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Fluctuations of the ground surface at blasting operations on tunnel structures

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Abstract. The paper considers the fluctuations of the ground surface during blasting operations on tunnel structures. To estimate the vibration levels of the soil surface, under the explosive action inside a cylindrical cavity, we will consider the plane problem of elasticity theory as a first approximation. The main purpose of the work is to determine the stress-strain state of pipelines under the influence of seismic waves. As a result of this impact, longitudinal and transverse waves will propagate in the ground. To solve the problem, the reciprocity theorem is applied, for dynamic problems of elasticity theory and the results obtained are compared by wave dynamics methods. The obtained solution makes it possible to determine the vibration levels of the soil surface that occur during explosive impacts inside the cylindrical cavity of the elastic half-space. The results can be used to assess the vibration levels of the soil surface that occur in the structures of shallow tunnels laid by drilling and blasting.

1 Introduction

To perform a computational analysis of the dynamic state, an underground pipeline is considered as a cylindrical body located in an elastic medium [1, 2]. The explosive load can be described in various ways [3]. When solving the problem, the problems are mainly reduced to flat problems of the theory of elasticity [4, 5]. The calculation uses the finite element method in the form of displacements [6, 7]. The displacements of the nodal points of the finite element model are taken as the main unknowns. At the same time, to increase the efficiency of calculations, methods were used that take into account the features of matrix operations (matrix symmetry, the presence of a large number of zero elements, etc.). The entire mass of the pipeline is considered to be concentrated in the nodes of the calculation model, while the distributed mass of the segment is divided equally between its beginning and end [8,9]. The calculation of the seismic impact is carried out in many works by the method of dynamic analysis or linear spectral method [10]. In the case of calculation for one group of spectra, the displacements of all fixed nodes of the computational model are considered the same (the hypothesis of a "rigid" platform). In this case, the seismic load can

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be set for three mutually perpendicular directions in the form of accelerograms or response spectra [11-13].

In this paper, unlike others, numerical and analytical methods are used, and their effectiveness is evaluated comparatively.

2 Methods

2.1 Problem statement

In underground construction and, in particular, in tunneling, workings in hard rocks are most often carried out by an explosive method [1]. Explosive effects are characterized by a large release of energy in a short period of time. For example, when one kilogram of TNT explodes, with a charge length of 0.25 meters in 40 microseconds, more than J. Energy is released. Stress waves propagating in the ground from the explosion site can reach the "daytime" surface, which can lead to damage or destruction of ground objects.

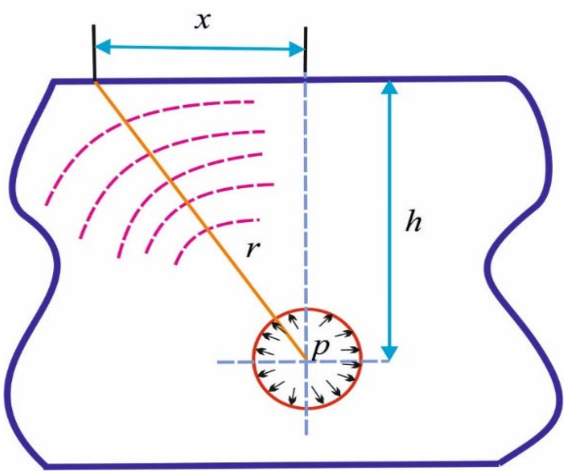

Fig. 1. Loading scheme for determining the stress-strain state.

To estimate the vibration levels of the soil surface, under the explosive action inside a cylindrical cavity, we will consider the plane problem of elasticity theory as a first approximation. We will assume that as a result of an explosion inside a cylindrical cavity, a uniform pressure acts on some sufficiently long part of it.

As a result of this impact, longitudinal and transverse waves will propagate in the ground. To determine the vibrations of the ground surface, we apply the reciprocity theorem and use the well-known analytical solutions to the problem of wave propagation in an elastic half-space under the influence of concentrated waves applied to the day surface. Consider two states of an elastic half-space with a cylindrical cavity. The first state (I): a concentrated force is applied to the surface of the elastic half-space (Figure 1). In order to avoid singularities, we will assume that the force is distributed over a small area. $F(t)$ The second state (II): the stress-strain state of the elastic half-space is created by a uniform pressure applied to the inner surface of the cylindrical cavity. $p(t)$ To determine the displacements of ground points during the propagation of longitudinal and $F_0 e^{i\omega t}$ transverse waves from a vertical harmonic force applied to the surface of an elastic half-space, we use the solution of G. Miller and N. Persey [2]:

$$u_r^v = \frac{F_0 \cos\varphi [1 - 2\delta^2 \sin^2\varphi] e^{-i\omega r/\alpha} e^{i\omega t}}{2\pi\rho\alpha^2 r \left\{[1 - 2\delta^2 \sin^2\varphi]^2 + 4\delta^3 \sin^2\varphi \cos\varphi [1 - \delta^2 \sin^2\varphi]^{1/2}\right\}} \quad (1)$$

$$u_\theta^v = 0 \quad (2)$$

$$u_\varphi^v = \frac{-F_0 \sin\varphi \cos\varphi [\delta^2 - \sin^2\varphi]^{1/2} e^{-i\omega r/\beta} e^{i\omega t}}{\pi\rho\beta^2 r \left\{[1 - 2\sin^2\varphi]^2 + 4\sin^2\varphi \cos\varphi [\delta^2 - \sin^2\varphi]^{1/2}\right\}} \quad (3)$$

where a is the velocity of longitudinal waves in the ground; β - the velocity of transverse waves into the ground; $\delta = \frac{\beta}{a}$ - the ratio of speeds,

$$r^2 = h^2 + x^2, \cos\varphi = h / r, \sin\varphi = x / r$$

To determine the displacements of ground points during the propagation of longitudinal and transverse waves from a horizontal harmonic force applied to the surface of an elastic half-space, $G_0 e^{i\omega t}$ we use the solution of J. Cheny:

$$u_r^h = \frac{G_0 \delta \cos\theta \sin\varphi \cos\varphi [1 - \delta^2 \sin^2\varphi]^{1/2} e^{-i\omega r/\alpha} e^{i\omega t}}{\pi\rho\alpha^2 r \left\{[1 - 2\delta^2 \sin^2\varphi]^2 + 4\delta^3 \sin^2\varphi \cos\varphi [1 - \delta^2 \sin^2\varphi]^{1/2}\right\}} \quad (4)$$

$$u_\theta^h = \frac{-G_0 \sin\theta e^{-i\omega r/\beta} e^{i\omega t}}{2\pi\rho\beta^2 r} \quad (5)$$

$$u_\varphi^h = \frac{G_0 \cos\theta \cos\varphi [1 - 2\sin^2\varphi] e^{-i\omega r/\beta} e^{i\omega t}}{2\pi\rho\beta^2 r \left\{[1 - 2\sin^2\varphi]^2 + 4\sin^2\varphi \cos\varphi [\delta^2 - \sin^2\varphi]^{1/2}\right\}} \quad (6)$$

The average radial displacements of an unsupported cylindrical cavity from longitudinal waves generated by a vertical force are determined by the formula

$$\Delta u_\alpha^v = \Delta u_r + \Delta u_\varphi + \Delta u_\theta \quad (7)$$

which, after substituting expressions for mean radial displacements:

$$\Delta u_r = \frac{b}{E}\rho\alpha\dot{u}_r^v; \Delta u_\varphi = \frac{\nu}{1-\nu}\frac{b}{E}\rho\alpha\dot{u}_r^v \text{ and } \Delta u_\theta = -\frac{\nu^2}{1-\nu}\frac{b}{E}\rho\alpha\dot{u}_r^v$$

takes the form:

$$\Delta u_\alpha^v = \Delta u_r + \Delta u_\varphi + \Delta u_\theta = \rho\alpha\dot{u}_r^v \frac{b}{E}\left(1 + \frac{\nu}{1-\nu} - \frac{\nu^2}{1-\nu}\right) \text{ or}$$

$$\Delta u_r^\alpha = \alpha\rho\dot{u}_r^v \frac{b}{2\mu} \quad (8)$$

Where p is the soil shear modulus (determined by the formula: $\mu = \beta^2\rho$).

Using expression (1) and performing the necessary transformations, we bring the resulting equation to a more convenient form [4]:

$$u_\alpha^v = \frac{(i\omega) b F_0 \cos\varphi [1 - 2\delta^2 \sin^2\varphi] e^{-i\omega r/\alpha} e^{i\omega t}}{4\pi\mu\alpha r \left\{[1 - 2\delta^2 \sin^2\varphi]^2 + 4\delta^3 \sin^2\varphi \cos\varphi [1 - \delta^2 \sin^2\varphi]^{1/2}\right\}} \quad (9)$$

We denote: P_0 - the amplitude value of the pressure during an explosion in a cylindrical cavity for a harmonic component with a frequency, $\Delta_{\alpha v}$ - the vertical movement of the ground surface, d - the distance to which the explosion pressure extends along the cylindrical cavity, - the distance from the point at which the oscillations are determined to the axis of the cylindrical cavity.

In accordance with the reciprocity theorem we have:

$$2\pi b d P_0 \Delta u_\alpha^v = F_0 \Delta_{\alpha v} \quad (10)$$

From what follows:

$$\Delta_{\alpha v} = \frac{P_0 b^2 (i\omega) d \cos\varphi [1 - 2\delta^2 \sin^2 \varphi] e^{-i\omega r/\alpha} e^{i\omega t}}{2\mu\alpha r \left\{[1 - 2\delta^2 \sin^2 \varphi]^2 + 4\delta^3 \sin^2 \varphi \cos\varphi [1 - \delta^2 \sin^2 \varphi]^{1/2}\right\}} \quad (11)$$

Horizontal vibrations of the ground surface transmitted by longitudinal waves during an explosion in a cylindrical cavity. The parameters of horizontal oscillations during an explosion in a cylindrical cavity are determined in the same way as vertical ones, except that instead of function (1), function (4) must be used. Omitting the intermediate calculations, we present the final result:

$$\Delta_{\alpha h} = \frac{P_0 b^2 (i\omega) d \delta \cos\theta \sin\varphi \cos\varphi [1 - \delta^2 \sin^2 \varphi]^{1/2} e^{-i\omega r/\alpha} e^{i\omega t}}{\mu\alpha r \left\{[1 - 2\delta^2 \sin^2 \varphi]^2 + 4\delta^3 \sin^2 \varphi \cos\varphi [1 - \delta^2 \sin^2 \varphi]^{1/2}\right\}} \quad (12)$$

Considering that horizontal and vertical vibrations of the ground surface transmitted by longitudinal waves that occurred during an explosion in a cylindrical mine occur in one phase, the amplitude of the oscillations can be determined by the formula:

$$\Delta_\alpha = \sqrt{\Delta_{\alpha v}^2 + \Delta_{\alpha h}^2} \quad (13)$$

Vertical vibrations of the ground surface transmitted by transverse waves during an explosion in a cylindrical cavity. The average radial displacements of an unsupported cylindrical cavity from transverse waves generated by a vertical force are determined by the formula:

$$\Delta u_\beta^v = \Delta u_r + \Delta u_\varphi + \Delta u_\theta \quad (14)$$

which after substituting expressions for average radial displacements:
$\Delta u_\varphi = \frac{b}{E} \rho \beta \ddot{u}_\varphi^v$; $\Delta u_r = \frac{\nu}{1-\nu} \frac{b}{E} \rho \beta \ddot{u}_r^v$ and $\Delta u_\theta = -\frac{\nu^2}{1-\nu} \frac{b}{E} \rho \beta \ddot{u}_r^v$
takes the form:

$$\Delta u_\beta^v = \Delta u_r + \Delta u_\varphi + \Delta u_\theta = \rho \beta \ddot{u}_\beta^v (1 + \frac{\nu}{1-\nu} - \frac{\nu^2}{1-\nu}) \cdot \quad (15)$$

Using expression (3) and performing the necessary transformations, we bring the resulting equation to a more convenient form:

$$\Delta u_\beta^v = -\frac{(i\omega) b F_0 \sin\varphi \cos\varphi [\delta^2 - \sin^2 \varphi]^{1/2} e^{-i\omega r/\beta} e^{i\omega t}}{2\pi\mu\beta r \left\{[1 - 2\sin^2 \varphi]^2 + 4\sin^2 \varphi \cos\varphi [\delta^2 - \sin^2 \varphi]^{1/2}\right\}} \quad (16)$$

Denote: vertical movement of the ground surface during the propagation of transverse waves, all other designations: and leave unchanged. In accordance with the reciprocity theorem we have:

$$2\pi b d P_0 \Delta u_\beta^v = F_0 \Delta_{\beta v} \quad . \quad (17)$$

From what follows

$$\Delta_{\beta v} = -\frac{P_0 b^2 (i\omega) d \delta \sin\varphi \cos\varphi [\delta^2 - \sin^2 \varphi]^{1/2} e^{-i\omega r/\beta} e^{i\omega t}}{\mu\beta r \left\{[1 - 2\sin^2 \varphi]^2 + 4\sin^2 \varphi \cos\varphi [\delta^2 - \sin^2 \varphi]^{1/2}\right\}} \quad (18)$$

3 Results and analysis

Horizontal vibrations of the ground surface transmitted by transverse waves during an explosion in a cylindrical cavity. Horizontal vibrations transmitted by transverse waves during an explosion in a cylindrical cavity are determined in the same way as vertical ones, but here we use function (6). Omitting intermediate calculations, we present the final result:

$$\Delta_{\beta h} = \frac{p_0 b^2 (i\omega)\cos\theta \cos\varphi [1 - 2\sin^2\varphi]^{1/2} e^{-i\omega r/\beta} e^{i\omega t}}{2\mu\beta r\left\{[1 - 2\sin^2\varphi]^2 + 4\sin^2\varphi\cos\varphi[\delta^2 - \sin^2\varphi]^{1/2}\right\}} \tag{19}$$

Considering that horizontal and vertical vibrations of the ground surface transmitted by transverse waves that occurred during an explosion in a cylindrical mine occur in one phase, the amplitude of the oscillations can be determined by the formula:

$$\Delta_\beta = \sqrt{\Delta^2_{\beta v} + \Delta^2_{\beta h}}\ . \tag{20}$$

An example of evaluating the vibrations of the ground surface during an explosion in a cylindrical cavity. As an example, we will determine the movement of the soil surface from an explosion in a cylindrical cavity at the following values of the initial data [14-15]: $a = 600\,м/сек$ - the velocity of longitudinal waves in the ground, $\beta = 350\,м/сек$ - the velocity of transverse waves in the ground, $p = 1700\,кг/м^3$ - the density of the soil, $\gamma = 0.0$ - the coefficient of internal friction of the soil material, $h = 20\,м$ - the depth of the cylindrical cavity, $b = 2.8\,м$ - the radius of the cylindrical cavity, - the distance from the point at which the vibration levels are determined before the projection of the tunnel axis onto the ground surface, the amplitude value of the harmonic component of the force with frequency , - the section of the cylindrical cavity on which the pressure acts. The obtained solutions for harmonic forces can be used for arbitrary effects using the Fourier transform.

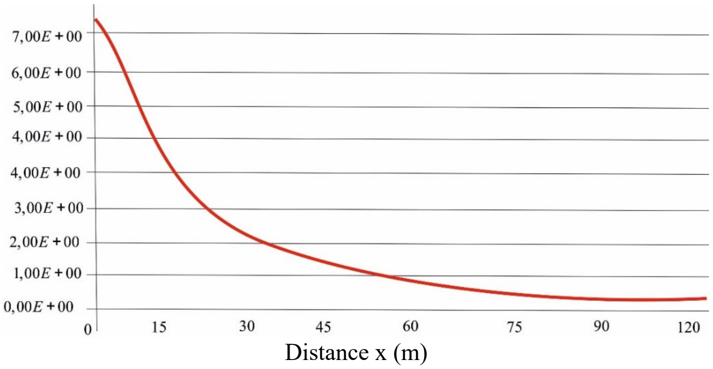

Fig. 2. Levels of vertical displacements of the ground surface transmitted by longitudinal waves during an explosion in a cylindrical cavity.

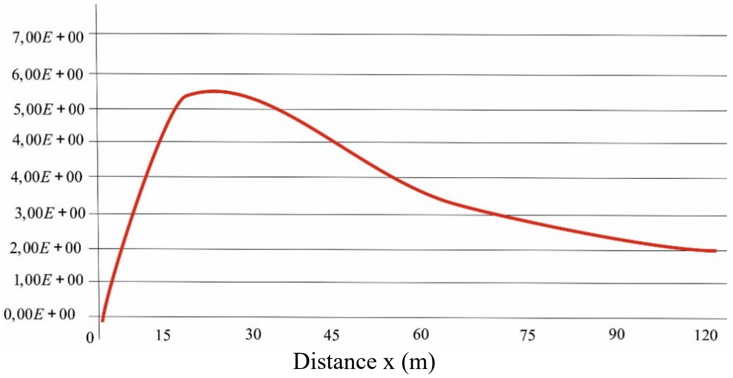

Fig. 3. Levels of horizontal displacements of the ground surface transmitted by longitudinal waves during an explosion in a cylindrical cavity.

4 Conclusions

A mathematical formulation of the problem under the influence of waves on a viscoelastic cylindrical body is proposed. Calculation methods, algorithm and programs for calculating the study of the dynamic behavior of the structure have been developed. Based on the results obtained, it was found that an increase in the thickness of the filler has a particularly significant effect on the change in the complex phase velocity at relatively small thicknesses of the filler. The resulting solution makes it possible to determine the vibration levels of the soil surface that occur during explosive impacts inside the cylindrical cavity of the elastic half-space.

The results can be used to assess the vibration levels of the soil surface that occur in the structures of shallow tunnels laid by drilling and blasting.

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