https://doi.org/10.30932/1992-3252-2019-17-48-78

Base Soil Reinforcement with Vertical Crushed Stone Columns in Cryolithozone



Taisiya V. SHEPITKO **Igor A. ARTYUSHENKO** **Pavel G. DOLGOV**

Shepitko, Taisiya V., *Russian University of Transport, Moscow, Russia.*
Artyushenko, Igor A., *Russian University of Transport, Moscow, Russia.*
Dolgov, Pavel G., *LLC Geotechnical Obosnovanie, St. Petersburg, Russia.*

ABSTRACT

Stabilization of permafrost soils of the roadbed base, constructed with assumption of thawing, thanks to improvement of their strength characteristics, requires development and selection of rational structural and technological solutions.

The objective of the study was to analyze the effectiveness of use of vertical columns of crushed stone in the permafrost zone and their influence on strength characteristics of the soil base. The study has used general scientific methods, modeling, simulation and comparative analysis.

This article proposes a method for improving strength properties of soil of the roadbed base within Obskaya–Salekhard section of the Northern Latitudinal Railway thanks to reinforcement of the roadbed base made with vertical columns of crushed stone, which increases stability of the structure.

The proposed basic technological model of construction of the roadbed includes the following main stages: preparatory stage, 1 stage – arrangement of vertical columns of crushed stone and granular sub-bases, 2 stage – additional compaction with a vibratory roller in case of mismatch of stability of bearing capacity and precipitation of the base to operating standards.

The studied object of the transport infrastructure was simulated both without the use of technology for reinforcing it with vertical columns of crushed stone and with its use. The stability coefficient was calculated, and the theoretical surface of embankment collapse was obtained using Midas GTS NX and Plaxis 2D software packages. The stability test of this structure was carried out both in a flat and in a three-dimensional setting.

The efficiency of using vertical columns of crushed stone to strengthen the embankments constructed on permafrost soils has been shown.

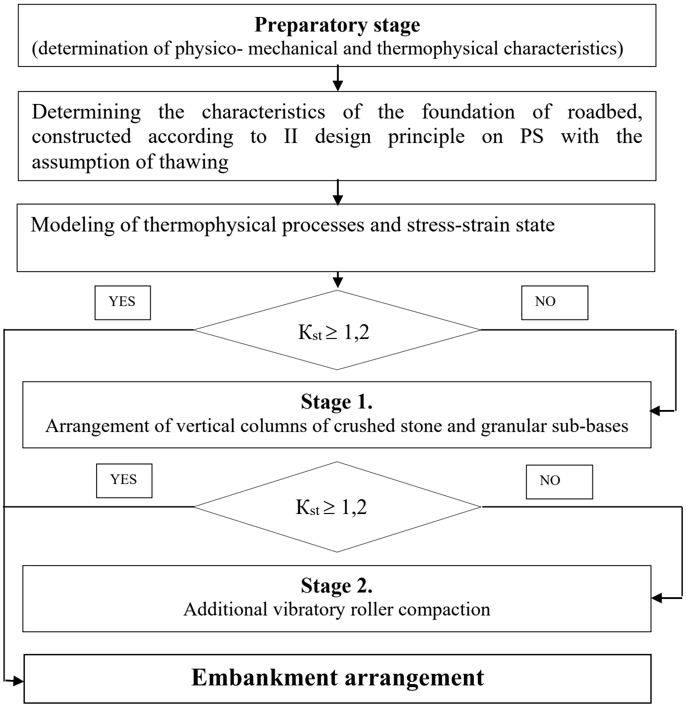
Keywords: transport, railways, roadbed, Northern Latitudinal Railway, permafrost soils, vertical columns of crushed stone, embankment stability, construction, civil engineering.

---

*Information about the authors:
Shepitko, Taisiya V. – D.Sc. (Eng), professor, director of the Institute of Track, Construction and Structures of Russian University of Transport, Moscow, Russia, shepitko-tv@mail.ru.
Artyushenko, Igor A. – Ph.D. student at the department of design and construction of railways of Russian University of Transport, Moscow, Russia, tywka351@mail.ru.
Dolgov, Pavel G. – general director of LLC Geotechnical Obosnovanie, St. Petersburg, Russia, dolgov@geotechfem.com.

Article received 18.04.2019, accepted 11.08.2019.

For the original Russian text of the article please see p. 68.



Pic. 1. Principal model chart of construction of roadbed with the assumption of thawing of permafrost soils using reinforcement with vertical columns of crushed stone: PS – permafrost soils; K_{st} – coefficient of stability of slopes of the embankment.

Introduction. During construction of transport facilities to ensure their reliability, it is necessary to take into account climatic, hydrological and permafrost processes [1; 2], while ignoring those factors could adversely affect not only the progress of construction, but also further operation of the facility.

Objective. The objective of the study is to analyze the effectiveness of use of vertical columns of crushed stone in the permafrost zone and their influence on strength characteristics of the soil base.

Methods. To achieve this objective, general scientific methods, modeling, simulation and comparative analysis were used.

For a reasonable choice of rational structural and technological design solutions, it is necessary to analyze and consider the engineering-geological and natural-climatic factors of the construction area.

For the areas with permafrost soils, a conceptual technology model has been developed intended for construction of the roadbed, erected with the assumption of thawing, using reinforcement with vertical columns of crushed stone.

Vertical columns of crushed stone are one of the methods for stabilizing soft soils, used to increase strength and reliability of the roadbed, compact the soil mass and reduce soil moisture [3, p. 17].

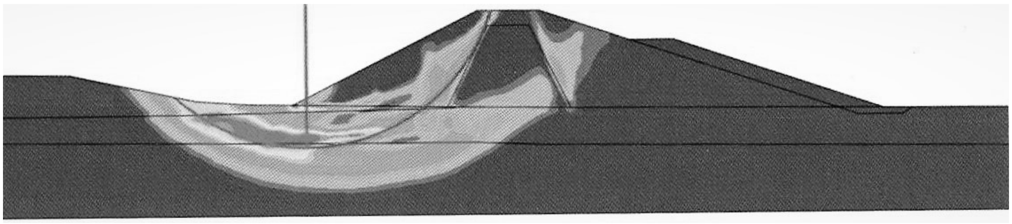
Results.

Principal technology model of reinforcement with vertical columns of crushed stone

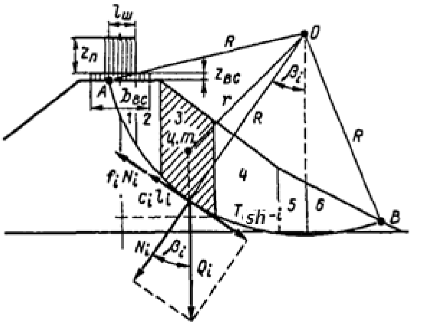
The proposed principal model (Pic. 1) has a block structure that combines the stages of implementation of this technology.

In the preparatory period, it is necessary to provide for the possible impact of negative factors on future foundation of the roadbed and take measures to eliminate them. For this, forecasting of heat engineering and physico-mechanical processes along with technological regulation of parameters of forecasting is carried out. This regards speed of consolidation and thawing, value of relative precipitation, depth of freezing and thawing, soil moisture, thermal conductivity of layers, etc. At the preparatory stage, bearing capacity of the active layer in the base under the embankment under the current operating load is also determined.

I stage of the application of the proposed technology includes arrangement of crushed



Pic. 2. Curved surface of possible displacement [7].



Pic. 3. Scheme for determining K_{st} of the embankment by the method of circular cylindrical surfaces of G. M. Shakhunyants: Q_i is the force acting on the surface of possible displacement, consisting of weight of the compartment and the load on it, which decomposes into normal $N_i = Q_i cos\alpha_i$ and tangential $T_i = Q_i sin\alpha_i$; $f_i N_i$ are friction forces; $c_i l_i$ are adhesion forces.

stone piles and granular sub-bases at the base of the embankment to improve strength characteristics of soils. The functioning of crushed stone piles as vertical drains is determined on the basis of the laws of processes developing in a weak layer [4, p. 12].

At II stage of the implementation of the basic technological scheme, soil strengthening is carried out through additional compaction with vibratory rollers, if the required bearing capacity of the base and stability of the embankment have not achieved in the previous stages.

At each of the stages of the proposed technological chart (Pic. 1), it is envisaged to clarify conformity of stability, bearing capacity and base precipitation to regulatory requirements. It should be clarified that during construction, constant monitoring of the physico-mechanical and thermophysical characteristics of the soil of the base is necessary.

Theory of roadbed design calculation

As the object for modeling, we have taken the section of Northern Latitudinal Railway of new Obskaya–Salekhard railway line limited by points PK 01 + 50-PK 06 + 50.

This section is a slope of the watershed surface of the glacial-marine genesis (m, gm II–III), which is gently sloping towards Vyndyad stream. The elevations are evenly lowering towards the stream. The surface slope averages 3–5°. The geological structure of the section: up to a depth of 6 m, soft-plastic and fluid-plastic loams are revealed; below, at a depth of 7 m, frozen sandy loam is found. Thickness of the seasonally frozen layer is of 1,5–2 m, seasonally thawed layer is of 2,9–3,0 m. An embankment with a height of 6 meters has been designed within the considered section [5, p. 16].

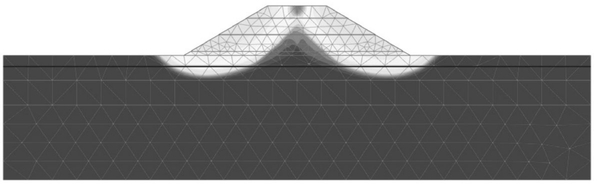
During the study, stability coefficient was calculated and theoretically collapsible surface of this embankment was obtained. The calculation was made by the method of round cylindrical surface of professor G. M. Shakhunyants [6, p. 37].

The stability test is carried out on the basis of consideration of the curved surface of a possible displacement. Such a technique is widespread when performing calculations on possibility of displacing the embankment soil and involving the base in the soil deformation (Pic. 2) [6, p. 37].

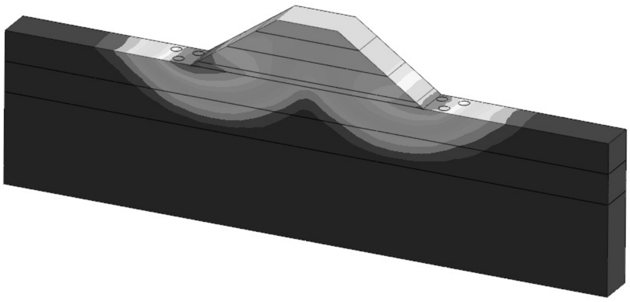
As the curved surface of a possible displacement represents the surface of a round cylinder, calculation of stability reduces to considering the conditions of possible changes in the mass of the soil when it moves along this surface relative to the axis of the round cylinder. The stability coefficient K_{st} of the array is determined in this case as the ratio of the moments of forces relative to this axis O (Pic. 3), resisting displacement, to the moment of forces relative to the same axis, trying to displace it.

Stability coefficient K_{st} is determined according to the formula:

$$K_{st} = \frac{\sum f_i N_i + \sum c_i l_i + \sum T_{irel}}{\sum T_{ish}}, \quad (1)$$



Pic. 4. The theoretically collapsible surface according to the calculation of stability of the embankment at PK 01 + 50-PK 06 + 50 of the section Obskaya–Salekhard of the new Northern Latitudinal Railway line, simulated with the Plaxis 2D software package environment (the minimum value of the stability coefficient is 0,953).



Pic. 5. The theoretically collapsible surface according to the results of calculating the embankment stability at PK 01 + 50-PK 06 + 50 of Obskaya–Salekhard section of the new Northern Latitudinal Railway line, simulated in Midas GTS NX software package environment in three-dimensional space (the minimum value of the stability coefficient is 1,077).

where T_{irel} is the tangential component, resisting the shift of the soil mass;

T_{ish} is the tangential component that seeks to move the soil mass.

The tangential component of shift resistance is determined by the formula:

$$\sum T_{iud} = \sum f_i N_i + \sum c_i l_i \ , \qquad (2)$$

where $f_i N_i$ are friction forces;

$c_i l_i$ are adhesion forces.

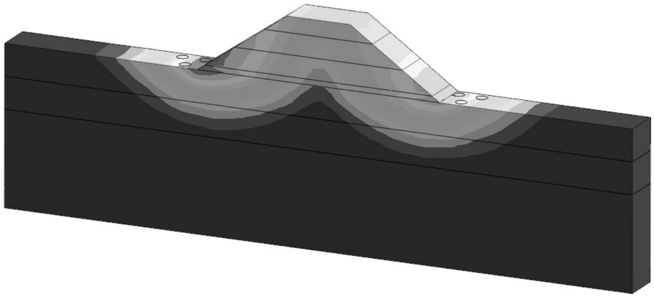
The obtained value of K_{st} is compared to the permissible value of stability coefficient, the normalization of which is given in SP [Construction Rules] 238.132600.2015 [8, p. 70]. If the value of K_{st} is less than the standard value k, then engineering solutions should be applied to improve the strength characteristics of the foundation of the roadbed.

Modeling stability of embankment slopes

As an analytical research tool, the Midas GTS NX and Plaxis 2D software packages were used [9; 10]. The stability test of the studied six-meter embankment was performed in a flat and three-dimensional settings respectively. As a result of calculations, it was found that the stability coefficients were, respectively, K_{st} = 0,953 and K_{st} = 1,077 (Pic. 4, 5).

In accordance with the requirements of the «Instructions for maintenance of the roadbed of railways» [11, p. 13], subject to geometric parameters of the roadbed consistent with roadbed typical cross-sectional profiles, the calculated coefficient of stability of slopes of the roadbed must be at least 1,2.

The calculation showed the need to improve the properties of the soil base. As an option for such an improvement, the decision on reinforcing them with vertical columns of crushed stone, which are intended to improve the weak soil of the base under buildings and structures, was accepted. In that case, the wellbore is formed by the method of vibroflotation, layer-by-layer filling of the well with crushed stone, and tamping of it is carried out using a vibroflotator under the impact of vibration and dead weight using compressed air or a combination of air and water. The next stage was to supply crushed stone to a vibroflotator hopper using a loader, and then through the pipeline to the bottom of the well. Due to reciprocating movements, a pile body is formed with predetermined design



Pic. 6. The theoretical collapse surface according to the results of calculating the embankment stability at PK 01 + 50-PK 06 + 50 of Obskaya–Salekhard section of the new Northern Latitudinal Railway line (the minimum value of the stability coefficient is 1,852).

parameters, which depend on physical and mechanical properties of soils, providing required load-bearing capacity or filtration properties.

For design of vertical columns of crushed stone and a flexible grillage, granite crushed stone of a fraction of 20–40 mm was used.

The use of vertical columns of crushed stone (a material with high shear strength) creates lateral resistance in the soil. Due to the use of vertical columns of crushed stone, strength characteristics of the soil of the base are improved, which reduces settlement of foundations and increases bearing capacity of the soil [12, p. 757].

As well as before strengthening the base soil, after vibroflotation, the stability coefficient of the studied embankment was calculated by the method of circular cylindrical surfaces of professor G. M. Shakhunyants. The calculation results are shown in Pic. 6.

It was found that the minimum value of the stability coefficient was K_{st} = 1,852, which is significantly higher compared to the value of the stability coefficient of the embankment without reinforcing the base (1,077 with Midas GTS NX; 0,953 with Plaxis 2D). From a comparison of the presented Pic. 4–6 it is possible to see how the collapse surface changes: the dangerous slopes of the studied embankment stabilize and return to normal.

Conclusions. Analysis of the operation of the embankment at PK 01 + 50-PK 06 + 50 of Obskaya–Salekhard section of the new Northern Latitudinal Railway line, reinforced with vertical columns of crushed stone, showed that the dangerous sections of the theoretically collapsible surface of the embankment slopes stabilized, the stability coefficient increased to 1,852. The obtained result confirms the technical efficiency of the use of vertical columns of crushed stone to strengthen the embankments constructed with the assumption of thawing on the bases composed of permafrost soils.

REFERENCES

1. Roman, L. T. Mechanics of frozen soils [*Mekhanika merzlykh gruntov*]. Moscow, MAIK «Nauka/ Interperiodika», 2002, 426.
2. Tsytovich, N. A. Mechanics of frozen soils [*Mekhanika merzlykh gruntov*]. Moscow, Vysshaya shkola publ., 1973, 446 p.
3. Pivarč, J. Stone columns – determination of the soil improvement factor. *Slovak journal of civil engineering*, Vol. XIX, 2011, Iss. 3, pp. 17–21.
4. Priebe, H. J. Design of vibro replacement. *Ground Engineering*, 1995, Dec., pp. 31–37.
5. The positive conclusion of the state expertise No. 89-1-4-0465-12. Design documentation and engineering survey results (construction of the new railway line Obskaya–Salekhard) [*Polozhitelnoe zaklyuchenie gosudarstvennoi ekspetizy No. 89-1-4-0465-12. Proektnaya dokumentatsiya i rezultaty inzhernykh izyskanii (stroitelstvo novoi zheleznodorozhnoi linii Obskaya–Salekhard)*]. Salekhard, 2012, 91 p.
6. Shakhunyants, G. M. The roadbed of railways. Design and calculation issues: Study guide [*Zemlyanoe polotno zheleznykh dorog. Voprosy proektirovaniya i rascheta: Ucheb. posobie*]. Moscow, Transzheldorizdat publ., 1953, 828 p.
7. Completed projects of companies using Midas GTS NX. A new level of geotechnical calculations [*Vypolnennie proekty kompanii s primeneniem Midas GTS NX. Noviy uroven' geotekhnicheskikh raschetov*]. Moscow, 2017, 73 p.
8. SP 238.1326000.2015. Railway track [*SP 238.1326000.2015. Zheleznodorozhniy put'*]. Moscow, 2015, 71 p.
9. Midas GTS NX calculation guide [*Posobie po raschetam Midas GTS NX*]. Moscow, 2015, 306 p.
10. Plaxis 2D. User's manual [*Plaxis 2D. Rukovodstvo polzovatelya*]. St. Petersburg, «NIPInformatika» publ., 2012, 182 p.
11. SP 544. Instructions for maintenance of the roadbed of the railway track [*CP 544. Instruktsiya po soderzhaniyu zemlyanogo polotna zheleznodorozhnogo puti*]. Moscow, Transport publ., 2010. [Electronic resource]: https://epk-rzd.ru/wp-content/uploads/2015/09/CP-544.pdf. Last accessed 22.04.2019.
12. Salahi, A., Niroumand, H., Kassim, K. Evaluation of stone columns versus liquefaction phenomenon. *Scientific World Journal*, 2015, Iss. 20, pp. 739–759. ●