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APPLICATION OF NEW TECHNOLOGIES TO ENHANCE THE STABILITY OF HIGH EMBANKMENT SLOPES

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Abstract. This study aims to investigate the stability problems of high road embankment slopes in the Republic of Moldova, revealing shortcomings of classical methods. The authors propose a solution by using the RG system, equipped with specialized vibration drilling equipment from "RTG RAMMTECHNIC Gmbh". The method provides for the creation of piles in deep boreholes using the vibrating d, filling the cavities with soil, with subsequent compaction of soil in stages. Experimental field and laboratory research has demonstrated the effectiveness of this method. The results showed significant improvements in soil properties: increased density, strength, and deformation characteristics. The proposed technology offers advantages such as: increased load-bearing capacity of the soil-pile massif, practically complete elimination of dynamic effects on the ground and structures located in close proximity to the construction site, reduced manual labor costs, and a decrease in the overall cost of the construction work. The study aimed the application of this method in Moldova's road construction, highlighting its potential to counteract slope deformations caused by the action of various factors of any nature. The authors suggest the need for further research for refine the methodology, assess economic feasibility, and perform stress-strain analysis using the Finite Element Method. The study was concluded by outlining plans for future research on embankment slopes stabilized by soil piles using the RG installation.

Keywords: *embankment, slope, stability, soil pile, vibrodriver.*

Rezumat. Acest studiu a avut ca scop studierea problemelor de stabilitate ale pantelor rambleelor înalte ale drumurilor din Republica Moldova, dezvăluind neajunsurile metodelor clasice. Autorii propun o soluție prin utilizarea sistemul RG, înzestrat cu echipament specializat de forare cu vibrare de la "RTG RAMMTECHNIC Gmbh". Metoda prevede crearea de piloți în foraje adânci folosind lancea vibratoare, umplerea cavităților cu pământ, cu compactarea ulterioară a acestuia în etape. Cercetările experimentale, cele de teren precum și cele de laborator, au demonstrat eficiența acestei metode. Rezultatele au arătat îmbunătățiri semnificative ale proprietăților pământurilor: densitate sporită, rezistență și caracteristici deformaționale majorate. Tehnologia propusă oferă avantaje precum capacitate portantă sporită a masivului de pământ-piloți, eliminarea practic completă a efectelor dinamice asupra pământului și structurilor situate în imediata apropiere a șantierului, costuri reduse pentru munca manuală și o scădere a costurilor totale al lucrărilor de construcție. Studiul a avut ca scop propunerea aplicării acestei metode în construcția drumurilor din Moldova, subliniind potențialul său de contracarare a deformării pantelor cauzate de acțiunea diferitor factori de orice natură. Autorii sugerează necesitatea efectuării unor cercetări suplimentare pentru perfectarea metodologiei, evaluarea fezabilității economice și efectuarea analizei de tensiune-deformare folosind Metoda Elementului Finit. Studiul sa finalizat prin conturarea unor planuri pentru viitoarele cercetări privind asigurarea stabilității pantelor rambleelor înalte stabilizate cu piloți de pământ folosind instalația RG.

Cuvinte cheie: *rambleu, pantă, stabilitate, piloți de pământ, vibrator.*

1. Introduction

The analysis of surveyed embankments condition of Moldova's roadways indicates that in majority of cases, the stability of slopes is not fully ensured, as required by regulatory documents [1]. Examples include landslide deformations of the high embankment slope bypassing the city of Ialoveni, deformations of viscous-plastic flow in 8 embankments along the Chisinau−Poltava roadway, among others.

The complex engineering-geological conditions during construction often lead to frequent instabilities of embankment slopes of artificial structures on roads not only in Moldova. For example, in various regions of Ukraine, 33% of embankments with a height of more than 9.0 meters are deformed. The most frequent occurrences were observed in embankments constructed from clayey and loamy soils [2]. It is important to note that critical deformations occurred sometime after the construction of the embankments. This circumstance forces designers to apply of various additional measures to ensure the safety of such road sections throughout their operational lifespan.

However, it must be acknowledged that in the situation of the Republic of Moldova, even the adoption of radical measures in complex cases, especially if the destruction affects the roadway, as exemplified by the incident on the "Ialoveni's embankment", cannot entirely guarantee the long-term stability of embankment slopes during the operational period of a high embankment.

The assessment and assurance of the stability of artificial structures' slopes have been extensively examined in numerous works of domestic researchers: Cirlan A.V., Polcanov V.N., Rascovoi A.D., Syrodoev G.N., Timofeeva T.A., Ceban O.S., and foreign researchers: Budin A.Y., Dobrov E.M., Ginzburg L.K., Goldstein M.N., Harr M.E., Henkel D., Kazarnovsky V.D., Maslov N.N., Matsyi S.I., Skempton A.W., Shadunts K.Sh., Shakhunyants G.M., Šuklje L., Terzaghi K., Vyalov S.S. and many others [3-16].

In the publications of Polcanov V.N. and his students, the stability issues of artificial structures' slopes and natural slopes are examined from the position of the physical-technical theory of creep by Prof. Maslov N.N. [3].

Particular attention is given to the possibility of strength reduction of clayey soils over time as a result of structural cohesion failure and under the influence of other factors [4-6].

The nature of the strength of clayey soils cannot be fully elucidated. Hence, there are numerous cases of disturbance of slopes stability of embankments, excavations and natural slopes, deformations on which affect the subgrade of roads and railways [7].

Many leading scientists have repeatedly drawn attention to the difficulties that may arise due to underestimation of possible changes in the behavior of clays composing the slopes of artificial structures [8-10].

The key issue was the choice of design strength parameters when assessing the long-term stability of slopes and embankments [11, 12].

The operational safety of the structure and the need for the development of additional anti-deformation and anti-landslide measures will depend on how accurately stability calculations are performed [13].

Currently, debates over the choice of the calculation method for assessing the degree of slope stability are practically concluded. Numerical methods based on the Finite Element Method (FEM) have replaced engineering calculation methods, allowing for the creation of a spatial model and the calculation of the most probable slip surface [14-16].

To a lesser extent, inexpensive methods for ensuring slope stability have been developed for cases where it is necessary to increase the factor of safety.

In the Republic of Moldova, traditional methods are typically employed to ensure the stability of embankment slopes, including the construction of counterforts, including widening of the main platform, the installation of retaining walls made of driven and bored piles, the implementation of drainage systems, etc.

Modern methods such as jet grouting piles, "RITA" piles, which are a type of bored pile using discharge-impulse technology, and others, are not utilized due to the absence of corresponding equipment in the republic.

In order to strengthen the slopes of high embankments, more than 20 m high, engineering technologies used in China to solve the problems associated with the possible development of landslides on slopes can be used [17]. These can be: multi-point anchored piles, soil nailing strengthened by driven pipe grouting technique, cantilever piles, application of complex soil reinforcement scheme, etc.

A very promising method is the introduction of smart geogrids, which can both reinforce and monitor the stability for geogrid-reinforced slopes and embankments [18].

A good result to improve slope stability can be achieved through the use of Glass Fiber Reinforced Polymer (GFRP) polymers, used in many civil engineering applications [19].

The most economically efficient method for stabilizing earth structures at present is considered to be the use of geosynthetics [20]. Mulyono A. and other researchers suggest not overlooking the use of vegetation, which is one of the alternative technologies for preventing shallow landslide occurrences [21]. It should be noted that this method, as well as berms recommended by Arun Kumar Bhat [22] are used in Republic of Moldova to improve the characteristics of embankment slopes.

The analysis of publications and identified cases of deformations indicates that the development of methods to improve the stability of embankment slopes of roadways subgrade, remains a pertinent issue, requiring resolution.

In light of the above, the main objective of the present research was to substantiate the possibility of using soil piles made using RG-installation to improve the stability of embankment slopes/excavations.

2. Materials and Methods

To increase the stability of embankment slopes, the authors proposed using methods of deep compaction by means of soil piles, including the RG system.

The company "RTG RAMMTECHNIC Gmbh" is part of the BAUER Group. Through innovation and the implementation of modern technology, RTG has developed equipment with the highest performance in the market for pile construction and structures.

Piles were created using deep drilling vibrators. The hydraulic bucket located at the bottom of the installation created a cavity through horizontal oscillations. After the vibrator emerged on the surface, the cavity was filled with a concrete mix delivered by a pump.

Additionally, the construction of soil piles and widened piles made of gravel is also possible, Figures 1 and 2.

The methodology of preparing the foundation using ground borehole devices is not new [23, 24]. However, in the proposed technical solution, the drilling of boreholes was carried out with a vibrating drop under high pressure transmitted to the soil.

When filling the drilled hole with soil, the RG installation was used in conjunction with a "light" bulldozer, Figure 2.

The advantage of the proposed technology for stabilizing the embankment slopes/excavations, compared to traditional methods, is expressed in the following ways: increased load-bearing capacity of the soil-pile massif; practically complete elimination of dynamic effects on the ground and structures located in close proximity to the construction site; reduced manual labor costs; and a decrease in the overall cost of the construction work.

Figure 1. General view of the RG installation

Figure 2. Filling the drilled well with soil and its compaction

Due to the partial displacement of soil during drilling, the upper part of the compacted mass (buffer layer) was decompacted. This layer was subsequently removed or recompacted. The thickness of the buffer layer was determined by the expression:

$$h_c = d_c \cdot k_b, \tag{1}$$

where: d_c – diameter of the borehole assumed during its drilling with an impact projectile, $d_h = 1.2d$ (d, diameter of the tip, m); k_b – proportionality coefficient, accepted based on empirical data, equal to: for loams $k_b = 4$; for loams $k_b = 5$, and silts $k_b = 6$.

An alternative to the mentioned conventional method is a new technical solution proposed by the authors for soil compaction in embankment slopes. This solution is based on the installation of soil piles using a vibrodriver on the RG installation. The feasibility of using the RG installation to increase the bearing capacity of the foundation was studied by Rascovoi A. [25].

The assessment of the effectiveness of using the RG vibrodriver for constructing soil piles was based on a comparative analysis of the physical, strength, and deformation properties of soils before and after compaction. Additionally, the analysis involved the interpretation of images obtained through scanning electron microscopy (SEM) VEGA TS 5130, whose uniqueness allows obtaining information about the nature, composition, and structure of the soil, Figure 3.

The preparation of soil samples for electron microscopic studies and subsequent analysis were carried out in the laboratory of the National Center for Research and Testing of Materials at the Technical University of Moldova.

The experimental part of the study was conducted on three test sites consisting of loams and sandy loams with reduced density characteristics. Soil compaction was carried out by constructing soil piles using conventional drop hammer driving, as well as with the use of RG installation.

Figure 3. Microstructure investigation using SEM

3. Results and Discussion

Experiments conducted at the first test site showed that when drilling a hole with a diameter of 0.6 m using the conventional method, the dry soil density increases by an average of 0.1 g/cm^3 within a distance of up to 1.5 m from its axis. After the pile shaft was made, it increased by an average of 0.25 g/cm^3. The strength indicators were significantly improved. Specifically, the cohesion, which is a key characteristic determining the stability of embankment slopes, increased by 4.5 times compared to the initial values.

Deep soil compaction using ground pile devices was achieved by drilling holes with soil displacement to the sides, creating compacted zones around them. The drilled holes were backfilled with local loam with layer-by-layer compaction. When the holes were spaced at specific distances (from 2.5 to 5 diameters), a mass of compacted soil was formed, characterized by increased strength and deformation properties and lower compressibility.

Currently, driven ground piles are successfully used in construction, replacing expensive reinforced concrete driven and drilled piles.

Among the recent examples is the construction of the sports complex "Arena-Chisinau" in Stauceni, where 7000 soil piles were made to eliminate soil settlement issues.

On the second and third sites, compaction was carried out using the RG installation.

The assessment of changes in physico-mechanical properties due to compaction was carried out in the Ingeotehgrup laboratory on samples taken from the pile shaft and from holes drilled at specified distances from its center.

Tables 1 and 2 present the results of laboratory studies on soils and the pile shaft after compaction, compared with the average values of corresponding characteristics determined under natural conditions.

Analysis of the obtained results showed that the soil in the pile shaft exhibited high values of physico-mechanical properties:

- Dry soil density increased by 1.2 ÷ 1.4 times.
- Deformation modulus increased by 2 ÷ 4.5 times.
- Internal friction angle increased by 1.1 ÷ 1.7 times.
- Total cohesion increased by 2.9 ÷ 5.4 times.

To determine the dimensions of the compacted zone, studies on the microstructure of naturally occurring soils and soils after compaction were conducted. Samples were taken from the pile shaft and from excavations located at distances of 40, 60, and 80 cm from its outer boundary. The sampling depth was 2.5 m.

Table 1

Comparison of soil physical parameters

Soil type	Plasticity index I_P	Soil flow index I_L	Soil density ρ, g/cm^3	Humidity W, %	Dry soil density ρ_d, g/cm^3
The loam under natural conditions	12	< 0	1.57	12.0	1.39
The loam after compaction	8 ÷ 12	< 0	1.88 ÷ 2.09	8.0 ÷ 12.0	1.61 ÷ 1.91

Table 2

Comparison of mechanical properties of soils

Soil type	Relative subsidence ε_{sl}, ($P = \sigma_{zg}$)	Initial subsidence pressure P_{sl}, kPa	Deformation modulus E, MPa	Internal friction angle φ, degrees	Total cohesion c_w, kPa
The loam under natural conditions	0.002 ÷ 0.04	22 ÷ 212	9	18	16
The loam after compaction	No subsidence		18 ÷ 41	19 ÷ 31	47 ÷ 87

The research results of the microstructure change study are presented in the SEM images, Figure 4.

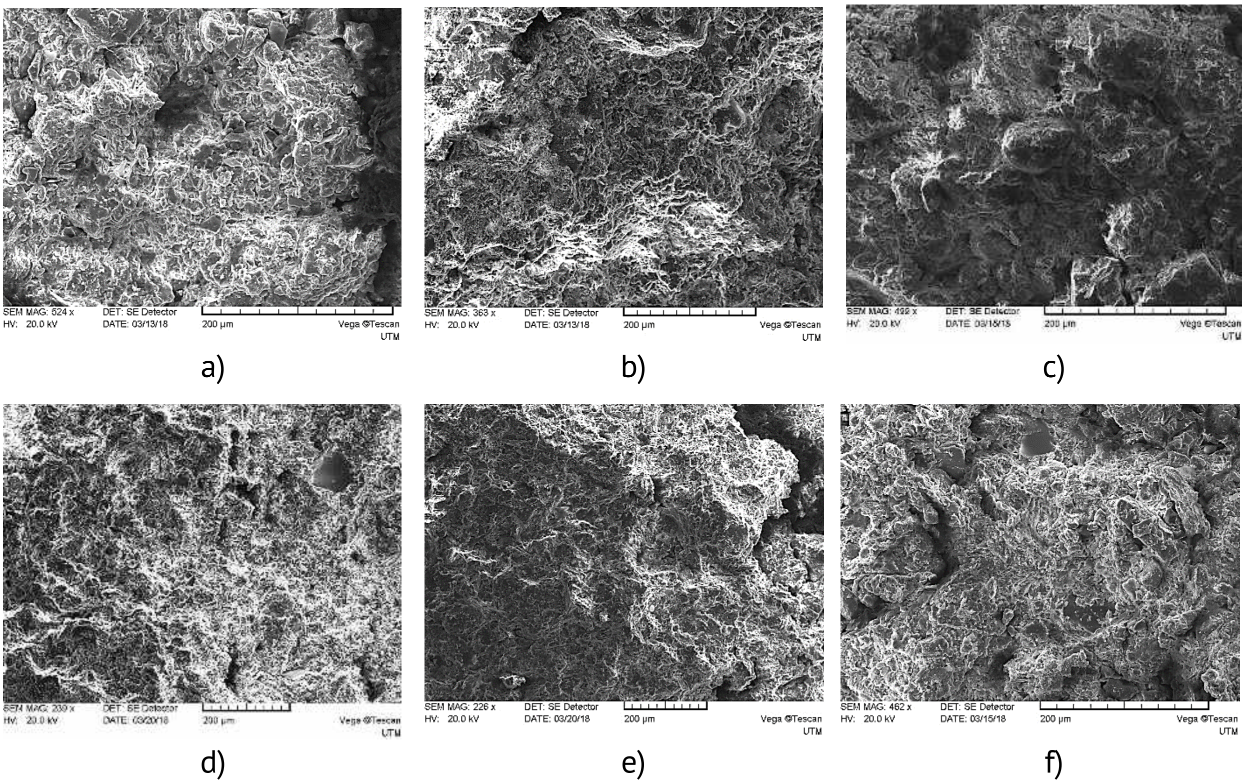

Figure 4. Microstructure of the investigated soil:
a) under natural conditions (before pile installation); b) ÷ f) compacted soil (after pile installation) sampled from the pile shaft (b) and at distances: 20 cm from the pile center (c); 40, 60, and 80 cm from the pile shaft (d, e, f, respectively).

The results of the computer analysis of the ground samples allowed studying the changes in the soil structure depending on the distance from the pile shaft, ranging from matrix to skeletal types [26-28].

It was revealed that the occurring anthropogenic transformations significantly improved the strength and deformation properties of the soil beyond the pile shaft. The analysis of the results of determining the physical-mechanical characteristics of the studied soil samples and studying the microstructure showed that with a diameter of the soil pile equal to 430 mm, the effective spacing between piles should not exceed 1.5 m, the minimum allowable distance in the clear between piles is 0.8 m; the maximum is 1.1 m.

The conducted research leaves no doubt about the improvement of the foundation transformed by the installation of soil piles using a vibratory pile driver. From a technological point of view, the method should be considered relatively simple, yet capable of ensuring significant efficiency in compacting the soils that make up the slopes of embankments.

According to the authors, the method of drilling holes and compacting soil can find wide application in road construction for stabilizing embankment slopes. Considering that, in most cases, slopes deform due to weathering and subsequent moisture infiltration into the soil, compacting with the insertion of additional volume of dry soil will make them less susceptible to the influence of these processes. By driving compacted holes with dry soil or rigid soil materials (gravel, crushed stone, sandy-gravel mixture, coarse sand, slag, etc.), dense masses can be created to prevent deformations and landslide manifestations in embankment slopes.

To enhance the deep compaction effect, it is possible to alternate soil piles with reinforced concrete piles installed in the drilled holes.

When designing the implementation project of this method, the depth of the holes, diameter, spacing between them, and other parameters of deep compaction should be determined based on achieving the required degree of soil density forming the embankment and calculations assessing the impact of the installed piles on enhancing the stability of its slopes.

The feasibility of employing the method using a vibratory pile driver RG-installation increases when the slope height does not exceed 10 to 12 meters. This is justified by the dimensions of the equipment currently available in the republic.

4. Conclusions and Recommendations

The conducted research allows us to discuss the possibility of using ground piles to enhance the stability of embankment slopes.

The data from laboratory tests indicated that the soils of the pile shaft exhibit reliable strength and deformation characteristics, surpassing these values by several times compared to soils in their natural state.

The conducted research has shown that the microstructure of the rocks serves as a sensitive indicator of anthropogenic transformations that occurred in the soil during the installation of soil piles, leading to the formation of a new modified microstructure, significantly different from the original.

The practical significance of the proposed technology lies in the fact that by implementing piles using the RG installation, significant reductions in the volume of work for slope reinforcement are achieved. Additionally, there is an improvement in the physical and mechanical properties of soils, a reduction in filtration characteristics, and consequently, enhancement of erosion control properties.

This technology can be utilized not only in the design and construction of "new" road sections but also in the reconstruction/repair of existing road segments.

The question of the economic feasibility of applying the specified methodology needs to be addressed based on a technical and economic comparison of options for pile installation on real objects.

The current research is planned to be continued with the aim of studying the behavior of the forming soil-pile mass under the conditions of prolonged dynamic loads from road transport and soil moisture, constituting the slopes of the embankment and the pile shaft.

It is anticipated that in the future, a calculation of the stress-strain state of the "pile-soil" system will be carried out using the Finite Element Method (FEM). The reliability of the FEM analysis results will be assessed through testing on problems for which an exact solution is known, and through observations of the condition of the embankment slopes, stabilized by the installation of ground piles using the vibratory pile driver RG-installation.

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