

# Bearing capacity of the subgrade for high-speed train traffic

Nodir Begmatov<sup>1</sup>, Ulugbek Ergashev<sup>1\*</sup>, Kuvandik Lesov<sup>1</sup>, Saulet Shayakhmetov<sup>2</sup>

<sup>1</sup>Tashkent State Transport University, 100167 Tashkent, Uzbekistan

<sup>2</sup>Kazakh National Research Technical University named after K.I. Satbayev NPJSC (Satbayev University), Almaty, Kazakhstan

**Abstract.** On the basis of theoretical research the problem of determining the bearing capacity of the main site of the earth bed poured from loess-like loam with regard to the action of vibrodynamic loads and reduction of strength properties of soils under its influence is solved. On the basis of solution of the theory of limit equilibrium it is possible to determine the deficit of bearing capacity, the value of which is the main indicator for a reasonable choice of design of reinforcement of the main site of the earth bed in order to increase its strength. On the basis of calculation of the earth bed strength, the variants of the earth bed construction are presented, providing the required strength of the earth bed made of loess-like loam with consistency index  $0,21 < J_L \leq 0,3$ , at high-speed train traffic. The presented transverse profiles can be recommended for application.

## 1 Introduction

In recent years, the network of high-speed and high-speed railways has been expanding in Uzbekistan [1, 2, 3]. In order to realise high train speeds and ensure guaranteed safety and comfort, it is necessary to widely introduce reliable, low-maintenance and cost-effective railway track designs.

Currently, the trends and directions of further development of railway transport in the Republic of Uzbekistan envisage the construction of a specialised high-speed railway line. High-speed and high-speed lines are necessary for the economic growth not only of the railway industry, but also of the country as a whole.

The development of high-speed train traffic on the railway network of Uzbekistan is closely connected with ensuring the necessary level of reliability of the railway track, including the earth bed as its load-bearing structure.

The earth bed of high-speed railways, as well as all other structures and facilities, must ensure continuous operation of a large dynamic system - the railway track. This requires strict compliance with a number of requirements, the main of which are: strength, stability, stability, minimum deformability, durability, maintainability, minimisation of construction and maintenance costs [3-6].

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\* Corresponding author: [ulugbek.ergashev.1988@mail.ru](mailto:ulugbek.ergashev.1988@mail.ru)

A significant part of Uzbekistan's railways is constructed of local loess-like soils. The need to calculate the load-bearing capacity of the earth bed poured from loess-like loam taking into account the vibrodynamic load arising during the movement of trains at speeds of 200-250 km/h.

## 2 Materials and Methods

The bearing capacity of the main site of the earth bed is determined by the values of the limiting stresses on its surface, depending on the strength properties of soils, and on the magnitude of the vibrodynamic impact [7]. The theory of limit equilibrium was applied to the railway subgrade by Professor I.V. Prokudin taking into account the action of vibrodynamic loads and reduction of strength characteristics of soils under their influence. [7].

The method of calculating the bearing capacity of the earth bed is based on the solution of the plane problem of the theory of limit equilibrium, the basic system of equations of the plane problem consists of the equations of motion of the soil medium and the condition of Coulomb's limit equilibrium and has the following form [7]:

$$\left\{ \begin{array}{l} \frac{d\sigma_z}{dz} + \frac{d\tau_{zy}}{dy} = Z + \rho \cdot \frac{d^2 \cdot U}{dt^2} \\ \frac{d\tau_{yz}}{dz} + \frac{d\sigma_y}{dy} = Y + \rho \cdot \frac{d^2 \cdot V}{dt^2} \\ \sigma_1 - \sigma_2 = (\sigma_1 + \sigma_2 + 2 \cdot C_{dn} \cdot ctg\varphi_{dn}) \cdot \sin\varphi_{dn} \end{array} \right. \quad (1)$$

Where:  $\sigma_z, \sigma_y$  - components of normal stresses, respectively in vertical and horizontal planes, t/m<sup>2</sup>;

$\tau_{zy}, \tau_{yz}$  - components of tangential stresses, t/m<sup>2</sup>;

$U, V$  - displacements at oscillations in the direction of axes  $Z$  and  $Y$ ;

$\sigma_1, \sigma_2$  - maximum and minimum principal stress;

$C_{dn}, \varphi_{dn}$  - adhesion and angle of internal friction of the soil, which perceives the vibrodynamic load;

$Z$  and  $Y$  - volumetric forces, with the direction of the  $z$  axis vertically downwards  $Z = \gamma$ , and  $Y = 0$ ;

$\gamma$  - volumetric weight of the soil, t/m<sup>3</sup>;

To obtain the solution, the system is transformed by introducing two new unknowns: the inclination angle  $\delta$  of large principal stresses to the  $y$ -axis and the stress magnitude  $\sigma_1$  expressed through the principal stresses by the following formula:

$$\sigma = \frac{1}{2}(\sigma_1 + \sigma_2) + C_{dn} \cdot ctg\varphi_{dn} \quad (2)$$

After substituting this expression into the third equation of the system (1), we obtain:

$$\frac{1}{2}(\sigma_1 + \sigma_2) = \sigma \cdot \sin\varphi_{dn} \quad (3)$$

It is known that it is possible to represent the stress components along the corresponding coordinate axes through the values of principal stresses using the formulas:

$$\sigma_z = \frac{1}{2}(\sigma_1 + \sigma_2) - \frac{1}{2}(\sigma_1 - \sigma_2) \cdot \cos 2\delta \quad (4)$$

$$\sigma_y = \frac{1}{2}(\sigma_1 + \sigma_2) + \frac{1}{2}(\sigma_1 - \sigma_2) \cdot \cos 2\delta \quad (5)$$

$$\tau_{zy} = \frac{1}{2}(\sigma_1 - \sigma_2) \cdot \sin 2\delta \quad (6)$$

## 3 Results and Discussion

### 3.1 Input data and calculation results

The embankment was calculated, the section is two-track, the earth bed is composed of loess-like sandy loam with consistency index  $J_L = 0.3$ , on a solid base.

Height of the embankment,  $H_n = 3.0$  m;

Thickness of ballast layer  $h_b = 0.5$  m;

Embankment slope 1:1.5;

Width of the main site,  $B = 13.0$  m;

Distance between the paths  $M = 4.5$  m;

Loess-like loam with consistency index  $J_L = 0.3$  has the following characteristics [8]:

Cohesion  $C = 1.7$  t/m<sup>2</sup>;

Angle of internal friction  $j = 21$  degrees;

Volume weight  $g = 2.15$  t/m<sup>3</sup>.

Coefficient of relative reduction of specific adhesion  $K_C = 0.35$ ;

Coefficient of relative reduction of angle of internal friction

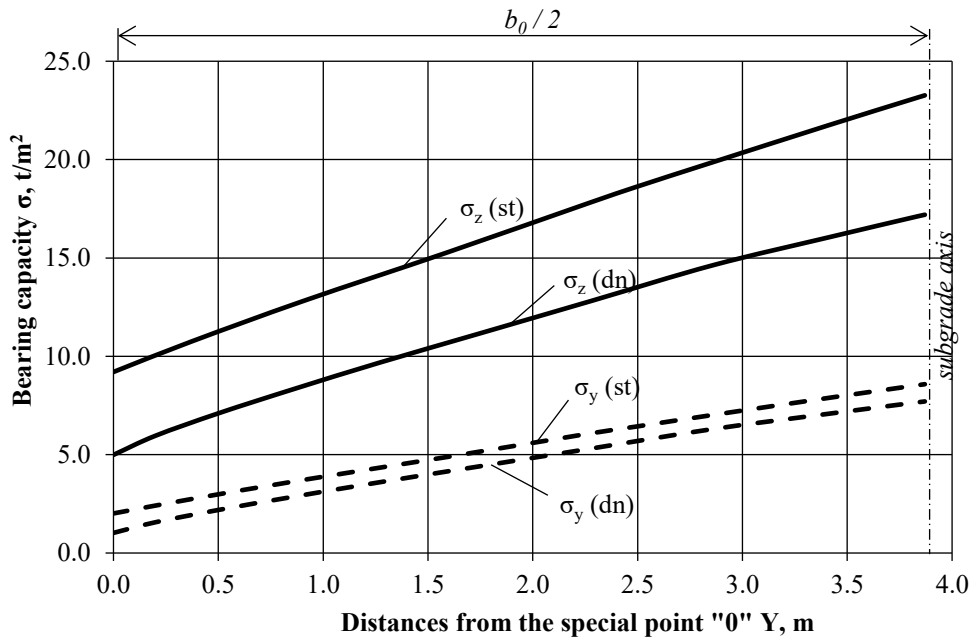
$K_\phi = 0.20$ ;

The amplitude of oscillations according to [9], at a speed of 250 km/h  $A_0 = 276$  μm;

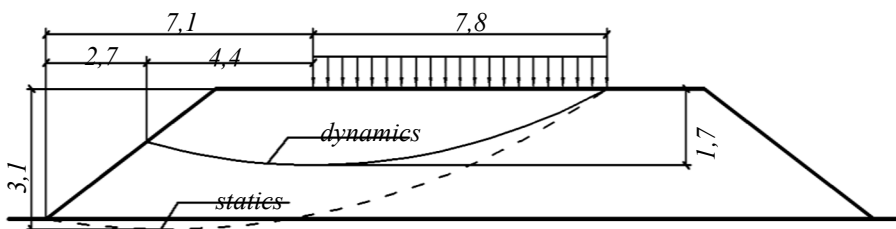
The calculation results are presented graphically (Fig. 1). Fig. 1 shows the results of calculation of bearing capacity of the main site of the earth bed, dumped from loess-like loam, under the action of static and vibrodynamic loading. The figure shows that the maximum acting stress from the rolling stock is registered on the main platform in the sub-rail section. Consequently, the minimum difference between the effective and ultimate load will occur in the section along the axis of the rail, which in this case will be removed from the special point "0" at a distance of 0.9 metres. Analysing the results of calculation in the under-rail zone under the action of vibrodynamic loads, we obtain the value of ultimate stresses in the vertical plane equal to 8.5 t/m<sup>2</sup>, and in the horizontal plane – 2.9 t/m<sup>2</sup>. Accordingly, under the action of static load they were 12.8 t/m<sup>2</sup> and 3.7 t/m<sup>2</sup>, i.e. taking into account the action of vibrodynamic load led to a decrease in the strength of the main site of the earth bed in the sub-rail section in the vertical plane in 1.5 times, and in the horizontal plane in 1.3 times. This fact once again emphasises the need to take into account the action of vibrodynamic loading in calculations of the strength of embankments constructed from loess-like sandy loam.

On the basis of the calculation, the envelopes of the slip lines were plotted (Fig. 2). In Fig. 2, the dashed line shows the largest slip line obtained in the calculation using the strength characteristics determined under static loading. As can be seen from the figure, the zone of soil mixing under the influence of vibrodynamic impact decreased from 7.1 m to 4.4 m, i.e. practically 1.6 times, and the depth of the soil sliding zone decreased from 3.1 m

to 1.7 m, i.e. 1.8 times. It is obvious that the reduction of the soil sliding zone under the action of vibrodynamic load causes the reduction of the bearing capacity of the earth bed. In dynamics there is a squeezing of soil on the slope, with less mass of soil involved, and in statics there is destruction of the entire slope.



**Fig. 1.** Results of calculation of bearing capacity of the earth bed of loess-like loam under static and dynamic conditions (with consistency index  $J_L = 0.3$ )



**Fig 2.** Slip line under the action of loads

### 3.2 Investigation of the influence of various factors on the bearing capacity of the main site of embankments composed of loess-like sandy loams

The bearing capacity of the main site can be influenced by various factors such as:

Soil clay conditions characterised by consistency index,  $J_L$ ;

The slope of the embankment;

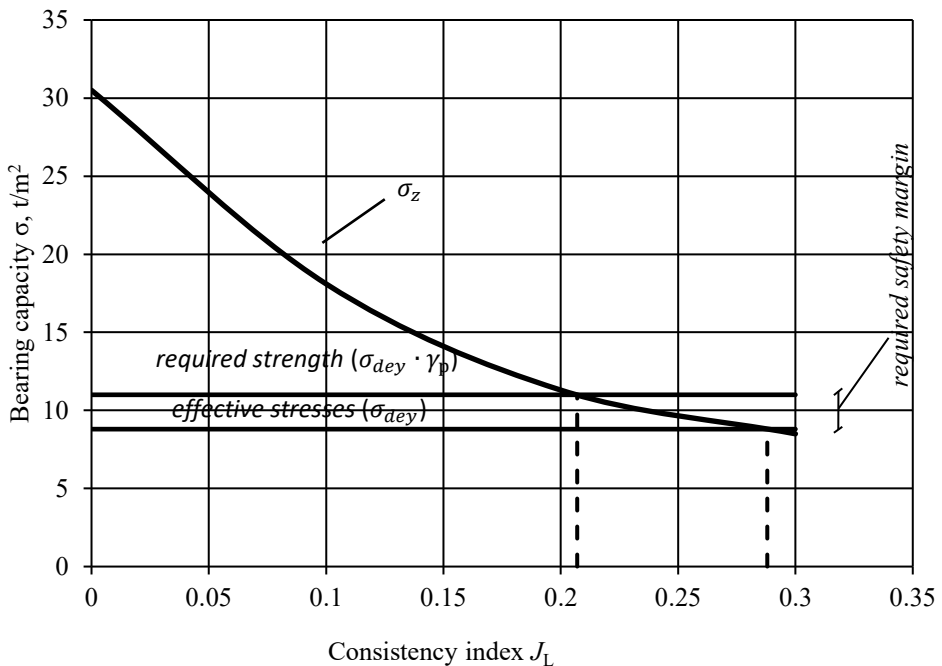
The width of the main embankment site.

The main results of such studies are summarised below.

#### 3.2.1 Influence of the condition (consistency index) of loess-like loam on the bearing capacity of the main site

The study of the influence of the consistency index of loess-like loam on the bearing capacity of the main site of the subgrade was carried out for the embankment, perceiving the vibrodynamic impact occurring at a speed of 250 km/h. The calculation results are presented in Figure 3.

The analysis of Figure 3 indicates that loess-like loam in the solid state ( $J_L \leq 0$ ) has a high bearing capacity exceeding the required strength by 2.8 times. The bearing capacity decreases with increasing consistency index. Loess-like loams with consistency index up to 0.21 provide the required strength of the main site for the operation of the earth bed, with the movement of trains with speeds up to 250 km/h. At consistency index from 0.21 to 0.29 the earth bed works in conditions of absence of the required strength reserve. At consistency index of loess-like loam  $J_L > 0.29$  the strength of the earth bed is not provided, as the bearing capacity of the main site is less than the acting stress. Thus, the earth bed poured from loess-like loam with consistency index more than  $J_L \geq 0.21$  requires reinforcement for the operation of the earth bed for the movement of trains with speeds up to 250 km/h.



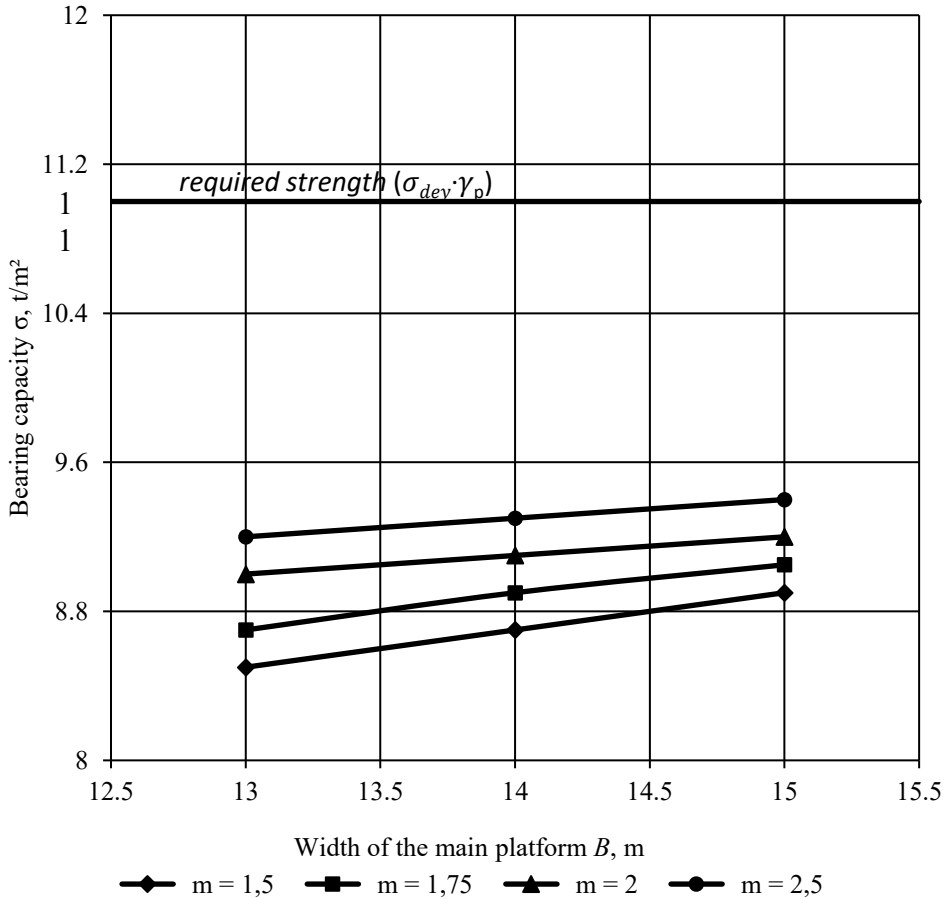
**Fig. 3.** Dependence of bearing capacity of the main site on consistency index of loess-like sandy loam

### 3.2.2 Influence of embankment design parameters on the bearing capacity of the main site

The influence of geometrical parameters of the embankment design on the bearing capacity of the main site was investigated by changing the embankment slope and the width of the main site. The calculation was performed at consistency index of loess-like loam  $J_L = 0.3$ . The earth bed absorbs the vibrodynamic load, at a speed of 250 km/h. The results of calculation are presented in Figure 4.

The analysis of Fig. 4 shows that when changing the slope embedment from 1:1.5 to 1:2.5, as well as when changing the width of the main site from 13 to 15 m, there is an increase in the bearing capacity of the main site. However, this increase is not sufficient to achieve the required strength of the subgrade. Based on the graph in Fig. 4 we can draw the following conclusion: embankments made of loess-like soils with consistency index  $J_L = 0.3$

do not have the required strength for high-speed train traffic, even if the slope embedment is more than 1:1.5 and the width of the main platform is more than 13 m.



**Fig. 4.** Dependence of change in bearing capacity of the main site made of loess-like loam from embankment design parameters (with consistency index  $J_L = 0.3$ )

### 3.3 Installation of a protective layer on the main site of the subgrade

The main design solutions to ensure the strength of the main embankment platform of loess-like soils of railways for high-speed train traffic should provide for either reducing the load on the main platform or increasing its load-bearing capacity. To date, there are various methods of reinforcing the subgrade for high-speed traffic in the design practice. One of the traditional methods of reinforcing the subgrade is the construction of a protective layer of drainage soil. In order to ensure the required strength on the main site made of loess-like loam with a consistency index of more than 0.21, the construction of a protective layer of drainage soil is recommended. The thickness of the protective layer is determined by calculation. For the protective layer we use the soil with the following characteristics:

- Soil type of the protective layer - crushed stone-sandy-gravel mixture (CSGS);
- Specific cohesion of the soil –  $C = 1.7 \text{ t/m}^2$ ;
- Angle of internal friction –  $\varphi = 40^\circ$ ;

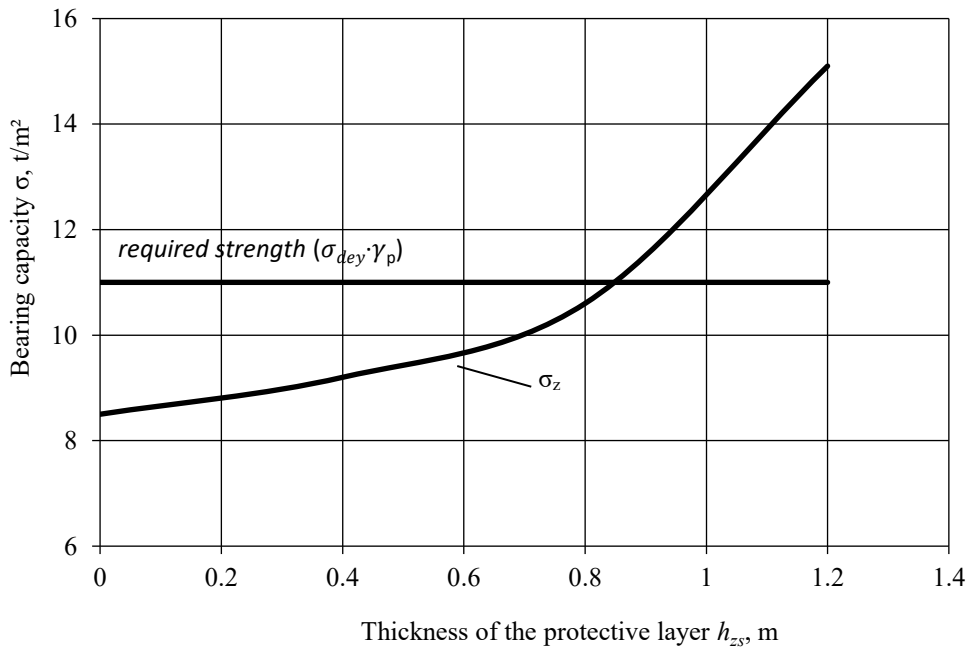
Volume weight of soil –  $\gamma = 1.75 \text{ t/m}^2$ ;

Coefficient of relative reduction of adhesion –  $K_c = 0.17$ ;

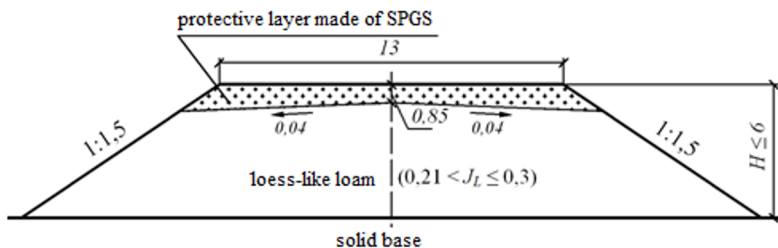
Coefficient of relative reduction of angle of internal friction –  $K_\phi = 0.12$ .

Calculation is made at consistency index of loess-like loam  $J_L = 0.3$ , and the value of vibration amplitudes – 276 mcm, which occur at a speed of 250 km/h. The results of calculation are presented in Fig. 5.

The analysis of Fig. 5 shows that as the thickness of the protective layer increases, the bearing capacity of the main platform increases. However, the required strength of the main site is achieved at the thickness of the protective layer of 0.85 m. According to STN Ts-01-95 [10], the minimum thickness of the protective layer for sandy loam is 0.5 m, but with a thickness of 0.5 m the required strength is not provided. On this basis, when designing an earth bed structure made of loess-like loam with a consistency index of  $0.21 < J_L \leq 0.3$  for high-speed traffic, the thickness of the protective layer should be at least 0.85 metres. The cross-sectional profile of an embankment made of loess-like loam with consistency index  $0.21 < J_L \leq 0.3$ , with a protective layer is shown in Figure 6.



**Fig. 5.** Dependence of bearing capacity of the main site of loess-like sandy loam on the thickness of the protective layer (with consistency index  $J_L = 0.3$ )



**Fig. 6.** Transverse profile of the embankment made of loess-like sandy loam with consistency index  $0.21 < J_L \leq 0.3$ , with protective layer construction

### 3.4 Arrangement of a reinforced protective layer.

In recent years, one of the most promising and widely used in transport construction methods of reinforcing the earth bed has become the use of various types of geosynthetic materials (geotextiles, geogrids, geogrids, geocells, geocomposites, geomats, geomembranes of various types and other materials) [11-15].

The inclusion of geosynthetic reinforcement in the protective layer can significantly improve the overall strength and service life of the structure.

To reduce the thickness of the protective layer, we will reinforce the protective layer with one layer of geogrid. According to the normative data [10] the minimum thickness of the protective layer for loess-like sandy loam is 0.5 m, therefore the thickness of the protective layer is assumed to be 0.5 m. At the thickness of the protective layer of 0.5 m the deficit of bearing capacity is 1.6 t/m<sup>2</sup>. The deficit of bearing capacity is the main indicator for selection of geogrids, based on "Recommendations on application of polymeric materials (foams, geotextiles, geogrids, polymeric drainage pipes) for reinforcement of the earth bed during track repair" [16]. It is obvious that the design tensile strength of the geogrid,  $R_p$ , under the constantly acting load should be not less than the deficit of bearing capacity, i.e.  $R_p \geq 1.6$  t/m, and the short-term resistance of the geogrid to tearing  $R_o$  (the characteristic of the geogrid brand is given in the manufacturer's passport) will be related to  $R_p$  by the following formula [16]:

$$R_o = R_p \cdot \gamma_o \cdot \gamma_1 \cdot \gamma_{rm} \cdot \frac{1}{K_\tau} \quad (7)$$

where,  $\gamma_o$  - coefficient, taking into account the heterogeneity of the geogrid material and the error arising during its operation,  $\gamma_o = 1.05$ ;

$\gamma_1$  - the coefficient, taking into account the damage of geogrid material at laying and during operation in the layer of crushed stone,  $\gamma_1 = 1.03$ ;

$\gamma_{rm}$  - coefficient, which takes into account the reduction of geogrid strength under the influence of aggressive soil environment, depending on soil acidity. Geogrids with tensile strength of not less than 10 t/m are so resistant to aggressive influences that during the long term of operation their design strength does not decrease, then  $\gamma_{rm} = 1.0$ ;

$K_\tau$  - coefficient, taking into account the reduction of short-term tensile strength under the action of load during the design life of the structure, analogue of the creep coefficient of the material. For geogrids with a tensile strength of at least 10 t/m,  $K_\tau = 0.6$ , taking into account the action of temporary periodically recurring load from the rolling stock.

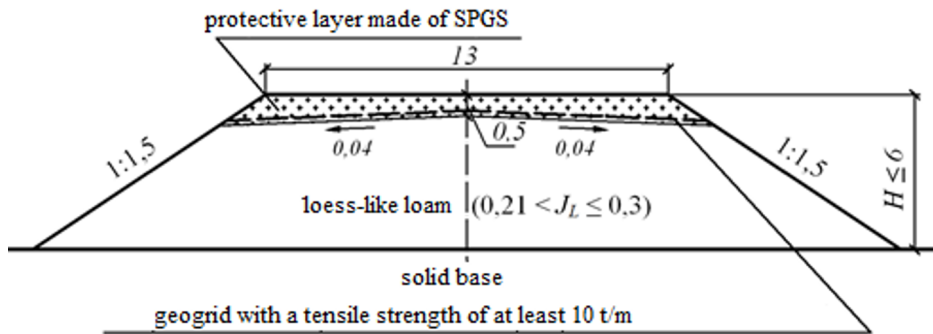
$$\text{Then: } R_o = 1.6 \cdot 1.05 \cdot 1.03 \cdot 1 \cdot \frac{1}{0.6} = 2.9 \text{ t/m.}$$

Thus, according to the value of  $R_o$ , a type of geosynthetic material with a tensile strength of at least 10 t/m is selected.

$$\text{Hence, } [R_p] = \frac{[R_o] \cdot K_\tau}{\gamma_o \cdot \gamma_1 \cdot \gamma_{rm}} = \frac{10 \cdot 0.6}{1.05 \cdot 1.03 \cdot 1} = 5.6 \text{ t/m.}$$

Taking into account the reinforcement of the protective layer with geogrid, the bearing capacity at the main area of the subgrade in the section along the rail axis is 14.8 t/m<sup>2</sup> and the required strength of the subgrade is provided. The cross-sectional profile of the embankment made of loess-like loam with consistency index  $0.21 < J_L \leq 0.3$ , with the reinforced protective layer is shown in Figure 7.





**Fig. 7.** Cross-sectional profile of an embankment made of loess-like loam with consistency index  $0.21 < J_L \leq 0.3$ , with a reinforced protective layer

## 4 Conclusion

Theoretical studies of the bearing capacity of loess-like loam subgrade, perceiving the vibrodynamic impact of passing trains, occurring at a speed of 200 - 250 km/h, give grounds for the following conclusions.

1. Under the action of vibrodynamic load there is a decrease in the bearing capacity of the main site of the earth bed poured from loess-like loam. So at train speed of 250 km/h bearing capacity decreased by 1,5 times in vertical plane and by 1,3 times in horizontal plane in comparison with static load. This fact indicates the necessity to take into account the action of vibrodynamic load in calculations of strength of embankments constructed from loess-like loam.

2. loess-like loam in the solid state ( $J_L \leq 0$ ) have high bearing capacity providing reliable operation of the earth bed. With increasing consistency index the bearing capacity decreases. Loess-like sandy loam with consistency index up to 0.21 provides the required strength of the main site for the operation of the earth bed, when trains move at speeds up to 250 km/h. At consistency index from 0.21 to 0.29 the earth bed operates in conditions of absence of the required safety margin.

3 Based on the calculation of the strength of the earth bed, the variants of the earth bed design are presented, which provide the required strength of the earth bed made of loess-like loam with consistency index  $0.21 < J_L \leq 0.3$ , for high-speed train traffic. The presented embankment transverse profiles can be recommended for use.

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