Improving the Effectiveness of Strengthening Slopes of the Embankment

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Abstract. A study was conducted to assess the stability of soil slopes of the subgrade of roads and railways. The main causes of destruction (erosion) and loss of stability of the soil slope of great steepness are considered. The modern methods of strengthening and protecting the slopes of the embankment from erosion and sliding under its own weight are analyzed. The method of strengthening slopes with shotcrete is considered in detail. Recommendations are given on increasing the efficiency of the use of shotcrete while strengthening the soil slopes of the subgrade embankment. Mathematical modeling of the stability of the slopes of the subgrade with a laying from 1: 1 to 1: 0.25 is carried out, the stability of the steep slopes is also considered. Using modern software systems, the finite element method has been used to evaluate the stress-strain state and stability of the slope of the subgrade.

1. Introduction

Due to the intensive economic development of the country and the construction of new modern buildings and structures, there is a need for the construction of modern roads in a number of regions of the Russian Federation that differ in complex soil conditions. The complexity of the design and construction of roads in such areas, the need to use modern materials and methods, as well as individual solutions related to ensuring the stability of the structure, are due to the increased requirements for the reliability, durability and safety of the structure during construction and during operation [1, 2].

The stability of the slope of subgrade and road excavation is one of the most important characteristics, ensuring a long service life of the road structure. It is influenced by many external factors: waterlogging, erosion, seismic activity, soil conditions of the design area, the climatic conditions of the area [3, 4].

These factors directly affect the design of the road: its characteristics in plan view and longitudinal profile, the structure of cross-section of road and the slope ratio. All this imposes certain limitations - designers are forced to take into account more different features of the construction area, and if the design conditions do not allow the use of existing methods and standard solutions to increase or maintain the stability of slopes, they change the direction of the designed road, increasing its construction length and, as a result, the cost of construction [5].

The existing methods for slope protection, which are most often used in the design and construction of roads today, fulfil their functions and increase the stability of slopes, but do not provide complete protection against erosion, due to their design defects, which affects the service life of the facility [5 - 7]. Violation of the stability of the slope of subgrade or excavation will be caused by the inability of the
protection to fulfil its functions in the long term and will threaten the safety of road users [1, 8, 9]. In addition, the erosion of slopes over a long period can lead to the complete destruction of the road and paralyze traffic for an indefinite period, which will cause significant economic losses and disrupt freight traffic between settlements.

2. Modern methods for slopes protection
In the road construction, geosynthetic materials or concrete cloth and cast-in-place reinforced concrete constructions are mainly used to increase the stability of slopes [6, 10 – 13].

Geogrid is usually used for strengthening the slopes of embankments and excavations, which is a cellular structure heat-welded from strips of high-strength material. By tension, a horizontally and vertically stable grating is formed in the working plane, which is designed to reinforce the topsoil filling the geogrid cells. The operating principle is the following: increasing adhesion between the topsoil and the soil of slope by elements perpendicular to the surface of the slope - geogrid cells. This wedging allows the geogrid to break the continuity of the sliding surface and to resist the shear of slope. The main function of the geogrid is to limit shear deformations and strengthen soils in various climatic and hydrogeological conditions.

Precast reinforced concrete structures are most often used as retaining walls, combining the functions of increasing the stability of slopes and the resistance of the structure to an erosion process [10, 12]. The main disadvantage of such structures is their high cost and complexity of installation. That is why precast reinforced concrete structures are being replaced by technologies of reinforcing slopes with concrete cloth and shotcrete.

The concrete cloth technology Concrete Canvas is the most promising. This material consists of two textile layers connected to each other by textile fibers, with a “filling” of cement mixture, the inner surface of which is covered with a PVC layer. The operating principle is to concrete or cover the slope with a layer of insulating material that prevents the influence of external destructive factors on the soil. The ability of the material to cover any uneven surfaces and harden within 24 hours exceeds the strengthening ability of geogrids and cast-in-place reinforced concrete structures.

Shotcrete is another promising method of protecting the slope from erosion [11, 13]. Shotcrete is a method of creating a cast-in-place reinforced surface by applying a concrete mixture under pressure using a shotcrete machine. Shotcrete holds well on any, even vertical and steep slopes and surfaces, does not require formwork, it is not difficult to transport it to the work site, because the flexible transport pipeline easily passes narrow places, and therefore it is possible to work in space-limited conditions.

According to the economic comparison of above-mentioned structures (table 1), it was determined that the concrete cloth is the most economically inexpedient, and the strengthening by geogrids is the most advantageous. The problem of the high cost of reinforcing slopes with concrete cloth is the economic inexpediency, which is caused by the high cost of the material purchased from the supplier, due to the mark-up on transportation from the manufacturing country (United Kingdom).

| Method for slope protection | Geogrid | Concrete cloth | Shotcrete |
|-----------------------------|---------|----------------|-----------|
| Reinforcement area | 100 m² | 100 m² | 100 m² |
| Cost, ths. rub. | | | |
| Materials and articles | 172,85 | 650,00 | 66,00 |
| Execution of work | 2,13 | 0,62 | 169,20 |
| Overhead costs | 1,41 | 0,36 | 86,58 |
| Estimated profit | 0,79 | 0,24 | 44,80 |
| Total cost, ths. rub. | 177,18 | 651,22 | 366,58 |
| Labour intensity | | | |
| Man hours | 25,92 | 3,09 | 413,94 |
| Machine hours | 0,51 | 0,48 | 245,95 |
When calculating the cost of reinforcement, it was determined that a larger percentage of the total cost, for reinforcements with geogrids and concrete cloth, is materials. For shotcrete, a significant part of the total cost is overheads and estimated profit, because the work is associated with the use of specialized equipment and highly skilled workers. Since the shotcrete method is the most promising in our opinion, it is necessary to calculate the stability of the slopes of the embankment reinforced with shotcrete.

3. Assessment of the stability of slopes of the embankment

The assessment of the stability of reinforcement of natural or artificial slopes is based on the distribution of forces on the surface (Figure 1) and involves the calculation of the stability of the structure based on the calculated value of the stability coefficient \( k_{st} \) and its comparison with the standard (required) value \([k_{st}]\). \[14 - 17\]

\[ k_{st} \geq [k_{st}], \]  

(1)

The system will be in equilibrium under the following condition

\[ T - T' = 0, \]  

(2)

where \( T \) is the shear stress of the soil; \( T' \) is the friction force.

The equation of the method for calculating circular cylindrical sliding surfaces of Karl Terzaghi without taking into account seismic and seepage forces, based on which conclusions are drawn about the effectiveness of reinforcement, is written as follows \([17 - 20]\):

\[
k_{st} = \frac{\sum (N_i \cdot \rho_{gr} + c_i \cdot l_i) \cdot R}{\sum (T_i \cdot R)}
\]

(4)

\[ N_i = Q_i \cdot \cos \alpha_i, \quad T_i = Q_i \cdot \sin \alpha_i, \]

(5)

where \( \alpha \) is the angle of slope between the tangent to the arc of the sliding surface and the horizontal surface; \( \varphi_i, c_i \) – angle of internal friction and specific adhesion of a particular soil on an arc of the surface of a circular cylindrical surface \( l_i \); \( R \) is the radius of the curve of the circular cylindrical sliding surface; \( Q_i \) is the weight of the soil.

The program GenIDE32 was used to solve this problem, namely, the calculation of the slope of the excavation, reinforced by shotcrete using various reinforcing meshes, made of steel and fiberglass.
The calculation model is created from three macrocells with specific coordinates. The stability coefficient of the slope is calculated for the following slope ratios: 1:1; 1:0.5; 1:0.25; 1:0. The height of the excavation in all four cases is 11 meters.

After that, the calculation model is divided into finite elements, which are subsequently assigned the parameters of a particular soil or material and therewith the number of the desired zone is set (Figure 2).

Table 2. Parameters of soils and materials with the serial number of the zone.

| № | N | Gv | E | v | f(Rc) | c(Rc) | Name               |
|---|---|----|---|---|------|-------|--------------------|
| 1 | 1 | -18.4 | 160000.0 | 0.35 | 24.0 | 14.0 | N1 Soft sandy loam |
| 2 | 4 | -19.2 | 35000.0 | 0.27 | 42.0 | 0.0 | N3 Wet. gravel     |
| 3 | 5 | -24.0 | 327272.7273 | 0.2 | 10500.0 | 8500.0 | N4 Shotcrete       |

Figure 2. Parameters of soils and materials with the serial number of the zone.

Given that the main function of reinforcement in concrete is to work in tension and rupture, the calculated modulus of elasticity of reinforcement using fiberglass reinforcement is taken greater, namely, 30,000 MPa, when reinforcement using steel reinforcement has modulus of elasticity of 20,000 MPa.

Since the program does not take into account too narrow finite elements, and the thickness of the reinforcement used in calculation is 15 cm, it became necessary to calculate the modulus of elasticity required for this calculation model \(E_{req}\), considering the calculated value \(E_{calc}\), the calculated thickness of the reinforcement \(t_{calc}\) and the average thickness of layer of the finite elements, performing the role of reinforcement \(t_{fact av}\). The calculated values are presented in table 2 [6, 14, 16].

\[
E_{расч} \cdot t_{расч} = E_{мрет} \cdot t_{фактрс}.
\]

It follows from here that

\[
E_{мрет} = \frac{E_{расч} \cdot t_{расч}}{t_{фактрс}}.
\]

Table 2. Calculation of \(E_{req}\) for the use of various reinforcement

| Slope ratio | Shotcrete with steel reinforcement | Shotcrete with fiberglass reinforcement |
|-------------|-----------------------------------|---------------------------------------|
|             | \(E_{calc}\), kPa                  | \(E_{calc}\), kPa                      |
| 1:1         | 20000000                           | 30000000                              |
| 1:0.5       | 20000000                           | 30000000                              |
| 1:0.25      | 20000000                           | 30000000                              |
| 1:0         | 20000000                           | 30000000                              |
|             | \(t_{calc}\), m                    | \(t_{calc}\), m                      |
| 1:1         | 0.15                              | 0.15                                  |
| 1:0.5       | 0.15                              | 0.15                                  |
| 1:0.25      | 0.15                              | 0.15                                  |
| 1:0         | 0.15                              | 0.15                                  |
|             | \(t_{fact av}\), m                 | \(t_{fact av}\), m                   |
| 1:1         | 1.375                             | 1.375                                 |
| 1:0.5       | 1.604                             | 1.604                                 |
| 1:0.25      | 1.7185                            | 1.7185                                |
| 1:0         | 1.833                             | 1.833                                 |
|             | \(E_{req}\), kPa                   | \(E_{req}\), kPa                      |
| 1:1         | 2181818,182                       | 3272727,273                           |
| 1:0.5       | 1870324,19                        | 2805486,284                           |
| 1:0.25      | 1745708,467                       | 2618562,7                             |
| 1:0         | 1636661,211                       | 2454991,817                           |

After introducing all the required parameters and characteristics, it is necessary to determine the boundary value of the stability coefficient \([kst]\), which is 1.00 in this calculation.

The main part of the calculation begins with determining the minimum value of \(kst\) for slope without strengthening. The calculation model is presented in Figure 3.
Figure 3. Model for calculating the stability of the slope without strengthening.

The coefficient $k_{st}$ [Terz] > [kst], which indicates the fulfillment of the condition, but according to other calculations, this coefficient is less than unity, which indicates the instability of the slope and the need to strengthen it [15, 18]. For steeper slopes, the main coefficient $k_{st}$ [Terz] decreases, which is shown in summary table 3.

The calculation model is designed to solve the problem of the action of body forces - gravity and dead weight. Under the dead load, all material must be in a state of uniaxial compression without the possibility of lateral expansion. The correctness of the solution is checked when deriving the Lode-Nadai coefficient:

$$\sigma_v = \frac{2 \cdot \sigma_2 - \sigma_1 - \sigma_3}{(\sigma_1 - \sigma_3)},$$

where $\sigma_v = +1$ is uniaxial tension, $\sigma_v = 0$ is pure shear, $\sigma_v = -1$ is uniaxial compression. For other values of $\sigma_v$, the material is in a complex stress state (Figs. 4 and 5).

Figure 4. Distribution of stresses $\sigma_v$ in the calculation model.
Figure 5. Distribution of stresses $\sigma_{yy}$ in the calculation model.

The assessment of stability was carried out by the program according to the following methods:

1. Circular cylindrical sliding surface - the program automatically creates many sliding surfaces with a certain step, on each of which the values of stress and strength of the finite elements are calculated, after that the stability coefficient $k_{st}$ is determined for each of them and the minimum $k_{st}$ is taken as the calculated value.

2. Fixed sliding surface - for the calculation, the finite elements are manually set, after that the program constructs the sliding surface on which the selected finite elements will be connected, for which the strength and stress values will be calculated, based on which the minimum calculated stability coefficient $k_{st}$ will be determined.

3. Power function - for the calculation, two finite elements are manually set, after that the program automatically builds a slide line as a power function, selecting the necessary finite elements, then calculating their strength and stress values and determining the calculated stability coefficient $k_{st}$.

According to the results of calculation, a summary table 3 has been compiled, showing the change in the stability coefficient depending on the steepness of the slope and the reinforcement material.

Table 3. Summary table of calculated $k_{st}$ [Terz].

| Slope ratio | 1:1 | 1:0.5 | 1:0.25 | 1:0 |
|-------------|-----|-------|--------|-----|
| Required value $K_{norm}$ | 1,00 | 1,00 | 1,00 | 1,00 |
| Slope without strengthening | 1,04 | 0,92 | 0,85 | 0,90 |
| Shotcrete with steel reinforcement | | | | |
| Circular cylindrical sliding surface | 1,49 | 1,41 | 1,31 | 1,30 |
| Fixed sliding surface | 1,43 | 1,65 | 1,33 | 1,45 |
| Power function | 1,54 | 1,56 | 1,44 | 1,10 |
| Shotcrete with fiberglass reinforcement | | | | |
| Circular cylindrical sliding surface | 1,54 | 1,45 | 1,39 | 1,37 |
| Fixed sliding surface | 1,44 | 1,65 | 1,34 | 1,48 |
| Power function | 1,55 | 1,57 | 1,45 | 1,15 |
4. Conclusions
According to the analysis, it was found that not all the reinforcements are applicable for the same tasks. Concrete cloth or shotcrete are applicable for strengthening rocky soils and steep slopes, geosynthetic materials are most economically beneficial for strengthening non-rocky dispersive soils, but slopes reinforced with shotcrete have the best strength properties.

The idea of improving the shotcrete method has been put forward by replacing the steel reinforcement with fiberglass reinforcement. The idea is due to the large labor costs of the work with the use of steel reinforcing mesh, in addition, steel reinforcement has significant disadvantages compared to composite fiberglass reinforcement. The use of fiberglass reinforcement can lead to a decrease in the total cost of reinforcement and a decrease in the complexity of work.

Using the program GenIDE32, the stability of slopes was calculated and the effectiveness of improving the shotcrete method using composite fiberglass reinforcement was substantiated. The assessment of the stability of slopes of the embankment of various steepness showed that the type of reinforcement in shotcrete does not affect the effectiveness of reinforcement, but the use of fiberglass reinforcement gives slightly better results (2-5%). Thus, taking into account the lower cost of fiberglass reinforcement, its use when reinforcing slopes with shotcrete can be considered economically feasible.

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