Assessment of the Effect of Inertia Forces in Problems of Underground Pipeline Seismodynamics

D.A. Bekmirzaev, R.U. Kishanov

Abstract: ***A research to assess the effect of inertia forces in solving specific problems of seismodynamics of underground life support systems is conducted in the paper. A calculation algorithm is constructed using the finite difference method; a system of applied programs based on the developed algorithms and their debugging is created. Dangerous points of maximum normal stress occurrence under seismic loading in underground pipeline are determined taking into account elastic pipe-soil system interaction. The limits of inertial load effect on the behavior of underground systems are estimated.***

The possibility of considering the seismodynamic problems of underground structures in quasistatic and static statements is substantiated theoretically. The methods of solving the equations of underground pipeline vibrations are given with account for elastic interactions in the pipe-soil system under seismic effect - seismodynamic and quasistatic methods.

The conducted computational and experimental studies allow solving the problems of assessing the stress-strain state of pipelines under seismic loading, which is important for practical calculations.

Keywords: underground pipeline, seismo-dynamics, seismic effect, interaction, soil, elastic constants, parameters of the viscosity, model, seismic load.

I. INTRODUCTION

At the initial stage of formation of a dynamic theory of earthquake resistance of underground pipelines, there was practically no information about damage and destruction of underground structures during earthquakes. There were only single data on the consequences of earthquakes in Japan (Tokyo, 1923), the USA (California, 1906), Turkmenistan (Ashgabat, 1948), Uzbekistan (Tashkent, 1966) and several others.To date, the problem of analyzing the behavior of underground pipelines in seismic regions is one of the most relevant problems [1-4]. In this regard, there arises a need to single out a separate class of problems for the dynamic theory of earthquake stability of underground structures, in which it is possible to neglect the self-mass of structure and to conduct research in the framework of a quasistatic theory. In static theory of seismic resistance the structure is taken as a rigid body, in the case of an underground structure, it is assumed that under seismic effect it moves together with soil. The models proposed by the authors take into account the structure strain and its motion relative to surrounding soil and the "soil-structure" system interaction. This quasistatic theory differs from static one. Dynamic theory, due to its generality and versatility, relies on a rather complicated mathematical apparatus that is not always accessible for the engineers; its results cannot always be formulated in the form of calculation formulas and norms suitable for direct technical decisions. We have analyzed the available materials related to the earthquake resistance of underground pipelines in order to highlight a range of tasks, the study of which should be carried out in a quasistatic statement.

Revised Manuscript Received on January 05, 2020

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II. METHODOLOGY

Ground structures are mostly destroyed by the inertia forces initiated by an earthquake. The structure interaction with the base can also affect the stress state characteristics. Damage and destruction of one building does not affect the neighboring ones, as for the underground life support systems (primarily, the pipelines), the inertia force does not significantly affect when compared with the forces of interaction in the pipe-soil system, in some cases they can be neglected, which greatly simplifies the task.

The bases to account for the forces acting on extended structures during an earthquake caused by soil strain were first proposed in [1–4] under the assumption of mutual displacement of the underground pipeline relative to soil due to the difference in their displacements. The equation of motion of an underground pipeline is written in the form [5]

$$-\rho F\frac{\partial^2 u}{\partial t^2}+EF\frac{\partial^2 u}{\partial x^2}-\pi D_H k_x\left(u-u_0\right)=0\,, \qquad (1)$$

where E, F and D_H are the elastic modulus of the pipeline material, its cross-sectional area and the outer diameter of the pipe, respectively; k_x is the coefficient of longitudinal pipe-soil interaction; ρ is the density; u_0 is the law of soil motion along the longitudinal axis of the pipeline.

Some researchers [4-6] solve dynamic equation (1), neglecting the effect of inertia forces in the form

$$\frac{\partial^2 u}{\partial x^2}-p^2\left(u-u_0\right)=0\,, \qquad (2)$$

where $p^2=\pi D_H k_x/EF$.

The problem of longitudinal vibrations of an underground pipeline under seismic motion is solved by the analytical method and the finite difference method.

The solutions of equations (1) and (2) are found in the following form

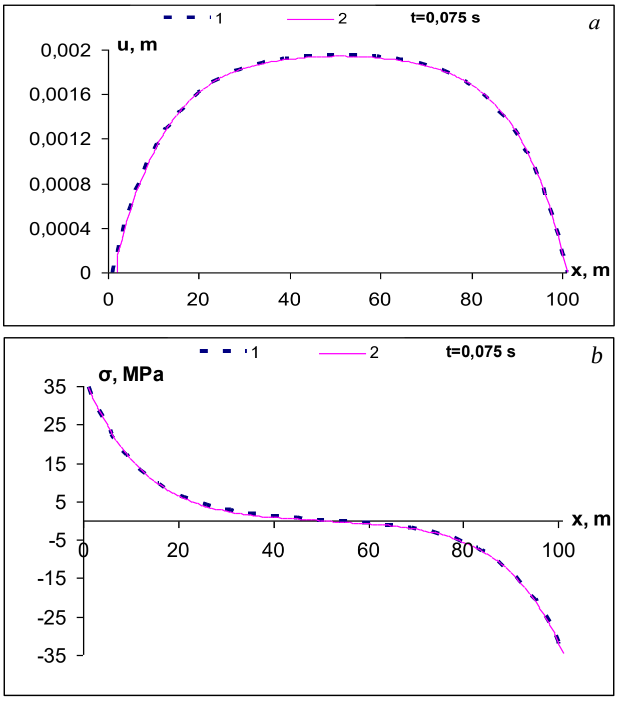
$$u_i^{j+1} = \alpha_{i+1} u_{i+1}^{j+1} + \beta_{i+1}$$

III. RESULT AND DISCUSSION

Task 1. Consider a pipeline, both ends of which are rigidly fixed. The mechanical geometrical parameters are taken as follows: E=2·10^5 MPa; ρ=7.8·10^3 kg/m^3; D_H=0.5 m; D_B=0.49 m; l=100 m; $u_0(t)$=a_0·sinωt; a_0=0.002 m; ω=2π/T; T=0.3 s; k_x=1.5·10^4 kN/m^3.

Equation (2) is taken as the equation of motion of longitudinal vibrations, solved by the method of finite differences of the second order of accuracy in an implicit scheme. Calculation results are presented in the form of tables and graphs of changes in maximum displacements and stresses along the x axis of the pipeline.

Figure 1 shows the comparison of the solutions of differential equations (1) with inertia force and (2) without inertia force. The graphs show that the maximum values and curve forms coincide (Figure 1, *a* and *b*).



1– without inertia force; 2– with inertia force.

Figure 1 - Change in longitudinal displacements (*a*) and normal stresses (*b*) along the pipeline at a set point of time

From the analysis of figure 1 it follows that their forms practically coincide (figure 1, *a*, *b*), and the maximum values give an error in problems solution of about 6 - 10%.

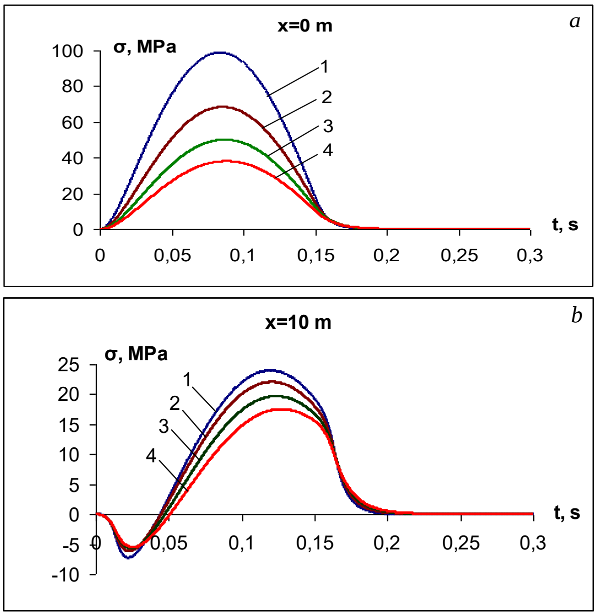
Task 2. Consider the case when one end of underground pipeline is flexible and the other is free. Mechanical and geometrical parameters are taken as follows: E=2·10^5 MPa; ρ=7.8·10^3 kg/m^3; l=100 m; ω=2π/T; T=0.3 s; a_0=0.004 m; C_p=800 m/s; k_x=2·10^4 kN/m^3; K_N=29·10^4 kN/m. An impulse impact in the form (3), was chosen as the law of soil motion.

$$u_0(x,t) = \begin{cases} a_0 \sin \omega\left(t - x/C_p\right), & at\ \ t > x/C_p \ \text{ and } \ t > T/2, \\ 0, \ \ at \ \ t < x/C_p \ \text{ and } \ t < T/2. \end{cases} \quad (3)$$

The results of problem solution are presented in the form of graphs, the analysis of which allows tracing the changes in displacements and normal stresses of the underground pipeline depending on various geometrical relations.

Figures 2, *a*, *b* show that when the condition t> T/2 is met, the load is set in the form of a half-wave, which affects the values of stresses arising in underground pipelines, otherwise the load is absent and the pipeline makes free vibrations.

The figure shows the graphs of changes in normal stresses for different values of the pipeline diameter. Their analysis shows that with an increase in the pipeline diameter, seismic resistance of the pipeline increases.

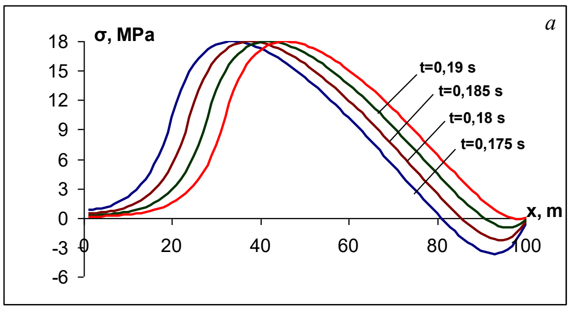


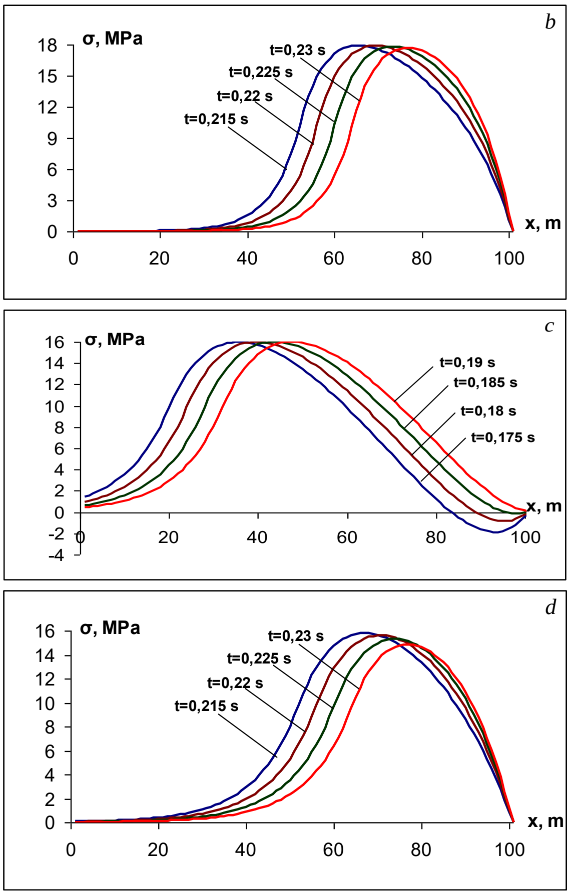
1–D_H=0.2 m, D_B=0.192 m, δ=0.004 m;
2–D_H=0.3 m, D_B=0.288 m, δ=0.006 m;
3–D_H=0.4 m, D_B=0.384 m, δ=0.008 m;
4–D_H=0.5 m, D_B=0.48 m, δ=0.01 m.

Figure 2 - Change in normal stresses (*a*, *b*) of the pipeline over time under impulse effect

Figure 3 shows the graphs of changes in normal stresses along the pipeline axis at set points of time; this allows us to observe the wave propagation in underground pipeline at set points of time.

As seen from Figure 3,*b*, the wave effect is observed in the cross-section of the pipeline x=35 m at pipeline diameter D_H=0.2 m, and from Figure 3,*d* - in the cross-section of the pipeline x=15 m at D_H=0.5 m. Thus, the greater the pipeline diameter, the earlier the wave effect on the pipeline is observed.





a, b – D_H=0.2 m, D_B=0.192 m, δ=0.004 m;
c, d – D_H=0.5 m, D_B=0.48 m, δ=0.01 m.

Figure 3 - Change in normal stresses along the pipeline at set points of time

Figures 4 and 5 show three-dimensional graphs of changes in longitudinal displacements and normal stresses in time and coordinate.

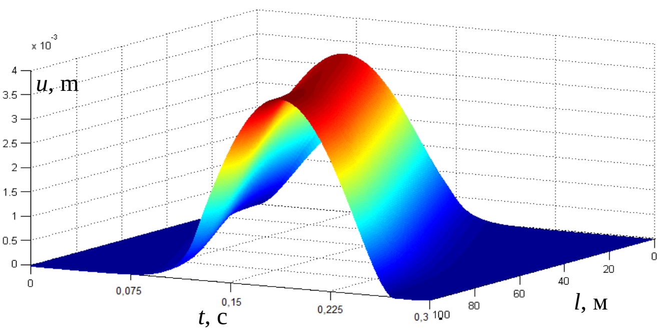


Figure 4 - Change in longitudinal displacements of underground pipeline

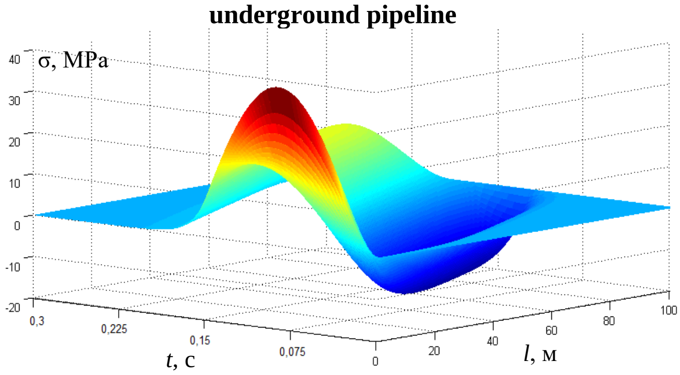


Figure 4 - Change in normal stresses of underground pipeline

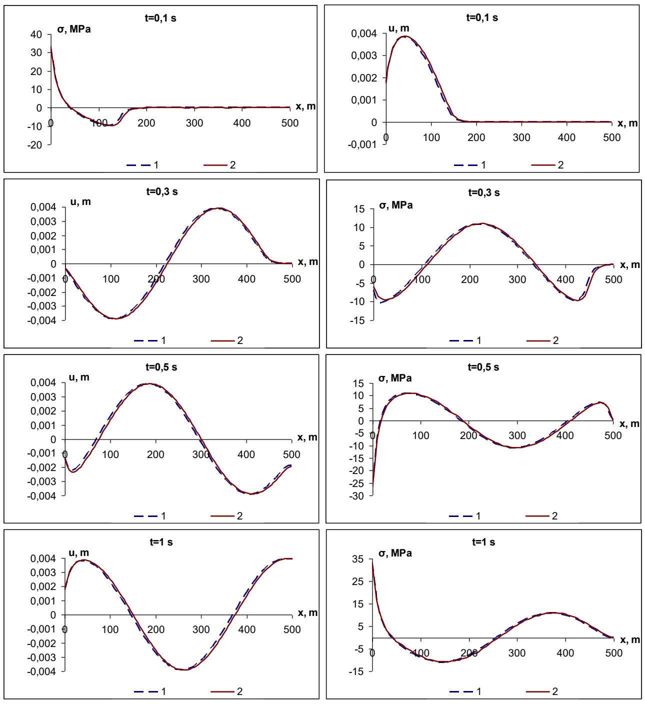
In the considered statements of the problem, the main role is played by condition (3). As seen from the figures, the bursts are not observed when the condition is met.

Task 3. Consider the case when one end of underground pipeline is flexibly fixed and the other one is free.

Mechanical and geometrical parameters are taken as follows: E=2·10^5 MPa; ρ=7.8·10^3 kg/m^3; k_x=2·10^4 kN/m^3; l=500 m; ω=2π/T; a_0=0.004 m; T=0.3; K_N=29·10^4 kN/m. An impulse impact, presented in the form (4), is taken as the law of soil motion

$$u_0(x,t)=\begin{cases} a_0 \sin\omega\left(t-x/C_p\right), & at\ \ t>x/C_p \\ 0, & at\ \ t<x/C_p \end{cases} \qquad (4)$$

The analysis of long underground pipelines during the wave propagation in soil in the form (4) is considered. Figure 6 shows the wave distribution in the pipeline sections in the time range 0.05 – 1 s, at the Mach number **M**<1 (**M**=C_p/a_T, $a_T=(E/\rho)^{1/2}$).

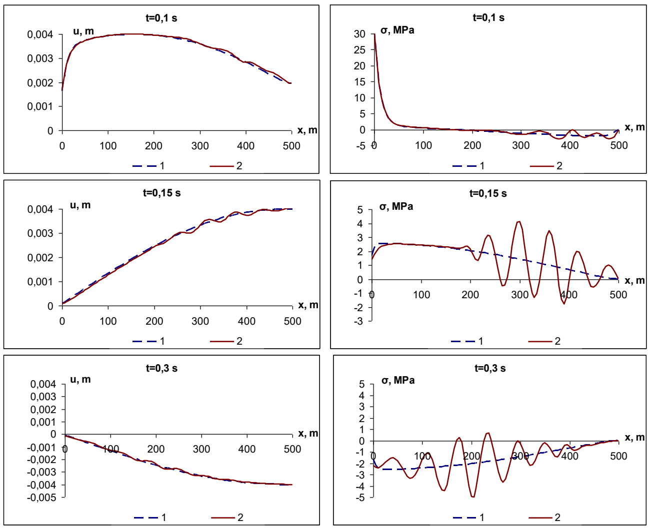


1 - without inertia force; 2- with inertia force.

Figure 6 - Change in longitudinal displacements and normal stresses along the pipeline at set points of time. C_p=1500 m/s, M<1.

It is found that at t=0.33 s the wave reaches the right end of the pipeline. At subsequent points of times, reverse wave propagation is observed in the pipeline, at t=0.66 s the wave completely returns to the cross section x=0. The problem is solved with and without inertia force, the results are quite close, their forms and maximum values of displacements and stresses coincide (see Figure 6).

Figure 7 shows the changes in longitudinal displacements and normal stresses along the pipeline axis at set points of time, when the soil propagation velocity is C_p=6500 m/s and the Mach number is **M**>1.



1 - without inertia force; 2 - with inertia forces.

Figure 7 - Change in longitudinal displacements and normal stresses along the pipeline at a set point of time. C_p=6500, M>1.

Here the results obtained are compared with inertia forces (curves 2) and without inertia forces (curves 1), and there a significant difference is observed between the results of the task: the forms and maximum stress values do not coincide at t=0.15 s, t=0.3 s. When the inertia forces are taken into account, the wave front is observed on the graphs of normal stress changes at t=0.1 s.

IV. CONCLUSION

It was revealed that the inertia force does not always have the same effect on the dynamics of underground structure system. Only in certain cases, the quasistatic statement allows to obtain satisfactory results.

As seen from the results, the advantage of quasistatic methods over dynamic ones is the relative simplicity of dynamic effect calculation, and the fact that the stress-strain state of the pipeline (displacement, stress) is determined by static calculation. This makes it possible to determine the pipeline behavior under dynamic load using simple finite-difference programs that do not enable to conduct rigorous dynamic analysis.

Thus, the results obtained using quasistatic calculations should be considered as a first approximation. It is necessary to provide sufficient safety margins for pipeline structures, or to verify the results of a quasistatic calculation using a more accurate, dynamic calculation.

The values of displacements and stresses are determined for various types of pipeline ends fixing. A significant effect of the types of pipeline ends fixing on the stress-strain state is shown. The obtained results of the problems solved with and without account for inertia forces, coincide in values.

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