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Evaluation of slope stability of railway embankments

Stabilité inclinée de digues de chemin de fer

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ABSTRACT
The results of the experimental and theoretical researches of slope stability of railway embankments are presented in the paper. The conclusions of criteria of similarity for modeling of the serviceability of railway embankments on geotechnical centrifuges under the vibro-dynamical loads from a train. In the paper the basic ways of reinforcement and stabilization of potentially-dangerous and deforming embankments of railways are shown, requirements to which are developed on the basis of results of centrifugal modeling of slope stability of a range of embankments, both on real prototypes, and on the basis of development of the generalized parameters of embankments according to the statistical data of the railway network of the Russian Federation.

RÉSUMÉ
Les resultats des recherches exprimentales et theoriques de stabilite incline de digues de chemin de fer sont presentes dans le papier. Les conclusions de criteres de similarite pour poser de la praticabilite de digues de chemin de fer sur les centrifugeurs geotechnical sous les charges vibro-dynamiques d'un train. Dans le papier les voies fondamentales de renforcement et de stabilisation de digues potentiellement-dangereuses et diformantes de chemins de fer sont montres, les exigences auxquelles sont developpees sur la base des resultats du fait de modeler centrifuge de stabilite incline d'une gamme de digues, tant sur les prototypes reels, que sur la base du developpement des parametres generalises de digues selon les donnes statistiques du reseau de chemin de fer de la Federation de la Russie.

1 INTRODUCTION

The most significant deformations of separate objects of the railway subgrade are failures of stability of their slopes.

Any object of the subgrade, including an intensively operated railway embankment together with external, natural influences and internal loads at studying stability of slopes, is regarded as an open dynamic system. If to treat a parameter of stability of such an embankment in a general way as interdependence between the factors holding a slope and the factors, leading to its failures, it can be written down as:

$$K_s(t) = f\,[\tau_0(t), \gamma_d(t), U_1(t), U_2(t), U_3(t), t], \qquad (1)$$

where K_s = coefficient of stability; τ_0 = generalized shear strength of soil, kPa; γ_d = unit weight of dry soil, кN/m^3; $U_1(t)$ = the function of external loads (external loads on an embankment from constructions, the weight of the track upper structure and the loads from the train); $U_2(t)$ = the function of natural factors (atmospheric precipitations, temperature, wind, flooding) ; $U_3(t)$ = the function of internal factors (pressure from the weight of the soil, moisture, pore pressure) .

The tasks of research of slope stability of the subgrade (as well as other geotechnical constructions) can be divided into two groups: the problems which aim at studying the physical nature of processes of infringement of stability of slopes (they can be carried out to check the hypotheses or various analytical decisions) and tasks of applied character when a definite construction with a definite goal to estimate the slope stability is studied.

2 ANALISYS OF SLOPE STABILITY OF EMBANKMENTS

An effective way of research slope stability of railway embankments is the method of physical modeling on geotechnical centrifuges (Yakovleva, T.G. Ivanov, D.I. 1980).

At centrifugal modeling all physical nature of the process of infringement of stability of slopes remains unchanged and even in most cases the geometrical similarity of blocks of displacement is provided. Therefore the experimental estimation on the models of slope stability can supplement or replace in very many cases theoretical methods of estimation. So only appropriate theoretical preparation is necessary for the experiment: the development of criterial equations of the process and their analysis, as well as the subsequent analysis of the results of experiments with the help of received criteria.

The practice of centrifugal modeling of slope stability is extensive. However, only in some works the estimations of the plan and parameters of stability are presented, in the majority of works the results of modeling are simply used.

In analysis of slope stability of railway subgrade in Russia the well-known method of calculation of stability by G.M. Shakhunyants is now frequently used according to which the stability of the slope is estimated by the coefficient of stability, which is calculated as:

$$K = \frac{\sum_{i=1}^{n} (f_i N_i + c_i l_i + T_{i-stab}) \dfrac{\cos(\phi_i)}{\cos(\beta_i - \phi_i)}}{\sum_{i=1}^{n} T_{i-fail} \dfrac{\cos(\phi_i)}{\cos(\beta_i - \phi_i)}} \qquad (2)$$

where n = number of slices into which the block of possible failure is divided by vertical sections; i and ϕ = the angle and coefficient of internal friction of the soil on the surface of displacement; N_i - a normal component of force of weight in slice including the static external pressure(N/m); c_i - cohesion,(kPa); l_i - length of a failure surface in slice (m); $T_{i\text{-}stab}$ = a tangential component of force of weight in slice with the static external pressure, directed at its maintaining (N/m); $T_{i\text{-}fail}$ = a tangential component of force of weight in slice with the static external pressure, directed at the failure of a slope (N/m); ϕ = the angle of inclination to the horizon of the surface of possible displacement in the slice.

The necessary criterion of similarity for modeling spontaneous deformation of a slope in a period of time, using the differential equation of deformability of the kind is calculated as:

$$\frac{\partial z}{\partial t} = R\frac{\partial^2 z}{\partial y^2} + \mu y\frac{\partial z}{\partial y} + \mu z, \qquad (2)$$

where y and z = coordinates of points of a slope, (м); R = the factor of deformability dependent on viscous properties of the ground, (m2/c); μ = the coefficient of proportionality between the speed and the parameter of displacement of a particle of the soil (1/c).

Having lowered the intermediate calculations, we obtain the general criterion of similarity of the process in question

$$\pi = \frac{\mu R t^2}{L^2} = idem \qquad (3)$$

where L = general linear size (m); t = time (c).

The received criteria can be used for planning experiments and the analysis of results of modeling and their transferring on natural objects.

For practical use the following criteria of similarity are recommended:

where P_{us} and P = external factors from the weight of the upper structure and the influence of a train, kN/m; W = moisture of soil; γ_d = density of dry soil, kN/m3; τ_0 = the generalized resis-

$$\pi_1 = \frac{P_{us}\cdot P\cdot W}{L^3\cdot\gamma_d\cdot\tau_0} = idem;$$
$$\pi_2 = P_{us}^2\cdot P^2\cdot\left(\frac{W}{L^3\cdot\gamma_d\cdot\tau_0}\right)_I\left(\frac{W}{L^3\cdot\gamma_d\cdot\tau_0}\right)_{II} = idem; \qquad (4)$$
$$\pi_3 = \frac{P_{us}^2}{L^4}\cdot\frac{P\cdot W}{(\gamma_d\cdot\varphi\cdot c)_n\,(\gamma_d\cdot\varphi\cdot c)_c} = idem$$
$$\pi_4 = \frac{R\cdot t}{L^2} = idem$$

tance to the shift of the soil, kPa.

In the second equation **(4)** index I designates characteristics of a subgrade, index II - his foundation. In the third equation of the system (4) index n characterizes properties of draining ground of ballast deepenings and loops of an exploited embankment, index c = cohesive soil embankments, kPa**.**

The distinctive feature of modeling of stability of slopes of embankments of railways is the necessity to take dynamic influence of train pressure into account.

The specifics of dynamic influence of train pressure on the subgrade is expressed in the following:

- Influence of external dynamic factors from passing trains on the ground layer is shown in occurrence of dynamic pressure, elastic fluctuations and vibrations; the size and an orientation of these influences is various in space and time;
- Owing to fluctuations and vibrations arise inertial and dispersive forces, the size and direction of which is also various in space and time;
- Influence of dynamic pressure on the ground layer is marked in the appearance of irreversible and convertible processes; these processes are stipulated at vibrations by infringement of structural reactions between particles and their units (for embankments these reactions are restored to a certain extent after deliberate condensation during construction); there is also a transformation of the cohesive water and clearing of immobilized water that reduces the resistance of the soil to a shift, as physically cohesive water possesses ability to resist shifting, free pore water, on the contrary, possesses ability of greasing; at vibrations and significant elastic settlements there is also the general time dilatation of the soil and as a consequence of it:
- Decrease of strength characteristics; all these phenomena and processes are shown non-uniformly in space and time;
- Duration of continuous influence of dynamic pressure is of great importance, as thus irreversible processes start to prevail above convertible in view of decrease in bearing capacity of the ground and resistance to shift that leads to its more intensive deformability; in this connection it is necessary to take into account the character and duration of the actions of dynamic influence on the model of the basic platform of subgrade, their cinematic communication with the model of the prototype.
- Influence of dynamic external factors should be such as to answer natural conditions of influence at which many factors, previously not taken into account or partially used by static calculations reveal themselves, factors: various microstructures of the soil, their natural physical properties - friction, cohesion, shear strength, molecular links of particles of soil and water, chemical cementation of structure, etc.;
- External dynamic influence is transferred to the subgrade through a ballast layer, the length of this transfer is such, that the problem can be considered as a 2D problem.

All the specifics should be whenever possible taken into account at the creation of dynamic model of train pressure and definition of operating conditions with it.

At modeling of dynamic influence of train pressure on the subgrade three variants of its cinematic communication with model of the subgrade can be realized: the model of pressure can transfer dynamic influences through models of rails, at a level of a ballast layer and at a level of the basic platform of the subgrade.

It is by process of elimination received; that it is the most expedient to carry out the application of dynamic model of train pressure at a level of the basic platform of model of the subgrade since modeling of the elements of the upper structure of a track is practically impossible because of their small sizes on the model.

The first condition is the preservation on the model in the same points and in the same moments of time of sizes of natural dynamic pressure, i.e. (i=1,2,3...). This condition will be executed, if at a level of the basic platform of a subgrade the stresses for the model and the prototype are equal:

Two criteria of similarity which are included in the basic criterion of similarity of N.A.Nasedkin are used:

$$\frac{P}{\rho\omega^2} = idem \qquad \frac{gl}{\omega^2} = idem \qquad (5)$$

where P = force of impact (kN); ρ = density (kg/m3); ω = speed of influence on the soil (m/s); g = earth gravity (m/c2);

l = the linear size (м).

The second criterion is similar to the criterion of Frude.

At centrifugal modeling:

$$n_p = n^2, n_\rho = 1, n_g = \frac{1}{n}, n_L = n \qquad (6)$$

The indicators of similarity for these criteria

$$\frac{n_p}{n_\rho \cdot n_\omega^2} = \frac{n^2}{1 \cdot n^2} = 1 \qquad \text{and}$$

$$\frac{n_g n_L}{n_\omega^2} = \frac{\frac{1}{n} \cdot n}{n_\omega^2} = 1$$

From conditions (6) it follows, that on the model the speed of influence on the soil should be the same, as in natural conditions.

It has been proved (Shakhunyants, G.M. 1953), that the only and necessary condition, providing equal characteristics of soil strength of nature and models in the same points, in the same moments of time, is $A_m = A_h$ and $\nu_m = \nu_h$.

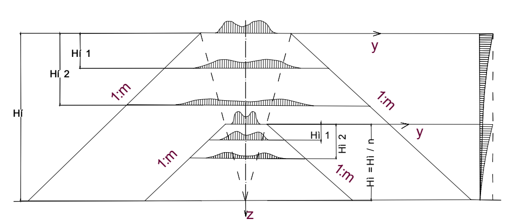

Figure1. Scheme of model load

For the creation on the level of the model of the basic platform of subgrade of the dynamic pressure, close to real, the special transmitting device was created.

This dynamic model is executed on MIIT centrifuge as a set of elastic beams of variable section from the material with the corresponding module of elasticity (e.g. textolite) - fig. 2.

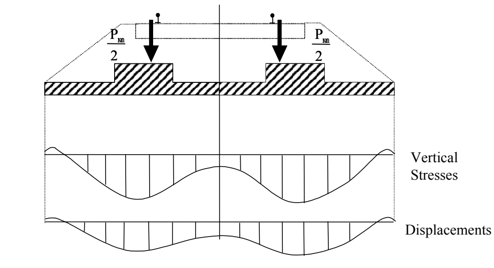

Figure 2. Scheme of the dynamic model executed on MIIT centrifuge

Force P_m (see Fig.2) equal from 0 up to 16 *kgf* can be transferred to every beam, meanwhile the dynamic pressures are created in the sections under forces P_m and vibrations can be transferred onto the subgrade under frequency from 0 to 200 *Hz*.

The efficiency of dynamic pressure has been tested in experiments where the settlements of the basic platform of model under certain pressure were calculated - fig. 3.

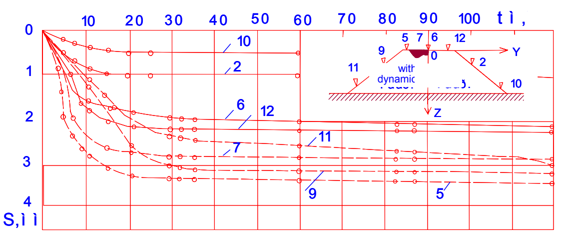

Figure 3. Settlements of embankments under loading of dynamic forces

For the estimation of efficiency of centrifugal modeling stability of objects of railway embankments, experiments on modeling embankments of different height have been executed.

It has been experimentally established, that at steeper slopes of model of an embankment, the weight of the soil in failure mass on slopes is more (fig. 4) that corresponds to the natural data.

Also it has been tested, whether the cylindrical form of the surface of failure is reproduced when modeling. The studying of formation of the failure surface on models has shown, that is reproduced - fig. 5-6**.**

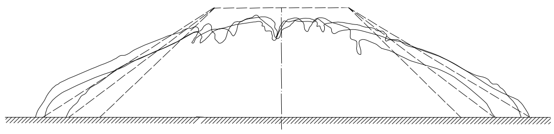
Figure 4. Influence of steepness of embankments on the model deforming

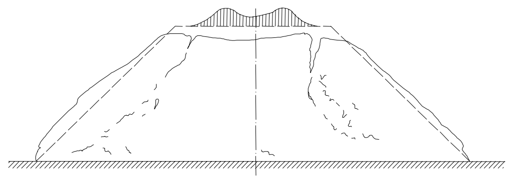
Figure 5. Deforming of the model at action of dynamic load

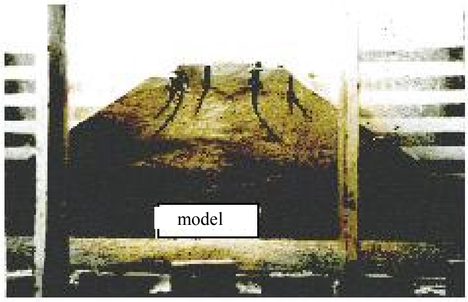

Figure 6. View of the model failure

When modeling the dependence of influence of moisture w and the height of embankments h on the value of destroying dynamic pressure of a train - fig. 7.

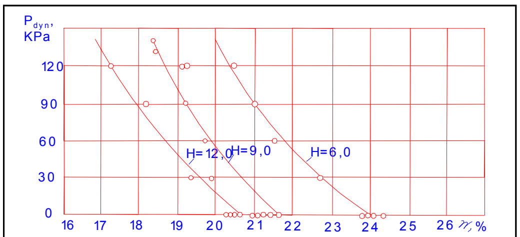

Figure 7. The destroying load vs. moisture

The received results have allowed to proceed to modeling of long used embankments. The schematic geological cross-section of one of such embankments is presented on fig. 8, (an embankment in height H=14,5 m on section Cherusti – Druzhinino the Gorki railway in Russia).

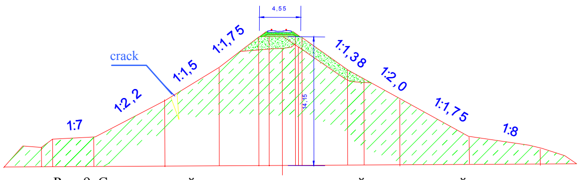

Рис. 9 Схематический инженерно-геологический разрез опытной насыпи
Figure 8. Engineering-geological cross-section of embankments

In the figure 9-10 the model of this embankment after modeling on the centrifuge, where the ballast deepening and ballast loops are clearly visible is submitted. On the model the formed elements of slope failures are visible.

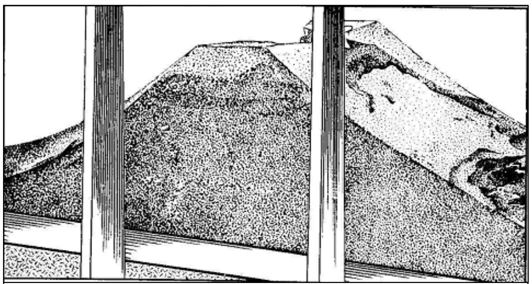

Figure 9. Deformed view of embankment model

Figure 10. View failure of model

On the basis of the results of centrifugal modeling of stability of slopes of some embankments both on real prototypes, and on the basis of development of the generalized parameters of embankments on the statistical data of railways of the Russian Federation number of effective ways of reinforcement and stabilization of potentially-dangerous and deforming embankments of railways and a number of normative documents on reinforcement of the subgrade of railways has been developed (Zaitsev A.A., Frolovsky Y.K. 2000).

In the figure 12 the photo of one of the embankments with reinforced by the gabion walls the design of which has been developed on the basis of technical instructions presented.

Gravitation

Figure 11. Reinforcing of the subrade on line Aleksandrov-Balakirevo (Northern Railway)

3 CONCLUSIONS

The carried out experimental and theoretical investigations of slope stability of subgrade have shown that the forms of surfaces of slope displacement of subgrade depend on the dynamic pressure of the train on the basic of the subgrade.

The specially created for such purposes device placed on the centrifugal machine has allowed to estimate the levels of destroying pressures of a train.

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