Influence of the train load on the stability of the subgrade at the speed of movement

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Abstract. The article deals with the vibration of the subgrade soil and for the sections of the sloping terrain of the location of the subgrade calculation methods. In the calculations, we use the finite element method, the advantages of which are the simplicity of obtaining systems of resolving equations and the possibility of thickening the grid of elements and taking into account the inhomogeneous deformation and density properties of the soil material. The stress-strain state caused by structural changes in the subgrade during high-speed train traffic is determined. It also determines the dependence of the increase in the stress in the embankment of the subgrade on its height during high-speed train traffic, the dependence of the stress in the embankment of the subgrade on its width during high-speed train traffic, and the dependence of the stress in the slopes of the notch its depth.

1 Introduction

Measurements of ground vibrations of the subgrade carried out by G. G. Konshin, G. N. Zhinkin, and T. G. Yakovleva showed that the characteristics of the ground decrease with distance from the bottom of the ballast prism, depending on the speed of movement and axial load [1].

Deformations of embankments of the subgrade are manifested in two schemes: with the appearance of cracks on the roadside, the axis of the path, or along the intertrack of the embankment, followed by the erosion and landslide of its slopes. These damages to the embankment can be detected in a timely manner, and measures can be taken. According to another scheme, the slopes of the embankments of a sudden while following by train.

The fundamental works of Russian scientists are devoted to solving the issues of the influence of train traffic intensity on the technical condition of the subgrade: E. S. Ashpiz, L. S. Blazhko, V. V. Vinogradov, B. E. Glusberg, V. I. Gritsyk, P. I. Dydyshko, A. G. Ivanov, A. Ya. Kogan, G. G. Konshin, V. O. Pevzner, I. V. Prokudin, G. M. Stoyanovich, G. M. Shakhunyants, V. A. Yavna, T. G. Yakovleva and many others [2-16].

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2 Materials and Methods

To determine the stresses in the subgrade from the train load, a static calculation scheme is used where the train is replaced by a rectangular strip load at the level of the main platform. The stress in the subgrade from this load is calculated using the formulas of the theory of elasticity for a uniform isotropic half-area. The problem of assessing the influence of train dynamics on the stressed state of the subgrade becomes particularly difficult in connection with the organization of high-speed traffic [17, 20].

The calculated models consider the external loads from trains and from the weight of the upper structure of the track, considering them static [18]. The load from the rolling stock is transmitted through the sleepers and the ballast layer to the subgrade-Figure 1 in the form of a stress diagram:

$$\alpha_{\text{ВН}} = L_{\text{ш}} \pm 2ctg\beta \quad (1)$$

or at $\beta = 60^0$

$$\alpha_{\text{ВН}} = L_{\text{ш}} \pm 1{,}115h \quad (2)$$

where: $L_{\text{ш}}$ is sleeper length;

h is the thickness of the ballast layer.

The stability of the earth masses is calculated from the conditions of complete and simultaneous destruction or displacement of the soil on any surface. The design of the subgrade is based on the condition of ensuring stability. At the same time, it should be taken into account that under different loads on the subgrade, its stress state cannot be the same.

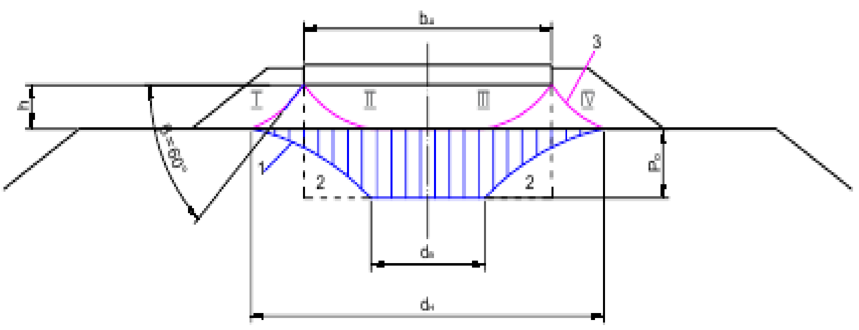

Fig. 1. Scheme of load transfer to the subgrade

1 is the actual epure of the load;
2 is conditional epure;
3 is pressure spreading cone;
I-IV is the point of pressure transmission to the subgrade.

In areas of terrain with a horizontal surface, a more accurate method for calculating natural stresses is adopted, based on known compression dependencies. For hillside terrain of the location of the subgrade may apply approximate methods of calculation. The main stage of the calculation of the embankment of the subgrade is to determine the volume stresses and the intensity of tangential stresses with the identification of surfaces with the maximum values of this importance. For calculations, we use the finite element method (FEM), the advantage of which is the simplicity of obtaining systems of resolving equations and the possibility of thickening the grid of elements and taking into account the inhomogeneous deformation and density properties of the soil material.

3 Results and Discussion

In our calculation model, the upper structure of the tracks is based on a subgrade, which is represented in the form of flat rectangular elements with eight nodes. The boundary conditions for the elements concerning the height of the embankment varied according to a linear law and are described by the generalized Hooke's law:

$$\bar{\sigma} = (Д\,\bar{\varepsilon}\,)k, \tag{3}$$

where $\bar{\sigma}$ are voltage components, $\bar{\varepsilon}$ are deformation components, Д is the elasticity matrix, к is coefficient of elasticity:

$$k = k_з k_д,$$

$k_з$ is stability margin factor, taking into account speed traffic;

$k_д$ is the coefficient of dynamism taken as a function of the frequency of natural vibrations of the embankment subgrade [19].

$$Д = [d_{ij}],\ \ (ij=1, 2, 3),$$

$$\bar{\sigma} = \{\sigma_x, \sigma_{y,} \tau_{xy}\}^{\mathrm{T}}; \qquad \varepsilon = \{\varepsilon_x, \varepsilon_{y,} \varepsilon_{xy}\}^{\mathrm{T}}.$$

The linear relationship between the tensor and stress components is as follows:

$$\left.\begin{array}{c}
\left.\begin{matrix} d_{11} \\ d_{12} \end{matrix}\right\} = a_{11}\left\{\begin{matrix} cos^4\,\varphi \\ sin^4\,\varphi \end{matrix}\right. + 2(a_{13} + 2a_{55}\,+) sin^2\varphi cos^2\varphi + a_{33}\left\{\begin{matrix} cos^4\varphi \\ sin^4\varphi \end{matrix}\right.; \\
d_{12} = a_{13}[a_{33} - a_{11} - 2(a_{13} + 2a_{55})]\, sin^2\varphi\, cos^2; \\
d_{13} = [a_{11}cos^2\varphi - a_{33}sin^2\varphi - (a_{13} + 2a_{55})cos^2\varphi]\, sin\varphi\, cos; \\
d_{33} = a_{55} + [a_{11} + a_{23} - 2(a_{13} + 2a_{55})]\, sin^2\,\varphi\, cos^2; \\
a_{11} = a_{22} + E_1(n - \nu_2^2)((1 + \nu_1) - 2\nu_2^2)^{-1} \\
a_{12} = E_1(\nu_1 n + \nu_2^2)((1 + \nu_1)[n(1 - \nu_1 - 2\nu_2^2]^{-1}; \\
a_{13} = E_1\nu_2\Big((n - \nu_1) - 2\nu_2^2\Big)^{-1}; \\
a_{33} = E_1(1 - \nu_1)(n(1 - \nu_1) - 2\nu_2^2)^{-1}; \\
a_{55} = G_1; \\
n = E_1E_2^{-1};
\end{array}\right\} \tag{4}$$

where $E_к$ is Young's modulus; $\nu_к$ is Poisson's coefficient; G_2 is shear modulus; φ is the angle of inclination of the isotropy plane to the axis Ox.

Similarly, we obtain an expression for an isotropic medium at $\varphi = 0$, $E_к=E$, $\nu_к = \nu$; $G_2 = \mathrm{E}\big(2(1 + \ \nu)\big)^{-1}$ and is written as:

$$[Д] = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1 & \frac{\nu}{1-\nu} & 0 \\ \frac{\nu}{1-\nu} & 1 & 0 \\ 0 & 0 & \frac{1-2\nu}{1(1+\nu)} \end{bmatrix} \tag{5}$$

To solve the problem of the stress-strain state of the subgrade, the principle of stationary total potential deformable Lagrange systems is used, which means that if the body is in equilibrium, then the sum of the work of all internal and external forces on any displacements is zero, i.e. it is rigidly fixed:

$$u+v=0.$$

We describe an algorithm for determining the stress state of plane elasticity problems. According to the FEM, the computational domain under study is divided into high-order quadratic elements. Within each element, the soil material is uniform.

The defining functions of the ratio form have the form:

$$\left.\begin{array}{c} h_1 = -0{,}25(-\xi)(1-q)(\xi-q+1) \\ h_2 = 0{,}5(1-q^2)(1-\xi) \\ h_2 = -0{,}25(1-\xi)(1-q)(\xi-q+1) \\ h_4 = 0{,}5(1-\xi)(1-q) \\ h_5 = 0{,}25(1+\xi)(1-q)(\xi-q-1) \\ h_6 = 0{,}5(1-q^2)(1+\xi) \\ h_7 = 0{,}25(1+\xi)(1+q)(\xi+q-1) \\ h_8 = 0{,}5(1-\xi^2)(1+q) \end{array}\right\} \tag{6}$$

The function of the movement within the element is determined by the formula

$$u = \sum_{i=1}^{q} h_i u_i v = \sum_{i=1}^{q} h_i v_i, \tag{7}$$

where *u, v* is moving any point; $h_i u_i i$ is 1,8 offset of q nodes.
Deformations within an element are determined by differentiation:

$$\varepsilon x = \frac{du}{dx}; \qquad \varepsilon y = \frac{dv}{dy}; \qquad v_{xy} = \frac{dv}{dy} + \frac{dv}{dx} \tag{8}$$

or

$$\{\varepsilon\} = [B]\{\delta\}, \tag{9}$$

where $\{\delta\} = \{\{u_{11}v, u_2, \dots\dots\dots, u_8, v_8,\}$,

$$B = \begin{bmatrix} \frac{dh_1}{dx} & 0 & \frac{dh_2}{dx} & 0 & \dots\dots\dots & \frac{dh_8}{dx} \\ 0 & \frac{dh_1}{dy} & 0 & \frac{dh_2}{dy} & 0 \dots\dots & \frac{dh_8}{dy} \\ \frac{dh_1}{dy} & \frac{dh_1}{dx} & \frac{dh_2}{dy} & \dots\dots\dots & \dots\dots\dots & \frac{dh_8}{dy}\frac{dh_8}{dx} \end{bmatrix} \tag{10}$$

The element stiffness matrix is defined using an integral of the form:

$$[K^c] = t \int_{-11}^{1} \int_{1}^{1} [B]^T [Д] [B] \det [J] \, d\,\varphi \, d\,\varepsilon. \tag{11}$$

The integral after applying the Gauss-Lagrange quadrature is reduced to the form

$$[\text{К}^{c}] = t\sum_{i=1}^{n}\sum_{j=1}^{n} N_i H_5 \ [\text{В}]^{\text{T}}[\text{Д}][\text{В}]\det[J], \tag{12}$$

where $N_i H_j$ (i, j = 1, 2, 3) is weight coefficients; n is number of integration points in the direction ξ and q.

The stiffness matrix of the systems [K] is formed by summing over all m elements of the stiffness matrix

$$[\text{К}] = \sum_{i=1}[K_i^e]. \tag{13}$$

If the stiffness matrix of the system [K] is known, then it is easy to obtain a basic system of algebraic equations relating nodal forces and with nodal displacements

$$[K] = \{v\} = \{F\}, \tag{14}$$

where v, F is, accordingly, the vectors of movement and forces of all nodes.

The system of algebraic equations is solved by the Gaussian elimination method.

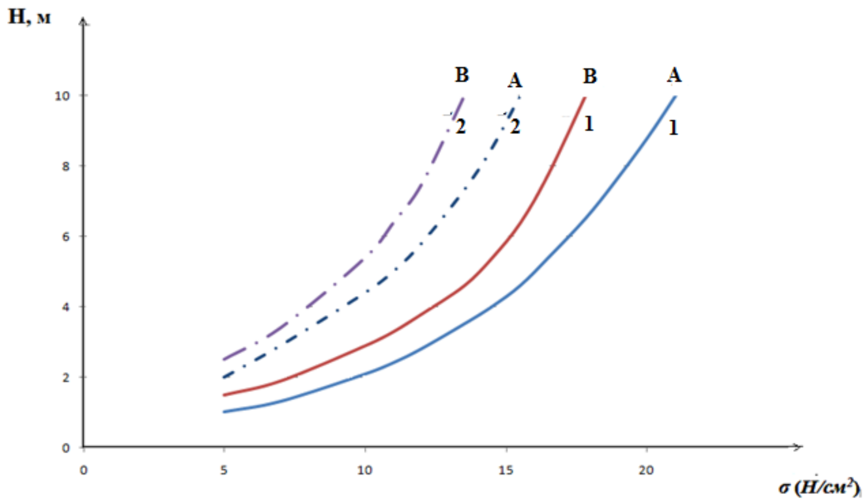

Fig. 2. Dependence of the increase in tension in the embankment of the subgrade on its height during high-speed train traffic: 1 is experimental data; 2 is theoretical calculations; A – at train speeds of up to 150 *km/h*; Б – at train speeds of up to 100 *km/h*.

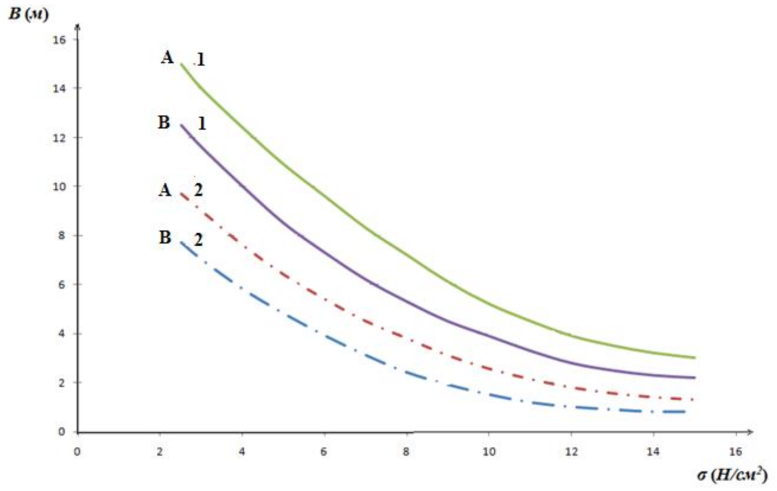

Fig. 3. Dependence of the stress in the embankment of the subgrade on its width during high-speed train traffic: 1 is experimental data; 2 is theoretical calculations; A – at train speeds of up to 150 *km/h*; Б – at train speeds of up to 100 *km/h*.

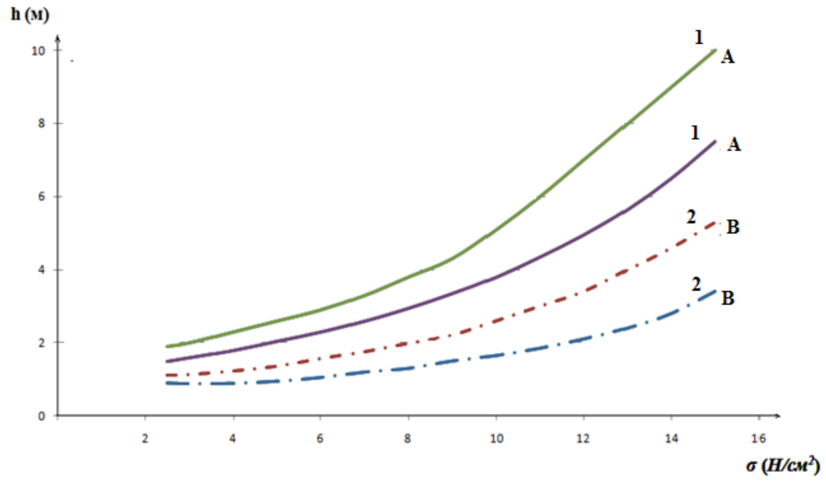

Fig. 4. Dependence of the stress in the slopes of the recess on its depth: 1 is experimental data; 2 is theoretical calculations for high-speed train traffic; A – at train speeds of up to 150 *km/h*; B – at train speeds of up to 100 *km/h*.

Experimental studies and theoretical calculations made it possible to determine the stresses in the embankments and recesses depending on the width, the height of the embankment and depth of the excavation of the subgrade (Figure 2-4) at speed train traffic up to 150 km/h in medium-density soils and low ground water levels.

4 Conclusions

The results of theoretical and experimental studies of the subgrade in high-speed train traffic suggest that the embankments are more stable at the height of up to 5 m and a width of more than 8 m, i.e., more stable double-track railways, and the depth of the recesses is assigned to 8 m, which is a refinement of the previously obtained results.

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