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ENSURING THE LONG-TERM STABILITY OF DEEP CUTTING SLOPES FORMED BY CLAY SOILS ON REPUBLIC OF MOLDOVA ROADS

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Abstract. The article presents research results on identifying the causes of landslide deformations along the M21 road, Brest-Chișinău-Poltava in the Republic of Moldova, using Maslov's physico-technical theory of creep, along with proposals for their stabilization. It highlights the geomorphological and geological characteristics contributing to landslide formation, focusing on the rheological properties of clayey soils. The studies included stability calculations based on laboratory investigations aimed at determining strength and rheological properties. Results demonstrated the dependence between soil moisture and structural cohesion, influencing landslide resistance and creep deformations. Proposed values for residual strength characteristics of clayey soils ensure long-term stability of deep excavation slopes without creep deformations, as well as values allowing economically feasible excavations with partial reduction of structural cohesion without compromising slope stability during operation.

Keywords: *loss of stability, rheology, soil strength, physico-technical theory, creep.*

Rezumat. În articol sunt prezentate rezultatele cercetările pentru identificarea cauzelor deformărilor de alunecare de-a lungul drumului M21 Brest-Chișinău-Poltava din Republica Moldova, folosind teoria fizico-tehnică de fluaj propusă de Maslov. N.N., precum și propuneri de stabilizare a acestora. S-au evidențiat caracteristicile geomorfologice și geologice care contribuie la formarea alunecărilor, cu accent pe proprietățile reologice ale pământurilor argiloase. Studiile au inclus calcule de stabilitate folosind rezultatele investigațiilor de laborator care aveau ca scop determinarea proprietăților de rezistență și celor reologie. Rezultatele au demonstrat dependența între umiditatea pământului și coeziunea structurală, influențând rezistența la alunecare și dezvoltarea deformărilor de fluaj. Au fost propuse valorile caracteristicilor de rezistență reziduală a pământurilor argiloase care ar asigura stabilitatea de lungă durată a taluzurilor săpăturilor adânci, fără a prezenta deformații de fluaj, precum și valorile acestora care ar permite realizarea economica a săpăturilor, cu reducerea parțială a coeziunii structurale, însă fără a afecta stabilitatea taluzurilor pe durata de exploatare.

Cuvinte cheie: *pierderea stabilității, reologie, rezistența pământului, teoria fizico-tehnică, fluaj.*

1. Introduction

In the practice of construction and operation of roads from Republic of Moldova there are many problems due to numerous incidents of landslide processes (Figures 1 and 2).

Figure 1. Landslide processes along the M21 road, Brest-Chisinau-Poltava

Foto: Polcanov Vladimir, May 2015.

Figure 2. Deformation of the left slope of the deep excavation at PC1441+00 of the M21 road, Brest-Chisinau-Poltava

Foto: Cirlan Alexandru, April 2017.

The geomorphological features of the territory determine the execution of deep excavations for the roads design. Undercutting often leads to the development of landslides, which can develop even on the slopes with inclination 5-6°.

In Republic of Moldova were recorded more than 16 thousand landslides. Most of them occupy the middle and upper side of slopes and develop in sand-clay rocks of middle-Sarmatian age (N_1S_2). Typically, landslides are generated on ancient and old landslide displacements, therefore, development of today landslides has inherited character.

Analysis of nature and manifestation conditions of landslide processes on the territory of Republic of Moldova revealed the role of rheological processes in the breaking the stability of natural slopes. At the same time, research has shown that the slopes stability of the road excavations was not studied enough [1].

The need to obtain reliable theories regarding the behavior of earth masses to solve complex engineering problems was postulated as early as Karl von Terzaghi's 1925 publication [2].

In the 1930s, the necessity to address practical problems, particularly the failure of some French dams and the commencement of construction works for the support structures of the hydroelectric power plant on the Svir River in Russia, situated on a thick layer of clays, prompted further research in this direction.

At the end of the 1930s, began the study of rheological processes of soils to determine the types and nature of soil deformations. These deformations were classified into: initially conditioned instantaneous deformations (reversible and irreversible); stable creep (attenuated) and progressive creep, as presented in various studies [3, 4].

Henkel D. J. [5] and Šuklje L. [6, 7] obtained the long-term strength curve, similar to those presented by other researchers, comparing the soil strength at the moment of slope failure with that before failure. They found that over 50-55 years, the soil strength decreased by 2.5−3 times.

Peterson R. provided clear examples of slope failures occurring 1/2−4 years after construction due to a reduction in their strength by up to 50%, as a result of the gradual decrease in soil strength over time [8].

The study of the rheological properties of soils is closely linked to the concept of "soil strength." Dr. B. Tiedemann first presented results on determining residual strength of intact clay structures [9]. Similar tests were conducted by Dr. M.J. Hvorslev in 1937 on two clays consolidated from suspension [10]. In 1952, J. MacNeil Turnbull provided practical guidance for the approximate determination of residual strength in some compacted soils [11].

Skempton A.W. [12, pp. 79-80], while studying the stability of slopes and embankments formed from overconsolidated English clays, addressed the issue of peak and residual strength, as slope stability directly depends on these characteristics. According to Skempton A.W.'s findings, the value of residual cohesion is very small or approximately zero. In other words, during the transition from peak to residual strength, the structural cohesion is completely depleted, and the internal friction angle decreases by 1-2°, and in some cases even by 10°. This statement by Skempton A.W. was contested by several renowned scholars, notably Maslov N.N., who demonstrated that structural cohesion in soils cannot be completely excluded, a point later agreed upon by Skempton A.W. in subsequent works.

Of particular interest is Maslov N.N.'s theory of soil strength, which posits that soil strength depends on the internal friction angle φ_w determined by the state of compaction-moisture and the total cohesion divided into structural cohesion C_c, which does not depend on the soil's compaction-moisture state, and viscous (hydrocolloidal) cohesion Σ_w, characteristic for each compaction-moisture state [4, 13].

In the study of landslide soil strength by scholars from the Goldstein M.N. school, based on the stable effect of loading regimes on strength, the concept of "long-term strength limit" was analyzed as the minimum possible value of strength for infinitely slow deformations during the formation and development of landslides. The reduction in shear strength is explained by increased clay moisture in the shear zone and the realignment of clay particles parallel to the shear direction [14-16].

Marinescu C. mentioned in his work that shear strength is a complex function resulting from the combination of two functions expressing interdependent processes: the physico-chemical characteristics of the soil and the manner in which it is loaded over time [17, pp. 95-96].

Christensen R.W. links clay deformation processes to a combination of recoverable deformations resulting from the bending and rotation of individual particles, and non-recoverable deformations resulting from the relative movement between adjacent particles at their contact points [18].

Considering that strength is largely determined by the duration of loading, some scholars, such as Cristescu S.L., Ștefănică M., Marin M. [19], presenting classical aspects of rheology, emphasize the real-world applicability of these concepts.

In addition to applied static loads, practical and theoretical interest also focuses on dynamic loads such as earthquakes, vibrations, etc. Research by Hu H., Yu D., Gu H. [20] in this direction has enabled the determination of rheological characteristics and the development of a rheological model that considers objective factors such as climate, weather, geological conditions, terrain features, etc.

The present work is focused on identifying the causes of landslide deformation along the M21 road Brest-Chisinau-Poltava in connection with its upcoming reconstruction and the need for such design solutions that will ensure its long-term safe operation.

2. Materials and Methods

For preventing the landslides in the future was identified the following main objectives of research:

- were studied the causes of landslide deformation in deep excavations,
- were received the design values for rheological properties of clay soils involved in landslide movement,
- were proved the economically viable and reliable profiles for slope excavations.

Soil analysis was mainly carried out on samples of the natural structure selected in the target areas destroyed by landslides. Some of the samples were tested after prolonged moisturizing in a sand bath. Indicators of physical properties of soils were determined by standard methods.

To obtain the values of strength characteristics, the direct shear tests were carried out by "fast shear" method.

The rheological characteristics: "creep threshold" and "coefficient of viscosity" were obtained by "constant deformation rate" method proposed by prof. Maslov N.N. [13]. The long-term strength parameters were set in accordance with the views of prof. Goldstein M.N. and his disciples: Turovskaya A.Y., Chernenko N.B., Timofeeva T.A [21, 22].

3. The results of the research

The peculiarities of geomorphological conditions of M21 road Brest-Chisinau-Poltava within the territory of the Republic of Moldova, which borders Ukraine, requires designing a significant number of road embankments, with height from 3-6 up to 15-20 meters and with deep excavations from 6 to 24 meters.

In areas where red-brown silty clay ($aldlQ_{III-IV}$) are a part of geological structure, these soil layers are involved in active deformation. As a result, for these areas are characteristic steep, close vertical, walls of breakdowns with height 12 and more meters. Below, in the clay rocks (N_1S_1) strains are characterized by plastic flow.

Based on the results of field work, existing cross-sections were built and compared with design cross-sections to identify the causes of slope deformations (Figure 3).

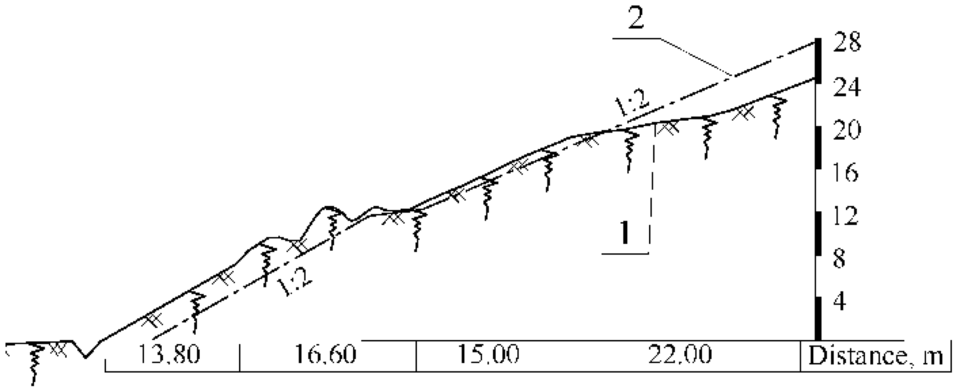

Figure 3. Schematic cross-section of left slope excavation:
1 – existing cross-section; 2 – design cross-section.

An analysis of the available material revealed the deformation confined to the watered clay sequence. Their main reason is the considerable steepness of slopes that the design was administered without regard to characteristics of clay rocks, causing the possibility of creep deformation and strength reduction of clay soil in time under the influence of long-acting shear stresses, as well as processes of weathering and additional moisture during rainfalls or other precipitations.

In order to study rheological parameters, soil sampling and laboratory tests were performed to determine: soil strength, creep threshold, and coefficient of viscosity.

The research results for strength of clays revealed natural moisture content in the range of solid consistency is primarily manifested discreteness factor that reflects the structural and textural characteristics of soil and degree of impairment of structural connections through natural zones of weakening defining the nature of deformation of hard clays, and the overlapping impact on the strength of strata of density, moisture content and consistency.

This is true not only for the majority of the studied landslides Neogene-Quaternary clay rocks in Moldova, but for Neogene clays of Odessa and Caucasus, which are forming landslide slopes. Factor of consistence, reflecting the role of hydrocolloidal cohesion in the overall cohesion and coefficient of viscosity, begins to manifest itself in transition from solid samples in to a semi-solid and semi-plastic state, and it's more determining for the character of deformation in plastic clays.

An approximate relationship $\tau = f\ (I_L)$ has been used for the samples, tested by the method of "prepared surface of shift", which simulates the loss of structural cohesion. Using the method of density-moisture by prof. Maslov N.N., dependence of internal friction angle and hydrocolloidal cohesion on the consistency was obtained (Figure 4).

The performed studies of the strength properties allowed at this stage to disclose the excavation with recommended design strength characteristics [23]:

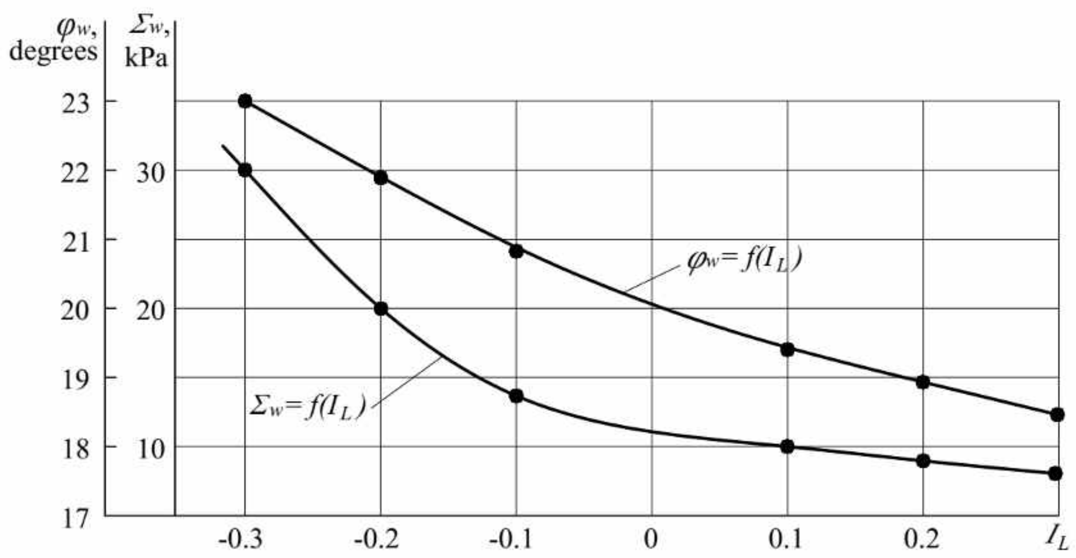

Figure 4. Graphs of the dependence of hydrocolloidal cohesion (Σ_w) and the angle of internal friction (φ_w) on consistency (I_L)

- excluding the time factor and the presence of weak areas, with possible failure of cohesion due to the additional moisturizing: for the depth $h \leqslant 15$m – φ=16°; C=44kPa; for h>15m – φ=16°; $C=\Sigma_w+0.5\cdot C_c$=85kPa;
- including the time factor: for the depth $h \leqslant 15$m, φ=16°; Σ_w=20kPa; for h>15m – values of residual strength φ=10°; Σ_w=9kPa;

In order to study the possibility of transition of the clay soils, which are forming the slopes of the excavations, in the state of creep, were determined by "creep threshold" values.

According to Maslov N.N. [4, 13], its theoretical expression is defined by Eq. (1):

$$\tau_{\lim} = p_n \cdot \mathrm{tg}\varphi_w + C_c \quad (1)$$

The process of creep in all cases will proceed under the influence of the remaining part of the shear stress Δτ, defined by Eq. (2):

$$\Delta\tau = \tau - \tau_{\lim} = \tau - \left(p_n \cdot \mathrm{tg}\varphi_w + C_c\right) \quad (2)$$

in the above expressions:
Σ_w – hydrocolloidal cohesion, kPa;
C_c – structural cohesion, kPa;
φ_w – true angle of internal friction, degree;
p_n – normal stress, kPa.

In most cases applied to the Neogene clays in Moldova, the local environment deprives us from the possibility of direct use of theoretical expression of determining the values of the "creep threshold" for natural soil structure. In these conditions, it is associated with exceptional heterogeneity of the rock.

It should be noted that despite the presence of considerable research in "creep threshold" this issue couldn't be considered fully resolved to this day. It attributes this fact, in particular, to an undisclosed feature of the nature of hard structural cohesion (C_c).

Rigid structural cohesion connections may have ionic nature; defined by cementation, crystallization, etc. In all cases, they are irreversible. However, studies carried out by Acad. Kazarnovskii V.D. show that hydrocolloidal nature of cohesion (Σ_w) in clay soils of hard and semi-solid consistence, which we encounter in the study of rocks that form the slopes of Moldova, may also condition the nature of the irreversible fragile shear strain. Thus, it is possible to determine to greater or lesser degree, the value of "creep threshold", like the rigid connection of the structural cohesion (C_c). This question is still not studied enough. However, in terms of rheological analysis, it has a primary importance.

In these circumstances, there is no way to fully trust the theoretical schemes and necessity to establish calculated values of "creep threshold" for the selected species of soil experimentally. Experiments were carried out on a "constant speed" by the method of Sotnikov S.N., improved by Polcanov V.N. It was performed more than 50 experiments lasting from 1 to 40 days at a speed $v=a\cdot10^{-8}...a\cdot10^{-10}$m/s. The samples were tested at natural moisture content, and after, were moisturized in boxes with wet sand. This allowed determination of the "creep threshold" in the range from solid to semi-plastic consistence and plotting graphs of it dependency on the consistency (Figure 5).

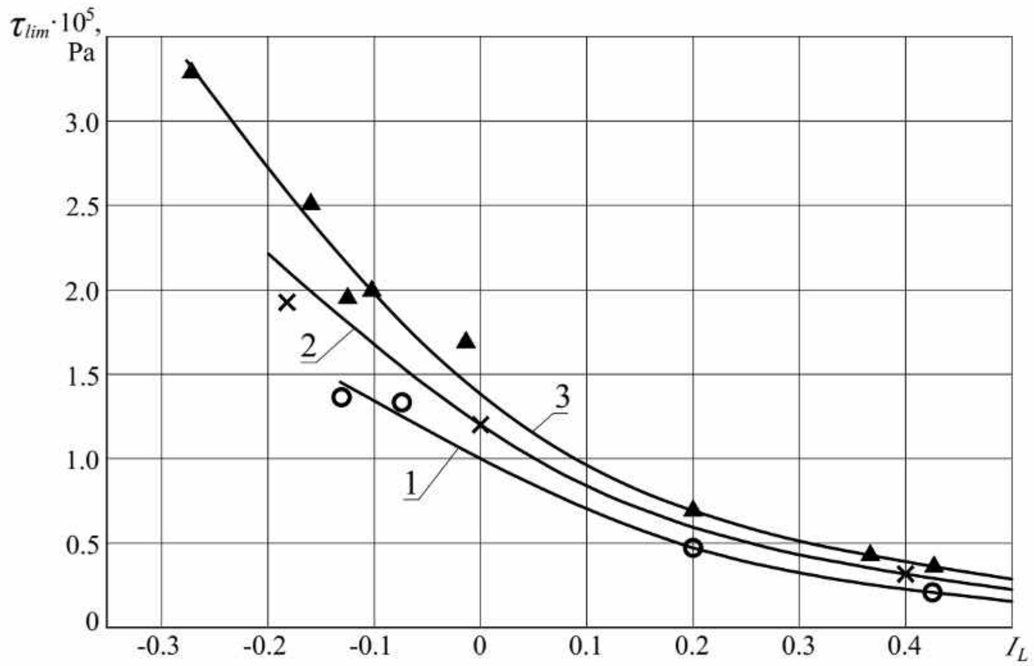

Figure 5. The graphs of dependence between "creep threshold" (τ_{lim}) of Neogene clays from cover layer and consistency (I_L), for diferent values of vertical loading, by tests with $v=5.8\cdot10^{-10}$m/s:
1 – for vertical loading p=1×10^{5}Pa; 2 – for p=2×10^{5}Pa; 3 – for p=3×10^{5}Pa.

Following the processing of the experimental data were obtained the expressions characterizing "creep threshold" (τ_{lim}) for clays from different zones of the landslide massif. These expressions are presented in Eq. (3):

$$\tau_{\lim,1} = 0,16p_n + 40\,kPa \text{ – for cover layer;}$$
$$\tau_{\lim,2} = 0,25p_n + 75\,kPa \text{ – for the bedrock layer;} \quad (3)$$
$$\tau_{\lim,3} = 0,09p_n + 9\,kPa \text{ – for the landslide displacement zone.}$$

These equations have been used during the rheological analysis. The possibility of development of creep deformation in the fundamental and cover stratum, as well as in the weakened area of their contact.

For the forecast of speed of creep deformation in slope excavation was used the dependence between viscosity and consistency. This allowed to establish the speed of the displacement of the cover array applied to the calculated index of liquidity (I_L).

Given the exceptional importance of the calculations for estimating the rate of creep surveyed landslides, similar calculations were performed for different values of the coefficient of viscosity (η) and degree of preservation primary structure of the soil (Figures 6-7).

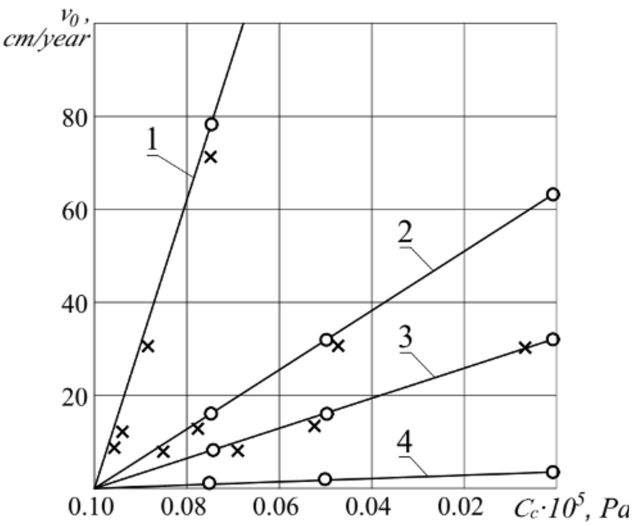

Figure 6. The graphs of dependence between speed of creep deformation (v_0) and structural cohesion (C_c) for different values of coefficient of viscosity (η):
1 – for $\eta=10^{11}$ Pa·s;
2 – for $\eta=5\cdot10^{11}$ Pa·s;
3 – for $\eta=10^{12}$ Pa·s;
4 – for $\eta=10^{13}$ Pa·s.

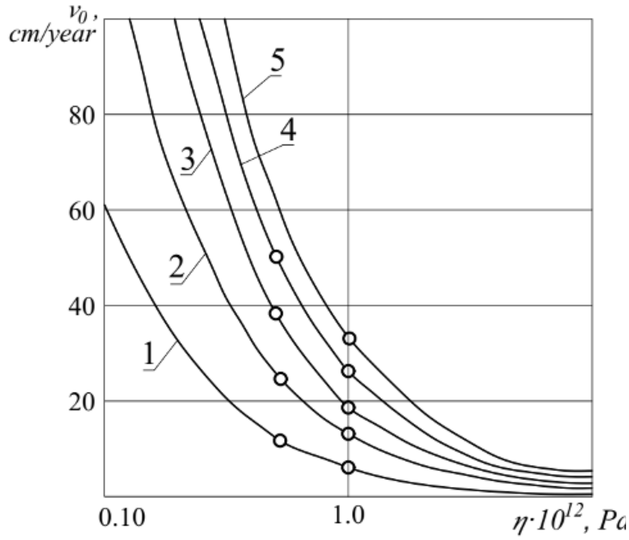

Figure 7. The graphs of dependence between speed of creep deformation (v_0) and coefficient of viscosity (η) at different values of structural cohesion (C_c):
1 – for C_c=0.08·10^5 Pa;
2 – for C_c=0.06·10^5 Pa;
3 – for C_c=0.04·10^5 Pa;
4 – for C_c=0.02·10^5 Pa;
5 – for C_c=0Pa.

It was found that in a soil with hard structural cohesion (C_c) defined by value approximatively equal to C_c=10kPa, speed of landslide displacement is practically zero. Essential value has the viscosity of the soil: if C_c=8 kPa, and $\eta=10^{11}$ Pa·s, v_0=60cm/year; at the same values of C_c and $\eta=10^{13}$ Pa·s, v_0=0.

Comparison of theoretical speeds creep deformation and actual field data for the dynamics of the landslide deformations on the surveyed sites has given satisfactory results.

In other words, the calculations and field studies were indicate the possibility of landslide movement with intensity of the order of several centimeters per year, followed by acceleration in time as a result of constant manifestation of creep.

As noted above, development of active deformation of slopes excavations is due to fall of watered strength in clay soils as a result of creep processes under the influence of tangential stresses caused by excessive steepness of slopes. In connection with the areas for future reconstruction on the results of exploration and of the research proposed by typification of the excavations by their geological structure. At the same time, based on the available materials and complexity of engineering-geological conditions, the following type's solutions were offered:

1. excavations, disclosed in homogeneous soils;
2. excavations, disclosed in sand-clay soils;
3. excavations, disclosed in difficult conditions, macroscopically homogeneous, sometimes watered, sand-clay soils.

For excavations with the known geological structure were constructed profiles of equal slope stability (with safety factor *K*=1.2), taking into account the rheological characteristics of clay soils, obtained during the executed researches (Figure 8).

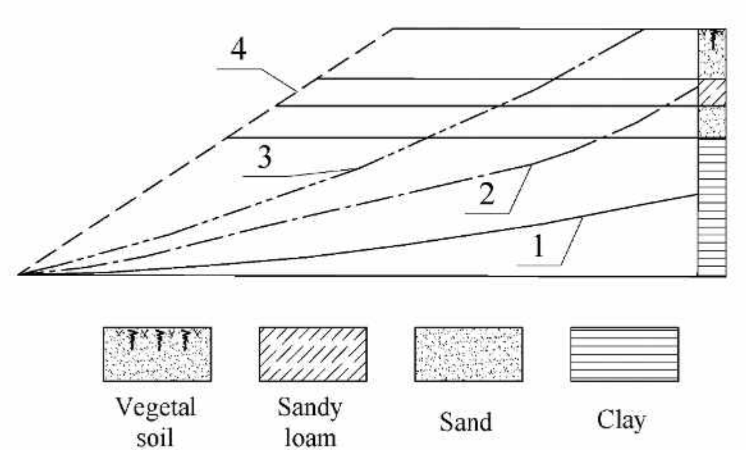

Figure 8. The cross-sections of excavation on P14375-14379, designed taking into account the rheological properties of soils:
1 – for C_c=9kPa, ϕ=5° (respectively $S=0.09p_n+9$kPa);
2 – for C_c=40kPa, ϕ=9° (respectively $S=0.16p_n+40$kPa);
3 – for C_c=65kPa, ϕ=12° (respectively $S=0.21p_n+65$kPa);
4 – for slope ratio 1:1.5.

As it is known, the real stability reserve is determined by the validity of the selected characteristics. Because of this, the main difficulty is to assess the accumulation time critical deformation, which in turn depends on the adopted "parameters" long-term strength ("creep threshold", "residual strength" and others.) The latter does not have a clear definition and require concretization and the accumulation of research results.

4. Conclusions and recommendations

1. Studies were show clay rocks in the bedrock have high values of rheological parameters. As a consequence, the development of the creep deformation in the strata at the depth of the bed-rock clays without visible surfaces of weakening were excluded.

2. The emergence of local surface displacements accrues at the cover stratum, which do not affect the overall stability of the slope.

3. Development of creep deformation by the weakened zones was confirmed by landslide manifestations, which took place on the slopes of excavations.

4. Essential influence on the speed of displacement was rendered by the coefficient of viscosity of soil (η). When $\eta=8\cdot10^{11}$Pa·s, and the value of structural cohesion C_c=8kPa, the displacement speed can reach values v=60cm/year. With the same value of the structural cohesion and the coefficient of viscosity $\eta=5\cdot10^{13}$Pa·s – the rate of displacement is reduced to zero.

5. Excavations, whose cross sections were designed based on the average statistical strength values (S=0.29p+65kPa) were found to be unstable. The deformations of their slopes were traced after 10 years on all the studied areas of the road.

6. The study of the rheological properties of the soil ensures the right choice of design parameters for design strength profiles slopes of deep excavations and allows to prove the need of protection measures to prevent the possibility of creep deformation.

7. Disclosure excavations by residual strength (S=0.09p+9kPa) eliminates the possibility of further development of deformation, it is uneconomical and impractical.

8. Long-term slope stability is provided by the disclosure of excavations in view of the rheological properties of soils. In these cases, the equilibrium condition is reached, assuming the partial destruction of the structural cohesion (S=0.16p+40kPa).

9. Disclosure of excavations on these parameters strength is economically feasible and ensures the safety of traffic and the service life of linear structures.

10. In some particular areas, the disclosure of excavations considering rheological characteristics of soils will require considerable land allotment. Therefore, in such areas to ensure long-term stability is recommended to provide lightweight retaining structures designed for active pressure under limiting conditions in combination with an appropriate drainage system.

Conflicts of Interest: The authors declare no conflict of interest.

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