have at least some influence on the course of the process. Therefore, when formulating the problem, a number of parameters are highlighted that play a decisive role in these operating conditions. When solving applied problems of earthquake resistance of underground structures, the question of the nature and magnitude of the forces arising at the contact of the surface of the structure with the environment in the presence of relative displacements is essential. The nature of the seismic movement of the soil in the vicinity of the structure is assumed to be known in advance. Thus, the interaction implies the nature and magnitude of the friction force acting on the surface of the structure in contact with the soil in the presence of relative displacements caused by the seismic load due to the difference in their physical and mechanical properties.

It has been experimentally established that the law of interaction of underground structures with various soils in the general case is non-linear. The parameters characterizing the nonlinear, elastic, plastic and viscous properties of the interaction of an underground pipeline with soil have been determined [20].

The work [21] presents an analysis of the dynamic response of an underground trunk pipeline under the action of a wave in the ground. It is assumed that the elastic pipeline has a finite length and an elastic model of the interaction of the pipe-soil system is considered, the equation of motion of which is given in [17,22].

II. METHODOLOGY / APPROACH

Since there are no generally accepted methods for predicting the actual propagation of seismic waves [23], most authors accept, representing the motion of the soil as a single sinusoidal wave. The movement of soil parallel to the pipe can be written as

$$u_0 = \begin{cases} A \cdot \sin \omega \left(t - x/C_p\right), & if \;\; t > x/C_p \,, \\ 0, & if \;\; t \le x/C_p \,, \end{cases} \tag{1}$$

where A is the amplitude of soil motion, ω is the frequency of oscillations of the seismic wave, determined by the formula: $\omega = 2\pi / T$; C_p - " apparent speed" of wave propagation (hereinafter we will use this under the name wave propagation velocity in the ground). The "apparent speed" of wave propagation in the ground can be large due to the angle of incidence of the wave to the axis of the pipeline or due to malleable joints of the pipeline. In [9] O'Rourke et al. concluded that C_p is always greater than the propagation velocity C_s of the shear waves *S* in the soil's surface strata, equal to $C_s = (G/\rho)^{1/2}$, with *G* and ρ tangential elasticity modulus and soil density, respectively. They also proposed a method for determining the apparent propagation velocity, obtaining C_p 2.1 km/s and 3.76 km/s for the 1971 San Fernando and 1979 Imperial Valley earthquake data, respectively. In [24] Committee on Gas and Liquid Fuel Lifelines considered that these values would be not appropriate for analysis, because they ignore changes in the wave shape from one point to other [14]. Consequently, in [13] Manolis et al. suggested for C_p values ranging between 1.2 and 3.0 C_s.

III. FORMULATION OF THE PROBLEM

Consider the problem of longitudinal vibrations of an underground pipeline with visco-elastic-plastic interaction at contact with the ground, with two types of fixation.

$$m \cdot \frac{\partial^2 u}{\partial t^2} - EF \cdot \frac{\partial^2 u}{\partial x^2} + \frac{\pi D \mu}{H} \cdot \left(\frac{\partial u}{\partial t} - \frac{\partial u_g}{\partial t} \right) + \pi D k_x \cdot (u - u_g) \cdot \left[1 - \omega(u - u_g)\right] = 0 \tag{2}$$

where $\omega(u - u_g)$ is the function characterizing the nonlinear properties of the interaction. The form of this function is specified by approximating experimentally obtained diagrams of the dependence of the tangential force on the relative displacement of the pipes. The approximation of the $\omega(u - u_g)$ function depends on the physical and mechanical properties of the pipeline and the specific type of soil.

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1. If the restrictions at both ends of the pipeline are such that they prevent all relative displacements between the structure at the ends of the pipeline (wells, pumping stations or in places of sharp turns of underground pipes) and the pipe (fixed ends), then we assume that these ends are fixed to the ground, and get

$$u = 0 \quad \text{for } x = 0, x = l, t > 0. \tag{3}$$

2. If the restrictions at the ends of the pipeline are such that they can provide zero deformation (free ends), then the normal force is constant at $x = 0$ and $x = l$, and therefore

$$\frac{\partial u}{\partial x} = 0, \quad \text{for } x = 0, x = l, t > 0. \tag{4}$$

The nonlinearity function of the $\omega(u - u_g)$ interaction can have a different form depending on the magnitude and speed of the relative displacement $u - u_g$, $\dot{u} - \dot{u}_g$ and the background of the movement. The solution of equation (2) will also be different at different stages of movement.

If the nonlinear properties of the interaction are approximated by the bilinear law of change in the tangential force [25-26] Fig. 1, in which the transition from the zone of elastic interaction to the zone of plastic interaction with hardening is characterized by a change in the interaction coefficient k_x and the unloading is carried out by elastic, then the plasticity function $\omega^n(\bar{u}^n)$ is described by expressions of the form [25,27].

$$\omega^n(\bar{u}^n) = \begin{cases} 0, & n = 0 \\ c \cdot [\varphi^n \cdot \bar{u}^n + (1 - \varphi^n) \cdot \bar{u}^{n-1} + \psi^n \cdot \tilde{\bar{u}}^{s0}] / \bar{u}^n, & n = 1,2,.. \end{cases} \tag{5}$$

here n is the serial number of the stage of movement (to each n value there corresponds a rectilinear section of the diagram of Fig. 1.);

$\tilde{\bar{u}}^{s0}$ is the initial elastic limit of interaction; $\bar{u}^{n-1}, \bar{u}_g^{n-1}$ - values of movement of the pipe and soil at the end of the $(n-1)$ - th stage of movement; φ^n, ψ^n - dimensionless parameters taking the following values [25]

$$\varphi^i = \begin{cases} 0, & i = 2k \\ 1, & i = 2k+1, \end{cases} \quad \psi^i = \begin{cases} -1, & i = 4k+1, \ i = 4k+2, \\ 1, & i = 4k, \quad i = 4k+3, \end{cases} \quad k = 0,1,2,.. \tag{6}$$

γ– hardening coefficient.

$$\gamma = (k_x - k'_x)/k_x, \ k_x = tg\alpha, \ k'_x = tg\alpha' \tag{7}$$

$\bar{u}_{\bar{i}} = \tilde{\bar{u}}^{s\bar{i}}$ - new limit of interaction elasticity at the $\bar{i}$ stage of motion at

$$\bar{i} = 2k, \ k = 0,1,2,\ldots \ \tilde{\bar{u}}^{s\bar{i}} = \bar{u}^{\bar{i}-1} + 2\psi^{\bar{i}} \cdot \tilde{\bar{u}}^{s0}. \tag{8}$$

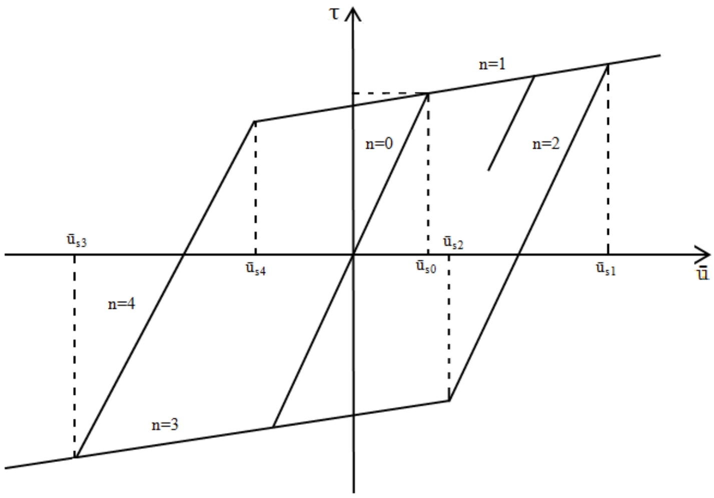

Figure 1 - The dependence diagram corresponding to the bilinear law of interaction

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We write equation (2) in relative displacements:

$$m \cdot \frac{\partial^2 \bar{u}}{\partial t^2} - EF \cdot \frac{\partial^2 \bar{u}}{\partial x^2} + M \cdot \frac{\partial \bar{u}}{\partial t} + K \cdot \bar{u}\left[1 - \omega(\bar{u})\right] = EF \cdot \frac{\partial^2 u_g}{\partial x^2} - m \cdot \frac{\partial^2 u_g}{\partial t^2} \qquad (9)$$

here $M = \frac{\pi D \mu}{H}$, $K = \pi D k_x$

Equation (9) is solved by the finite difference method in an implicit scheme; this scheme has absolute stability. It can be reduced to a SLAE with a tridiagonal matrix solved by the sweep method.

Consider a pipeline, for the case with loose and fixed both ends to the ground.

The equations of propagation of longitudinal waves (9) are solved by the method of finite differences of the second order of accuracy in an implicit scheme. The calculation results are presented in the form of graphs for the parameter x and t.

Next, the solutions of the differential equations of linear and nonlinear problems are compared. Consider the stress-strain state of a steel pipeline with fixed and free ends under longitudinal seismic action, taking into account the nonlinearity of the interaction.

Mechanical and geometric parameters are set in the following values: $E = 2.1 \cdot 10^5$ МПа; $\rho = 7.8 \cdot 10^3$ кг/м^3; $D_H = 0.61$ м; $D_B = 0.6$ м; $F = \frac{\pi\left(D_H^2 - D_B^2\right)}{4}$ м^2; $l = 100$ м; $\omega = \frac{2\pi}{T}$; $A_p = 0.004$ м; $T = 0.2$ с; $C_p = 800$ м/с; $k_x = 2 \cdot 10^4$ кН/м^3; $u_s = 0.0001$ м; $c = 0.2$;

IV. RESULTS & DISCUSSION

Visco-elastic-plastic interaction, unlike visco-elastic, beyond the elastic limit of interaction, the value of the coefficient of elastic interaction of the "pipe-soil" system decreases, that is, the resistance of the soil surrounding the pipe decreases, as we saw earlier, a decrease in the coefficient of resistance leads to a decrease in the relative displacement, exactly also in this case. With an increase in the compaction coefficient c, the maximum value of the relative displacement increases (see Fig. 2). Fig. 3 shows an increase in the maximum values of relative displacements with a change in the coefficient of interaction compression γ from 0 to 1.

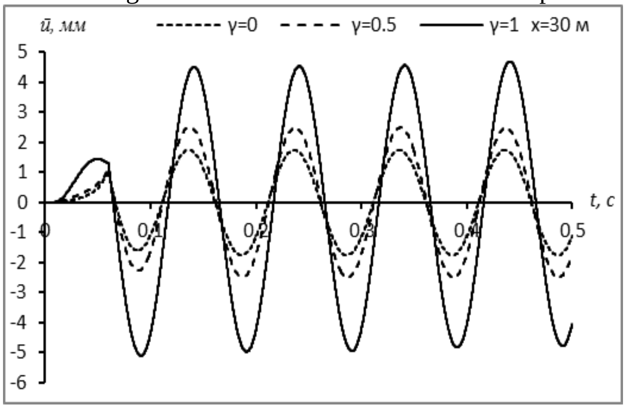

Fig. 2 Change relative displacement by time

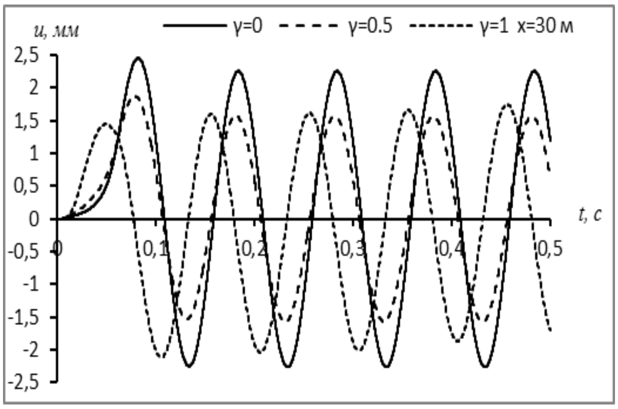

Fig.3. Change displacement by time

The absolute and relative displacement of both ends of the fixed underground pipeline shown in Figs. 4 and 5, proceeding from the boundary conditions at the ends for different values of the compression coefficient of the interaction, the movement is the same, but otherwise, with a decrease in the compression coefficient of the interaction, the amplitude and phase shift of the oscillations decrease.

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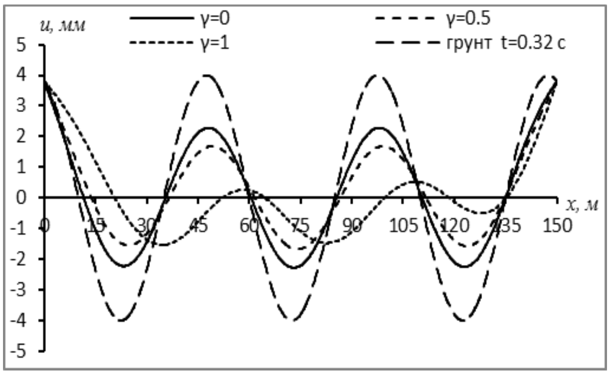

Fig.4 Change displacement along the coordinate

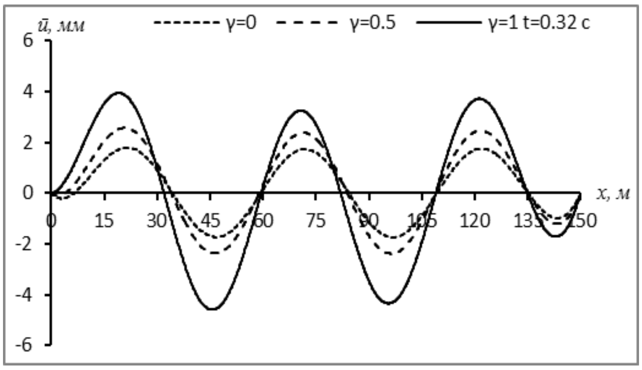

Fig. 5 Change in relative displacement along the coordinate

The phase shift of the oscillations in the interval γ = 0-0.8 is insignificant, and in the interval γ = 0.8-1 they progressively increase.

Given the increase in maximum relative displacement with an increase in the interaction compaction coefficient, the maximum absolute displacement should decrease. The maximum absolute displacement in the case of γ = 1 is greater than γ = 0.9, this is due to the phase shift of the oscillation. The phase shift prevents the conclusion for absolute displacement, depending on the coefficient of compaction of the interaction.

The greater the compaction coefficient of the interaction, the less stress. As shown in fig. 6, the greater the compaction coefficient, the greater the phase shift. At γ = 1, i.e., with dry friction, the phase shift is much larger, therefore, in Fig. 6, the stress values at γ = 1 are greater than at γ = 0.9, when the increase in the stress coefficient on the pipeline should decrease. Figure 7 shows the change in stress along the coordinate.

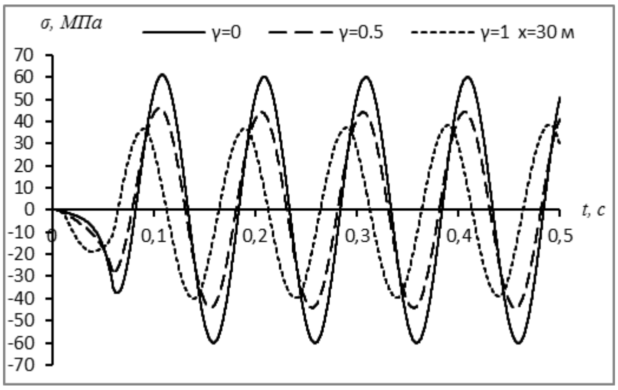

Fig. 6 Change in stress over time

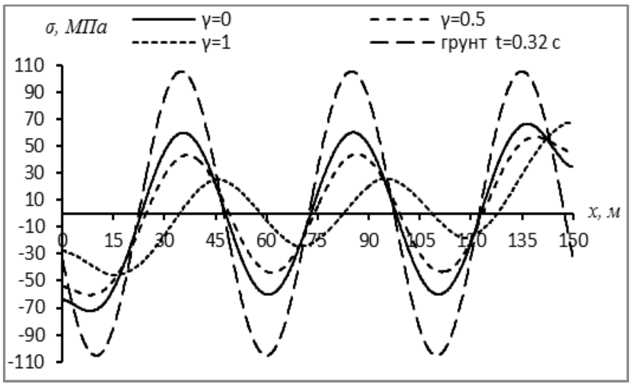

Fig. 7 Change in stress of pipe and soil along the coordinate

Now let's see the effect of fixing the SSS (stress-strain state.) on the underground pipeline. Above are results with fixed ends. Below, we compare the results with the free and fixed ends for different values of the interaction compression coefficient.

The type of fixation of the underground pipeline does not affect the movement of the underground pipeline for viscoelastic interaction of the pipe-soil system.

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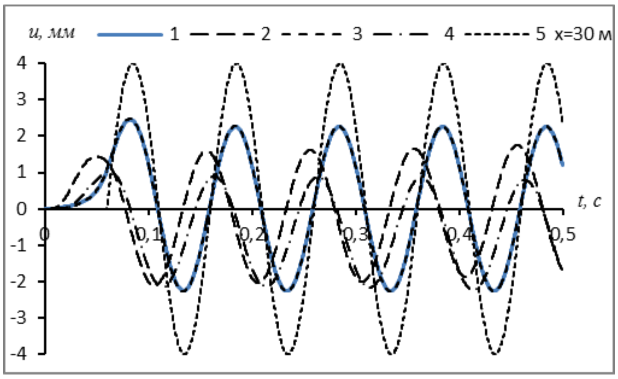

Fig. 8 Change displacement by time: 1- γ = 0, fixed ends; 2- γ = 1, fixed ends; 3- γ = 0, free ends; 4- γ = 1, free ends; 5- in the ground.

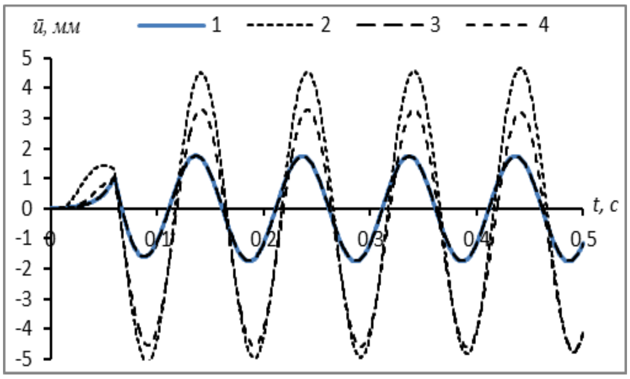

Fig. 9 Change displacement by time: 1- γ = 0, fixed ends; 2- γ = 1, fixed ends; 3- γ = 0, free ends; 4- γ = 1, free ends; 5- in the ground.

As shown in Figs. 8 and 9, for the compression coefficient γ = 1, the influence of the boundary conditions on the maximum values of the absolute and relative displacement is significant

A comparative analysis shows that taking into account the nonlinearity of the interaction of the pipeline with the soil leads to an increase in the relative displacements between the pipe and the soil and to a decrease in the value of the normal stress of the pipeline. In boundary conditions fixed to the soil, the maximum relative displacement is greater than in free boundary conditions, taking into account the nonlinearity of the interaction.

V. CONCLUSION

The SSS of an underground pipeline with linear and nonlinear interaction with soil has been investigated. Differential equations are given. The problems are solved by the finite difference method in an implicit scheme, two types of boundary conditions are taken into account.

Each specific case is brought up to numerical values, dangerous points of the occurrence of maximum normal stresses under the influence of seismic loads on the underground pipeline are determined.

Various regularities of the change in displacement and stress in the sections of steel pipelines in time and coordinate were established under the action of a traveling sine wave, in particular, it was shown that the resulting absolute maximum stress values when taking into account the nonlinear interaction of the pipeline with the soil are always less than with linear interaction.

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