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ANALYSIS OF THE STRESS-STRAIN STATE OF TUNNEL LININGS UNDER SEISMIC IMPACTS DIRECTIONATED ALONG THE AXIS OF TUNNELS

***Abstract**: Similar to the methods used to evaluate transverse reactions, longitudinal responses of tunnels are also evaluated using simplified analytical models and more complex numerical models, depending on the complexity of the soil-structure system, the level of seismic action and the responsibility of the structure. The following sections discuss a simplified method that assumes that the tunnel deformations correspond to the free field deformations and that the tunnel does not affect the soil deformations. A more refined method takes into account the interaction of the structure with the soil, for which a beam model on an elastic foundation is used.*

***Key words**: Differential equation, deformation, soil, structures, model, structure, tunnel, pressure, elastic medium, technique.*
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Introduction

If a rigid tunnel is in soft ground, there is a noticeable effect of structure-soil interaction, and therefore a technique based on equality of free field and structure deformations leads to a conservative result. In this case, to take into account the interaction of the structure with the soil, the model of a beam on an elastic foundation can be used [1-4]. The differential equation for the tunnel design can be written as:

$$EI\frac{d^4u_t}{dx^4}=P, \qquad (1)$$

where u_t - transverse displacement of the tunnel structure, m;

P - is the pressure between the structure and the surrounding soil, N/m. Assume that the soil is operating in the elastic stage, then the pressure P can be written as:

$$P=K_h(u_y-u_i), \qquad (2)$$

where K_h - is the base factor in the direction perpendicular to the tunnel axis, N/m^3. u_y - transverse displacements of free soil, m.

Differential equation for construction:

$$EI\frac{d^4u_t}{dx^4}=K_hu_y, \qquad (3)$$

or

$$EI\frac{d^4u_t}{dx^4}=K_hu_y=K_hD\cos\varphi\sin\left(\frac{2\pi x}{L}\right)\cos\varphi, \qquad (4)$$

We apply the Fourier transform to both parts of the equation, performing the inverse algebraic transformations, we get:

$$\bar{u}_I(v)=2\pi K_hD\cos\varphi\frac{\delta\left(v+\frac{2\pi}{L}\cos\varphi\right)+\delta\left(v-\frac{2\pi}{L}\cos\varphi\right)}{2i\left(EIv^4+K_h\right)}. \qquad (5)$$

After performing the inverse Fourier transform:

$$u_1(x)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\bar{u}(v)e^{-ivx}dv. \qquad (6)$$

we get:

$$u_1(x)=\frac{D\cos\varphi}{1+\frac{EI}{K_h}\left(\frac{2\pi}{L}\right)^4\cos^4\varphi}\sin\left(\frac{2\pi x}{L}\cos\varphi\right). \qquad (7)$$

Therefore, the curvature of the tunnel structure obtained by solving equation (3) is less than the curvature obtained using expression (7) with a factor:

$$R_1 = \frac{1}{1+\frac{EI}{K_h}\left(\frac{2\pi}{L}\right)^4 \cos^4\varphi}. \qquad (8)$$

The bending moment and shear force in the tunnel lining are determined by the equations:

$$M = \frac{\left(\frac{2\pi}{L}\right)^2 D\cos^3\varphi}{1+\frac{EI}{K_h}\left(\frac{2\pi}{L}\right)^4 \cos^4\varphi} EI\sin\left(\frac{2\pi\, x}{L/\cos\varphi}\right). \qquad (9)$$

$$V = \frac{\left(\frac{2\pi}{L}\right)^3 D\cos^4\varphi}{1+\frac{EI}{K_h}\left(\frac{2\pi}{L}\right)^4 \cos^4\varphi} EI\sin\left(\frac{2\pi\, x}{L/\cos\varphi}\right). \qquad (10)$$

The same approach can be used to derive an expression for the axial force. In this case, the differential equation has the form:

$$EA\frac{d^2u_a}{dx^2} = K_a(u_a - u_x), \qquad (11)$$

where u_a - longitudinal displacements of the tunnel structure, m;

u_x - longitudinal displacements of the soil corresponding to the "free field" (see Figure 1), m;

K_a - coefficient of elastic foundation directed along the axis of the tunnel, N/m^3.

Solving equation (11), we obtain axial displacements that correspond to the values of expression (8) multiplied by the coefficient R_2, which is always less than one:

$$R_2 = \frac{1}{1+\frac{EI}{K_h}\left(\frac{2\pi}{L}\right)^2 \cos^2\varphi}. \qquad (12)$$

From equation (12) we obtain axial forces in the tunnel lining:

$$Q = \frac{\left(\frac{2\pi}{L}\right) D\sin\varphi\cos\varphi}{1+\frac{EI}{K_a}\left(\frac{2\pi}{L}\right)\cos^2\varphi} EI\cos\left(\frac{2\pi\, x}{L/\cos\varphi}\right). \qquad (13)$$

The design forces are the maximum bending moment, transverse and longitudinal forces, which depend on the location along the tunnel structure, on the angle of incidence, φ - and on the length waves, L. The maximum effort can be obtained by setting equal $\sin\left(\frac{2\pi\, x}{L/\cos\varphi}\right)$ and $\cos\left(\frac{2\pi\, x}{L/\cos\varphi}\right)$ to one. To determine the angle of incidence, it is necessary to equate the partial derivatives of expressions (9) and (10) to zero. It follows that the maximum values will occur at $\varphi = 0$. For equation (13), the maximum value of the longitudinal force depends on the properties of the tunnel structure and the surrounding soil mass of the medium. It is generally recommended to use a wave incidence angle of $\varphi = 45^0$. This angle of incidence φ will maximize the value of the longitudinal force when the interaction between the soil and the tunnel lining can be neglected. The maximum effort is thus determined by the expressions:

$$M_m = \frac{\left(\frac{2\pi}{L}\right)^2 D}{1+\frac{EI}{K_h}\left(\frac{2\pi}{L}\right)^4} EI \qquad (14)$$

$$V_m = \frac{\left(\frac{2\pi}{L}\right)^3 D}{1+\frac{EI}{K_h}\left(\frac{2\pi}{L}\right)^4} EI \qquad (15)$$

$$Q_m = \frac{\left(\frac{2\pi}{L}\right) D}{2+\frac{EI}{K_h}\left(\frac{2\pi}{L}\right)^2} EI \qquad (16)$$

As noted above, equations (14), (15), (16) should have maximum values that depend on the wavelength *L*. Note that it is first necessary to determine the coefficients of the elastic foundation, K_h and K_a[5,11,12]. You can use the results of research scientists St. John C.M. and Zahrah T.F., who proposed a convenient and sufficiently justified expression for determining the coefficients of an elastic foundation:

$$K_h = K_a = \frac{16\pi G(1-v)}{3-4v}\frac{d}{L}, \qquad (17)$$

where: G_m - soil shear modulus, KN/m^2;

v- soil Poisson's ratio;

d- is the diameter of the tunnel lining, m;

L - is the length of the transverse wave, m.

It should be noted that the maximum value of the longitudinal force obtained using the method presented above should not exceed the maximum friction forces Q_{max} between the tunnel lining and the surrounding soil mass. The Q_{max} value can be determined using the following expression:

$$Q_{\max} = \frac{f\cdot L}{4}. \qquad (18)$$

where *f*- is the maximum friction force per unit length of the tunnel.

Calculation method that takes into account the effects of the interaction of the tunnel with the soil, characterized by two coefficients of the bed. Let us consider a tunnel lining in the form of an infinite beam with bending stiffness E_I lying on a foundation whose properties are described by a model with two elastic characteristics k_1 and k_2. The first bed factor k_1 is the compression factor, which is no different from the usual Winkler bed factor. The second bed coefficient k_2 is the shear coefficient, which makes it possible to express the intensity of the vertical shear force Q as the product of the coefficient k_2 by derivative of the draft function $Q = k_2 \frac{du}{dx}$. These shear forces also appear in loose and poorly cohesive soils due to engagement and internal friction between soil particles [6,7]. Using expression (4), we write a differential equation describing the bending of a beam lying on a foundation, the properties of which are described by a model with two elastic characteristics [8,10]:

$$EI\frac{d^4u_l}{dx^4} = -k_2\frac{d^2u_l}{dx^2} + k_1u_l = k_1D\cos\varphi\sin\left(\frac{2\pi x}{L}\cos\varphi\right). \quad (19)$$

Applying the Fourier transform to both sides of the equation, and performing the necessary algebraic transformations, we obtain

$$\bar{u}_l(v) = \frac{k_1D\cos\varphi}{EIv^4 + k_2v^2 + k_1}2\pi\frac{\delta\left(v + \frac{2\pi}{L}\cos\varphi\right) + \delta\left(v - \frac{2\pi}{L}\cos\varphi\right)}{2i}. \quad (20)$$

After performing the inverse Fourier transform:

$$u_1(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\bar{u}_i(v)e^{-ivx}dv. \quad (21)$$

we get:

$$u_1(x) = \frac{D\cos\varphi}{1 + \frac{k_2}{k_1}\left(\frac{2\pi}{L}\right)^2\cos^2\varphi + \frac{EI}{k_1}\left(\frac{2\pi}{L}\right)^2\cos^4\varphi}\sin\left(\frac{2\pi x}{L}\cos\varphi\right). \quad (22)$$

The curvature of the tunnel lining obtained by solving equation (19) is less than the curvature determined in accordance with expression (9).

The ratio between the curvatures is characterized by a multiplier:

$$R_3 = \frac{1}{1 + \frac{k_2}{k_1}\left(\frac{2\pi}{L}\right)^2\cos^2\varphi + \frac{EI}{k_1}\left(\frac{2\pi}{L}\right)^4\cos^4\varphi}. \quad (23)$$

The curvature of the tunnel lining obtained by solving equation (19) is less than the curvature determined in accordance with expression (9).

The ratio between the curvatures is characterized by a multiplier:

$$M = \frac{\left(\frac{2\pi}{L}\right)^2 D\cos^3\varphi}{1 + \frac{k_2}{k_1}\left(\frac{2\pi}{L}\right)^2\cos^4\varphi + \frac{EI}{K_h}\left(\frac{2\pi}{L}\right)^4\cos^4\varphi}EI\sin\left(\frac{2\pi x}{L}\cos\varphi\right), \quad (24)$$

$$V = \frac{\left(\frac{2\pi}{L}\right)^3 D\cos^3\varphi}{1 + \frac{k_2}{k_1}\left(\frac{2\pi}{L}\right)^2\cos^2\varphi + \frac{EI}{K_h}\left(\frac{2\pi}{L}\right)^4\cos^4\varphi}EI\cos\left(\frac{2\pi x}{L}\cos\varphi\right), \quad (25)$$

Comparing the obtained expressions, we find that the values of the displacement of the tunnel lining, the curvature of the tunnel and the internal forces obtained with two characteristics of the soil base are less than the values obtained using the Winkler elastic foundation.

The model of a prefabricated lining in the form of a beam with equivalent stiffness describes well the bending behavior of the tunnel. This allows us to conclude that such models can be used in the calculation of tunnels for seismic effects

Conclusions.

A simplified analytical method for calculating tunnels for seismic effects directed along the axis of the tunnels is proposed. An expression is obtained for determining the equivalent bending stiffness of prefabricated tunnel linings. This parameter is necessary in calculations in which tunnels are considered as beams with constant stiffness on an elastic foundation.

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