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THE PROBLEM OF THE UNDERGROUND PIPELINE VIBRATIONS IN THE VERTICAL PLANE

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Annotation: A system of differential equations of motion of an underground pipeline with natural boundary and initial conditions under spatial seismic loading is derived in the article. From the formulas obtained, it is necessary to determine the internal forces in the sections of the underground structure. Research methods are based on the variational equation of seismic loading of underground structures in a matrix form; methods of mathematical modeling and numerical methods for their solutions An algorithm and a program for the numerical solution of the resulting system of equations are compiled. Having determined the displacements, the internal forces in the sections of the underground pipeline are defined. The influence of the inertia of rotation of the section and the transverse shear on the values of displacements and force factors of the pipe is studied.

***Keywords*:** viscoelastic property, variational equation, boundary value problem.

1. Introduction

The study of seismic resistance of underground structures is of great practical importance. Simulation of underground structure vibrations plays an important role in solving this problem.

An assessment of the effect of amplification on motions in a free field, including underground structure, was conducted considering the tunnel-soil interaction and using numerical tools [1]. The 2D finite element method was used as numerical model to determine the effect of seismic amplification with different frequencies on surface vibration in the presence of a tunnel structure. The results showed that the presence of an underground structure increased seismic vibrations in the free field and tunnel, depending on the frequency of the external load and the local soil conditions.

Numerical modeling of seismic response of underground structures in water-saturated soil deposits is considered in [2]. To simulate the dynamic behavior of water-saturated soils during an earthquake, a complete fluid-solid relation model was developed, implemented using the commercial ABAQUS software with a user element. The model is then applied to simulate the seismic response of a structure buried in saturated soil. The influence of the depth of laying on the dynamic response of the underground structure was studied. Numerical simulation shows that the user-defined element developed in this article is able to simulate the dynamic response of an underground structure in a water-saturated subsoil. With an increase in the depth of laying, the stress in the underground structure is transferred from the outer walls, the upper and lower slabs of the structure to its internal columns. The stress in a deep underground structure during an earthquake changes more substantially than in a shallow underground structure.

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Seismic resistance of underground hydro-technical structures of various shapes under the influence of seismic waves was considered in [3]. The review is devoted to the above issues. Recommendations for improving the seismic resistance of underground hydro-technical structures under the influence of seismic waves are proposed. A model of seismodynamics under spatial loading of underground structures was developed in [4].

Systems of differential equations of motion with natural boundary and initial conditions were obtained in the article under spatial seismic loading of underground structures, taking into account the underground structure's interaction with the surrounding medium.

2. Methods

Research methods are based on equation of seismic loading of underground structures in a matrix form; methods of mathematical modeling and numerical methods for their solution.

3. Materials

The following boundary value problem was obtained for the coupled equations of an underground pipeline under spatial loading:

$$-A\frac{\partial^2 Y}{\partial t^2}+B\frac{\partial^2 Y}{\partial x^2}+C\frac{\partial Y}{\partial x}+D_{\Pi}Y+D_{\mathrm{A}}\left(Y-Y_0\right)+F=0, \tag{1}$$

$$\left[-\overline{B}\frac{\partial Y}{\partial x}-\overline{C}_{\Pi}Y+\overline{C}_{\mathrm{A}}\left(Y-Y_0\right)+P^{гр}\right]\delta Y\Big|_x=0, \tag{2}$$

$$A\frac{\partial Y}{\partial t}E\delta Y\Big|_t=0. \tag{3}$$

Underground structures under spatial loading perform joint, transverse and torsional vibrations. The resulting systems of differential equations (1), boundary (2) and initial (3) conditions for boundary value problems in relation to the seismodynamics of underground pipelines allow some simplifications for specific loading options.

Consider the case when an underground pipeline with a constant cross section and homogeneity along the pipeline length is loaded in the xz plane. At that, the rotational inertia of the cross section and the transverse shear are taken into consideration, so, $\theta=0,\ \nu=0,\ \beta_1=0, \upsilon=0,\ \alpha_1=0$; from the boundary value problem (1)-(3), in the partial case, for pipeline vibrations in a vertical plane, considering the inertia of rotation and transverse shear, we obtain:

$$-\rho F\frac{\partial^2 u}{\partial t^2}-\rho S_{a_2}\frac{\partial^2 \beta_2}{\partial t^2}+EF\frac{\partial^2 u}{\partial x^2}+ES_{a_2}\frac{\partial^2 \beta_2}{\partial x^2}-K_N(u-u_0)+N^{об}+N^{n}=0,$$

$$-\rho F\frac{\partial^2 w}{\partial t^2}+GF\frac{\partial^2 w}{\partial x^2}-GF\frac{\partial \alpha_2}{\partial x}+GS\left(\frac{\partial a_2}{\partial z}\right)\frac{\partial \beta_2}{\partial x}-K_{Q_z}(w-w_0)+Q_z^{об}+Q_я^{n}=0,$$

$$-\rho J_y\frac{\partial^2 \alpha_2}{\partial t^2}+\rho J_{za_2}\frac{\partial^2 \beta_2}{\partial t^2}+EJ_y\frac{\partial^2 \alpha_2}{\partial x^2}-EJ_{za_2}\frac{\partial^2 \beta_2}{\partial x^2}+GF\frac{\partial w}{\partial x}-$$

$$-GF\alpha_2+GS\left(\frac{\partial a_2}{\partial z}\right)\beta_2-K_{M_y}\left(\alpha_2-\alpha_2^0\right)-\left(M_y^{об}+M_y^{n}\right)=0,$$

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$$-\rho S_{a_2}\frac{\partial^2 u}{\partial t^2}+\rho J_{a_2 z}\frac{\partial^2 \alpha_2}{\partial t^2}-\rho J_{a_2}\frac{\partial^2 \beta_2}{\partial t^2}+ES_{a_2}\frac{\partial^2 u}{\partial x^2}-EJ_{a_2 z}\frac{\partial^2 \alpha_2}{\partial x^2}+EJ_{a_2}\frac{\partial^2 \beta_2}{\partial x^2}+$$

$$+GS\left(\frac{\partial a_2}{\partial z}\right)\frac{\partial w}{\partial x}+GS\left(\frac{\partial a_2}{\partial z}\right)\alpha_2-GJ\left[\left(\frac{\partial a_2}{\partial z}\right)^2\right]\beta_2-K_{M_{a_2}}\left(\beta_2-\beta_2^0\right)+M_{a_2}^{об}+M_{a_2}^{n}=0,$$

$$\left[-EF\frac{\partial u}{\partial x}-S_{a_2}(E,x)\frac{\partial \beta_2}{\partial x}-K_N^{гр}(u-u_0)+N^{гр}\right]\delta u\Big|_{x=0,l}=0,$$

$$\left[-GF\frac{\partial w}{\partial x}+GF\alpha_2-GS\left(\frac{\partial a_2}{\partial z}\right)\beta_2-K_{Q_z}^{гр}(w-w_0)+Q_z^{гр}\right]\delta w\Big|_{x=0,l}=0,$$

$$\left[-EJ_y\frac{\partial \alpha_2}{\partial x}+K_{M_y}^{гр}\left(\alpha_2-\alpha_2^0\right)-M_y^{гр}\right]\delta\alpha_2\Big|_{x=0,l}=0,$$

$$\left[-ES_{a_2}\frac{\partial u}{\partial x}+EJ_{a_2 z}\frac{\partial \alpha_2}{\partial x}-EJ_{a_2}\frac{\partial \beta_2}{\partial x}-K_{M_{a_2}}^{гр}\left(\beta_2-\beta_2^0\right)+M_{a_2}^{гр}\right]\delta\beta_2\Big|_{x=0,l}=0,$$

$$\rho F\frac{\partial u}{\partial t}\delta u\Big|_{t=0}=0,\ \rho F\frac{\partial w}{\partial t}\delta w\Big|_{t=0}=0,\ \rho J_y\frac{\partial \alpha_2}{\partial t}\delta\alpha_2\Big|_{t=0}=0,\ \rho J_{a_2}\frac{\partial \beta_2}{\partial t}\delta\beta_2\Big|_{t=0}=0, \qquad (4)$$

where all notations are the same as previous ones.

In (4), matrices and vectors have the fourth order [6-9], the implementation algorithm corresponds to the following scheme:

For $i=1,\ j=0$ we have;

$$Y_{1,1}=\frac{1}{2}\left(\tilde{\tilde{B}}Y_{1,0}^0+\tilde{\tilde{C}}Y_{2,0}^0+\tilde{\tilde{F}}_{1,0}-2\tau\, A^{-1}\,\dot{Y}_{i,0}^0\right),$$

for $i=i,\ j=0$;

$$Y_{i,1}=\frac{1}{2}\left(\tilde{A}Y_{i-1,0}+\tilde{B}Y_{i,0}+\tilde{C}Y_{i+1,0}+\tilde{F}_{i,0}\right)+\tau\, A^{-1}\,\dot{Y}_{i,0}^0,$$

for $i=N-1,\ j=0$;

$$Y_{N-1,1}=\frac{1}{2}\left(\tilde{\tilde{A}}Y_{N-2,0}^0+\tilde{\tilde{B}}Y_{N-1,0}^0+\tilde{\tilde{F}}_{N-1,0}\right)+\tau\, A^{-1}\,\dot{Y}_{N-i,0}^0, \qquad (5)$$

for $i=1,\ j=1$;

$$Y_{1,2}=\tilde{\tilde{B}}Y_{1,1}+\tilde{\tilde{C}}Y_{2,1}+\tilde{\tilde{F}}_{1,1}-Y_{1,0}^0,$$

for $i=i,\ j=1$;

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$$Y_{i,2} = \tilde{\tilde{A}}Y_{i-1,1} + \tilde{\tilde{B}}Y_{i,1} + \tilde{\tilde{F}}_{i,1} - Y^{0}_{i,0},$$

for $i = N-1,\ j = 1$;

$$Y_{N-1,2} = \tilde{A}Y_{N-2,1} + \tilde{B}Y_{N-1,1} + \tilde{C}Y_{N,1} + \tilde{\tilde{F}}_{N-1,1} - Y^{0}_{N-1,0}, \qquad (6)$$

for $i = 1,\ j \geq 2$;

$$Y_{1,j+1} = \tilde{\tilde{B}}Y_{1,j} + \tilde{\tilde{C}}Y_{2,j} + \tilde{\tilde{F}}_{1,j} - Y_{1,j-1},$$

for $i = i,\ j \geq 2$;

$$Y_{i,j+1} = \tilde{A}Y_{i-1,j} + \tilde{B}Y_{i,j} + \tilde{C}Y_{i+1,j} + \tilde{F}_{i,j} - Y_{i,j-1},$$

for $i = N-1\ j \geq 2$;

$$Y_{N-1,j+1} = \tilde{\tilde{A}}Y_{N-2,j} + \tilde{\tilde{B}}Y_{N-1,j} + \tilde{\tilde{F}}_{N-1,j} - Y_{N-1,j-1}. \qquad (7)$$

Having determined the displacements, the internal forces in the sections of the underground structure were calculated.

4. Results and discussion.

According to the algorithms obtained, programs were compiled in “Visual Basic-6” and implemented on a PC. The following values are assumed for pipe parameters E=2.1·10^8 kN/m^2, ρ=7.8 kN·s^2 /m^4, L=(10÷100) m, $R_н$=0.6 m, $R_в$=(0.57÷0.585) m, δ =(10÷30) mm. The pipe-soil interaction coefficient is - k_n=(3750÷37500) kN/m^3. Ground motion is taken as an impulse with a constant value.

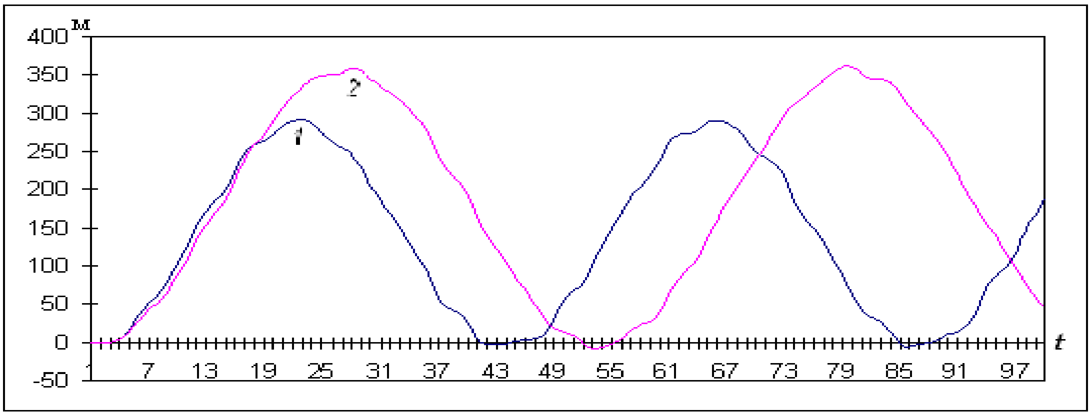

Fig. 1. Influence of transverse shear on bending moment.

To study coupled longitudinal and transverse vibrations of a steel underground pipe, taking into account the inertia of rotation and transverse shear under the action of a seismic load directed at an angle γ to the longitudinal axis of the pipe, the system of equations (1)-(3) was used, the implementation algorithm of which corresponds to the algorithm (5)-(7). The influence of the inertia of rotation of the section and transverse shear on the values of displacements and force factors of the pipe was studied; some results of the calculation are shown in Fig. 1 as graphs of displacement *u*, deflection *w* and moment *M*. In Fig. 1, curves 1 were plotted without considering the transverse shear, curves 2 were plotted with account for the rotational inertia and transverse shear.

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The calculation results showed that due to the influence of the inertia of rotation of the section and the transverse shear, the values of the longitudinal displacement u, vertical displacement w, the angle of inclination of the sections a, the longitudinal force N, the transverse force Q and the bending moment M increase noticeably. In the considered example, the difference in the values of these parameters varies from 5% to 15%.

5. Conclusion

An algorithm and a program for the numerical solution of the resulting system of equations were developed. After determining the displacements, the internal forces in the sections of the underground pipeline were determined. The influence of the inertia of rotation of the section and the transverse shear on the values of displacements and force factors of the pipe were studied.

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