Comparative analysis of calculation results of supporting structure of soil-cement piles

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Abstract

The article presents the results of comparison of the stress-strain state of 4 models of a retaining wall structure of soil-cement piles on a landslide-prone slope. This study compares the changes in the stress distribution and displacements in the model elements of the retaining structure of soil-cement piles depending on the design parameters and the method of piles location in the body of the soil mass. The comparison of models of supporting structures of soil-cement piles on a landslide-prone slope allowed obtaining:

–the comparative analysis of the quality work of individual elements of the supporting structure for strength and deformation in a three-dimensional representation;

–the comparative assessment of the performance of the supporting structure of soil-cement piles on a landslide-prone slope;

– histograms of dependences of changes in the angle of piles inclination to the vertical axis of their holding force, strength and deformation of the slope;

KEY WORDS: *landslide, soil-cement piles, support structure, comparative analysis, AutodeskInventor*

1. Introduction

The study of the process of physically nonlinear deformation is one of the main objectives of the finite element modeling in the task of geo-mechanical stability of landslide-prone slopes. The possibility of using soil-cement piles as supporting structures is an extensive topic for the research. Comparative calculations of the supporting structure of soil-cement piles for strengthening purposes allows you to determine the most optimal parameters of the structure itself, as well as its configuration, that is, it allows you to find its optimal location relative to the sliding massif for effective stabilization and strengthening of the slope. Analysis of the results of finite-element modeling of the stress-strain state of a landslide-prone slope was performed by comparing stresses in separate elements of supporting structures with different configurations — the possibility of arranging the piles in the vertical direction and at a certain angle of inclination to the vertical axis was considered. The possibility of combining soil-cement piles with a concrete grillage was also considered, where stresses, strains, and safety factors were compared too. In addition, the displacement of the slope model and the supporting structure in three directions: longitudinal, vertical and transverse were compared. The contact pressure on separate structural elements and the safety factors of separate elements of the models were compared, which made it possible to draw conclusions on how to strengthen the slope in order to obtain the most effective results of engineering protection of the landslide-prone part of the motor road.

The slope as a geotechnical object has many uncertainties. Geological anomalies, internal variability of soil properties, changes in environmental conditions, simplifications and approximations adopted in geotechnical models, human errors in design and construction are all factors contributing to uncertainty [1]. The probabilistic slope stability analysis, which reviews the data collected in histograms, is one of the theoretical methods for studying slope stability, which does not require extensive computational efforts connected with modeling, the development of own software for solving the problems of slope stability, which is perhaps the only advantage over the finite element method [2, 5]. For any slope there are an unlimited number of potential sliding surfaces. The slope may collapse or work poorly along any of the surfaces. In this regard, the most correct solution to the problem of instability in terms of model complexity is to find the solution by several methods, which should be the subject of comparison of the results [3].

The method of centrifugal modeling can also be used to study the stability of slopes [4], but due to the great complexity of preparation and work, it may not always be available because of the fact that it requires special technical equipment: centrifuge, lifting equipment and the laboratory for models testing. However, together with the finite element method, it can be used in studies of sliding surfaces and landslides for comparison of theoretical and practical results.

The comparison of the results obtained by several methods of calculation has deeper meaning and the analysis, compared with those studies that are limited to the use of only one of the methods for calculation. That is, for a complex problem or a system with multiple uncertainties, complex solutions are needed that are described in this work, namely, the comparative analysis of calculating results of the stability of a landslide-prone slope with reinforcement by means of soil-cement piles as a supporting structure with different configuration of elements.

2. Finite element modeling of a landslide slope

The statistic calculations of the finite-element model of the dangerous motor road section were performed in the AutodeskInventor 2019 software package (Fig. 1). In Fig. 1, the geological engineering layers that make up this section of the slope are presented in different colors. Each geological engineering element in the model (each layer) was assigned physical and mechanical properties according to the results of geological engineering surveys. The length of this section of the slope, which is considered according to the geological engineering cut, is 147.8 m, and its width is 8.4 m. On all external bottom and side faces, as a restriction on model displacement, supports without friction were specified. As a load, only own weight was applied for all elements.

The creation of three-dimensional models of retaining structures of soil-cement piles that is solids, as well as the creation of the slope model was carried out in software package AutodeskAutoCAD 2019 on the scale of 1: 1. From AutodeskAutoCAD 2019, volumetric 3d bodies were imported into AutodeskInventor 2019 software package as a finished assembly. The finite element mesh was created in AutodeskInventor 2019 automatically, using triangulation with a minimum element size factor of 0.01, a heterogeneity factor of 1.0, and a maximum angle value in the sides of the elements 60 degrees.

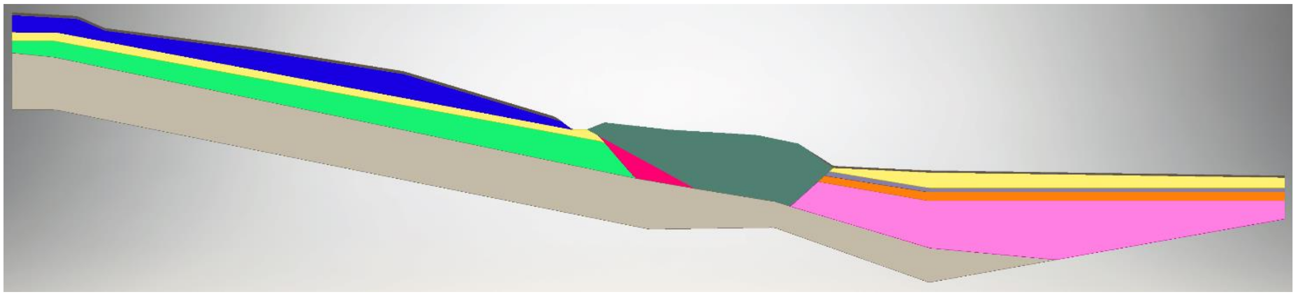

Fig.1. Side view of the three-dimensional model of the landslide-prone slope imported from AutodeskAutoCAD 2019 into AutodeskInventor 2019 software package

The location of the supporting structure of soil-cement piles with respect to the sliding body of the slope was chosen so that the piles cross the sliding surface of a possible landslide, while the supporting structure was located as accurately as possible in the zone of the lower bend of the curved sliding surface. The sliding surface itself was found by solving the stability problem in "OTKOS" software package (Fig. 2). The minimum coefficient of stability of this slope was 1.134 (according to the method of Lowe and Carafite), which suggests that this slope is in the state of ultimate stability, and therefore requires strengthening.

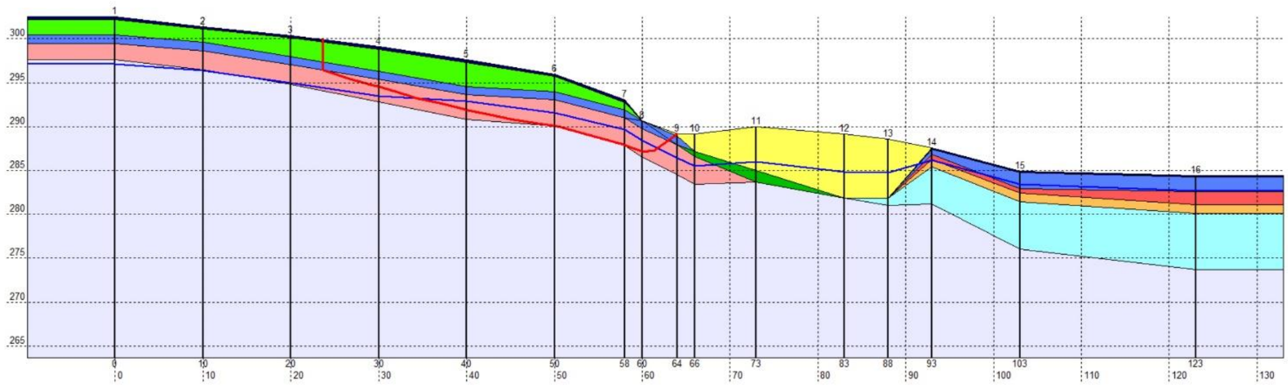

Fig.2. Determination of nature, location of the sliding surface and the slope stability coefficient in OTKOS software package. The red line shows the found sliding surface for the case when the factor of stability of the slope is minimum

3. Comparison of calculation results of finite element models

All the results of this study were collected and presented in the form of comparison histograms (Fig. 9-20), which were used to draw conclusions about the quality work of retaining structures with different configuration of soil-cement piles on a landslide-prone slope. Besides, according to some specific parameters, for clarity purposes, this article provides images of the stress-strain state of separate fragments of finite-element models of support structures (Fig. 3-8).

In Fig. 3, we can see that the difference in pile displacement along the length of slope sliding in the upper part of the pile and in the lower part differs by: 202.24 – 195.06 = 7.18 mm, which is 3.55% in this case. And in the case of inclined piles (Fig. 4), the displacement difference is 206.57 – 196.17 = 10.4 mm, which is 5.0%.

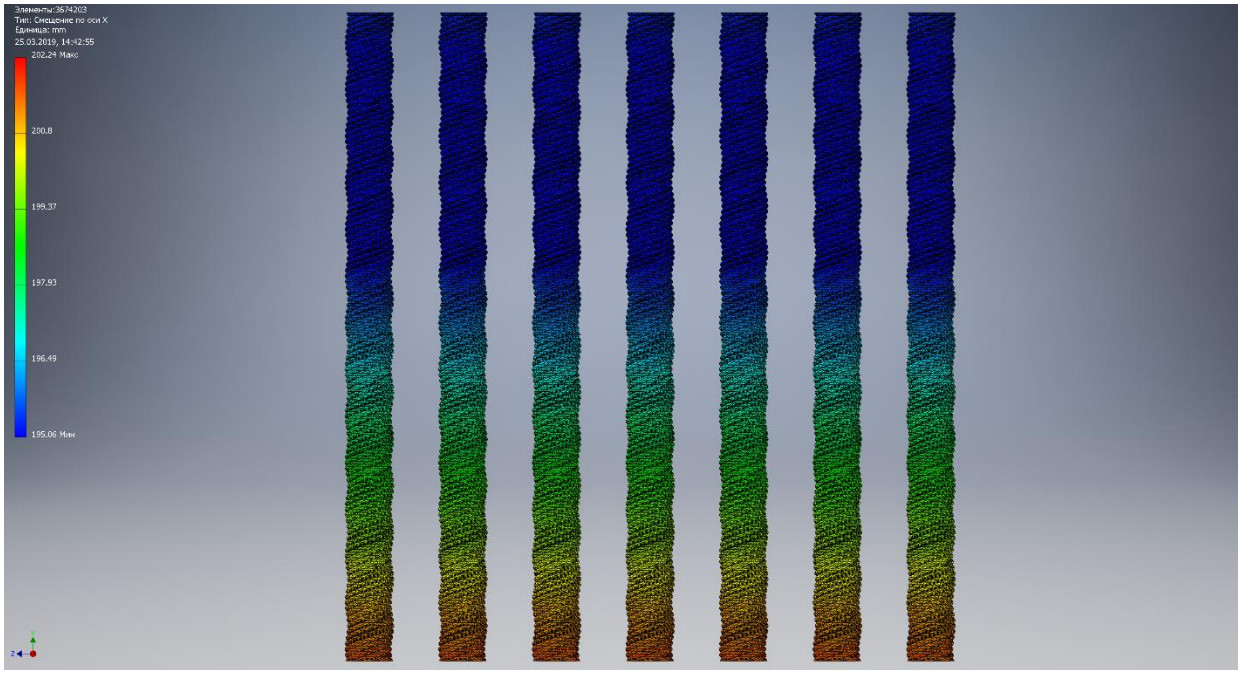

Fig. 3. Soil-cement piles – front view – a fragment of a finite element slope model with vertical piles joined by a concrete grillage –the isopole offset along the X-axis in AutodeskInventor 2019 software package

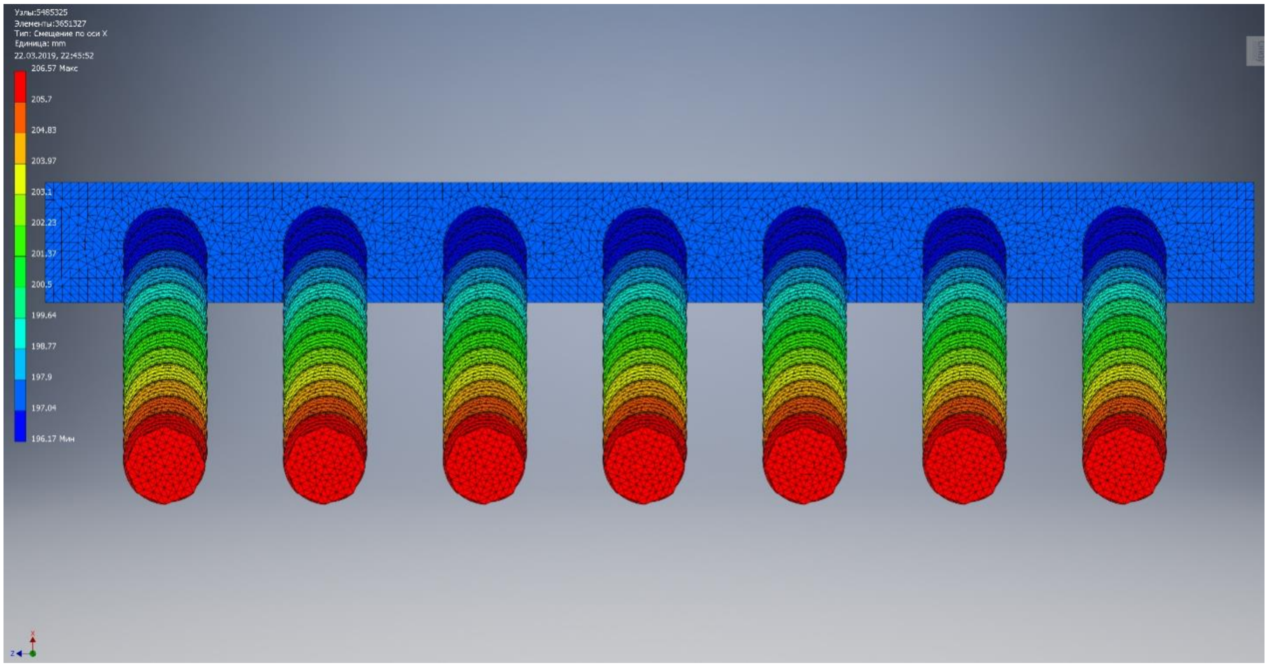

Fig.4. Soil-cement piles with a concrete grillage – bottom view – a fragment of a finite element slope model with inclined piles joined with a grillage – the isopole offset along X-axis in AutodeskInventor 2019 software package

Despite the fact that the difference in displacements in the structure of vertical piles turned out to be smaller, which at first glance is the first determining criterion for the quality of the structure, in Fig. 5 and Fig. 8, we see that the minimum safety factor in a concrete grillage is 0.53, which is significantly less than 1.0. This suggests that in this design there are problems with the strength of the material, since the geometrical parameters, physical and mechanical properties of the material of the grillages are the same.

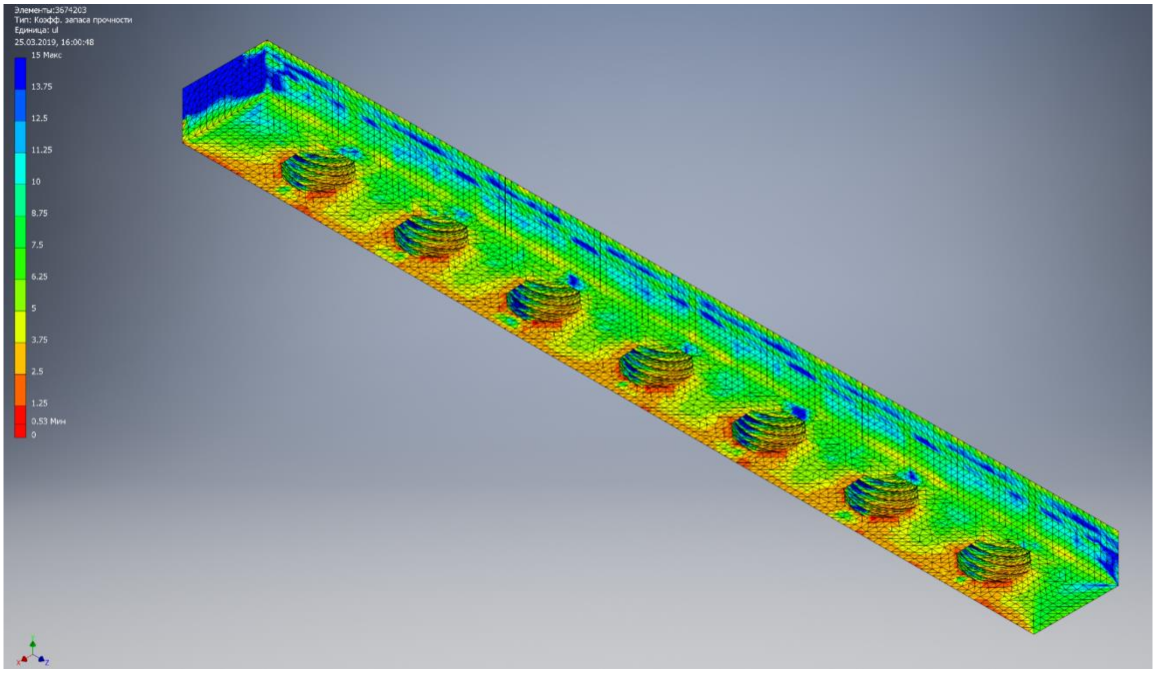

Fig.5. Concrete grillage – bottom-side-rear view – a fragment of a finite-element slope model with vertical piles joined with a grillage – isopole of safety factors in AutodeskInventor 2019 software package

The typical concentrations of differences in the displacement of the lateral face of the concrete grillage result from the action of compressive longitudinal forces that act in the grillage due to the limitation of the finite element model in the lateral faces to move transversely in the direction of slope sliding, which is clearly seen in Fig. 6. At the same time, the neutral plane, along which the longitudinal displacement tends to zero value, has a pronounced wave-like character.

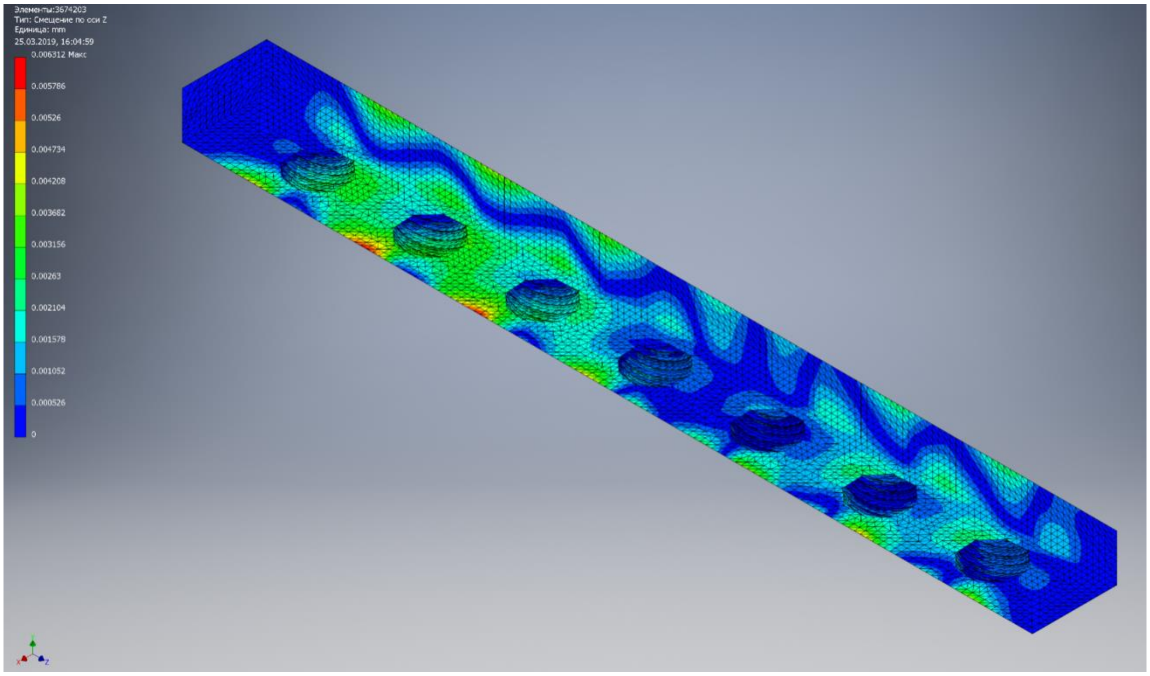

Fig.6. Concrete grillage – bottom-side-rear view – a fragment of a finite-element slope model with vertical piles joined with a grillage — isopole micro offsets along Z-axis in AutodeskInventor 2019 software package.

In the case of inclined piles joined with a concrete grillage, we see in Fig. 7 that the minimum safety factor is 1.18, that is, there is no problem with the strength of the material in the concrete grillage.

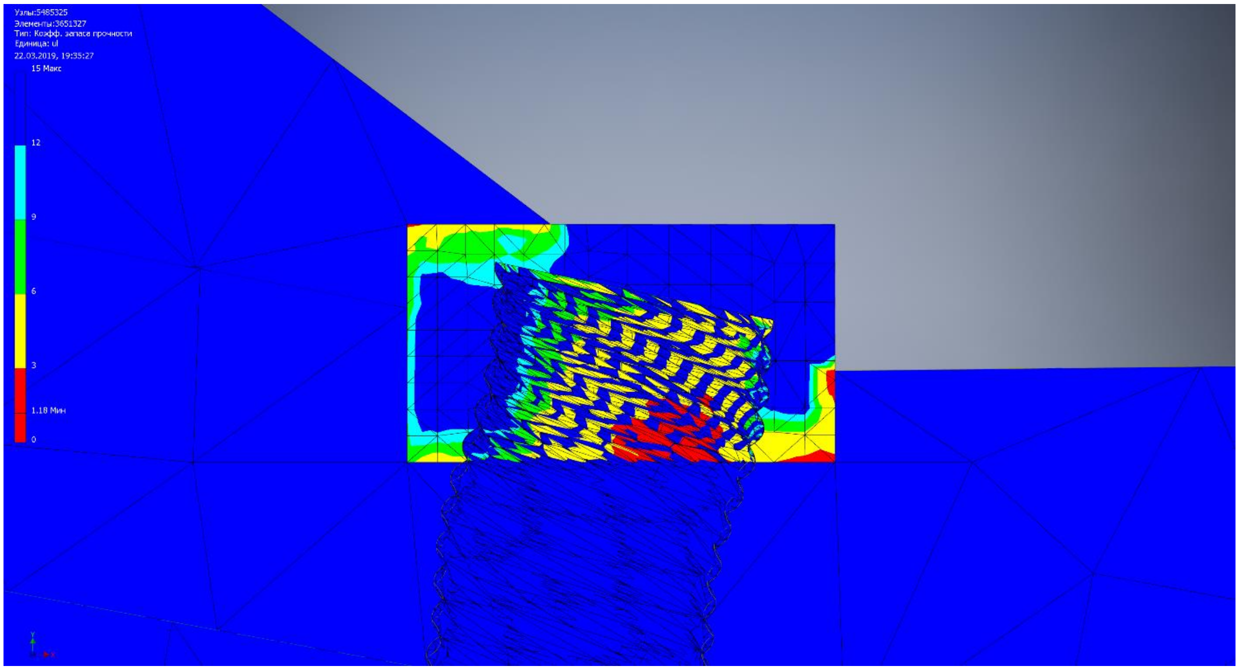

Fig.7. Fragment of a finite element model of a slope with inclined piles joined with a grillage — side view — cut — isopoles of safety factors in AutodeskInventor 2019 software package:
1 – concrete grillage, 2 – soil-cement pile

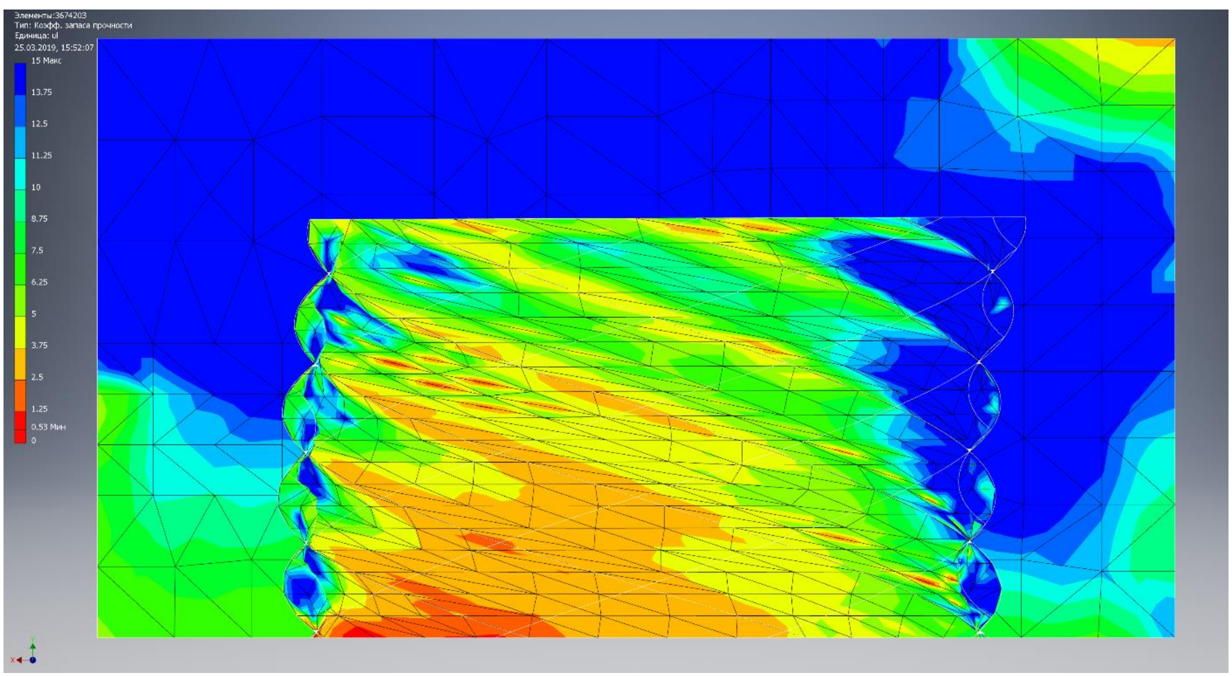

Fig. 8. Fragment of a finite-element model of a slope with vertical piles joined with a grillage — side view — cut — isopoles of safety factors in AutodeskInventor 2019 software package:
1 - concrete grillage, 2 – soil-cement pile

The analysis of the calculation results is presented in the form of histograms comparing such parameters as Von Mises stress (4th theory of strength), basic stresses, absolute displacements, displacements in three directions, contact pressure values, as well as safety factors of structural elements.

Von Mises stress in the concrete grillage in the case of vertical piles is 54.8% that is more than in the case of inclined ones, which explains such a small safety factor of 0.53 in the first case that is unacceptable in the construction of the grillage. The comparison of the main stresses in concrete grillages presents evidence that the maximum difference of the magnitudes of values is 60.9% (the first main stress with a positive value is taken for the comparison) – the result is not in favor of the design with vertical piles. The comparison of the lateral displacements of the model in concrete grillages is shown in Fig. 9. The maximum difference of values was 77.9% – relative deformation, the result is not in favor of vertical piles.

The comparison of contact pressure values in concrete grillages is shown in Fig. 12. The maximum difference between the values of the contact pressure along Z-axis is 65.2%. In this case, the retaining structure with vertical piles showed best performance compared with inclined piles.

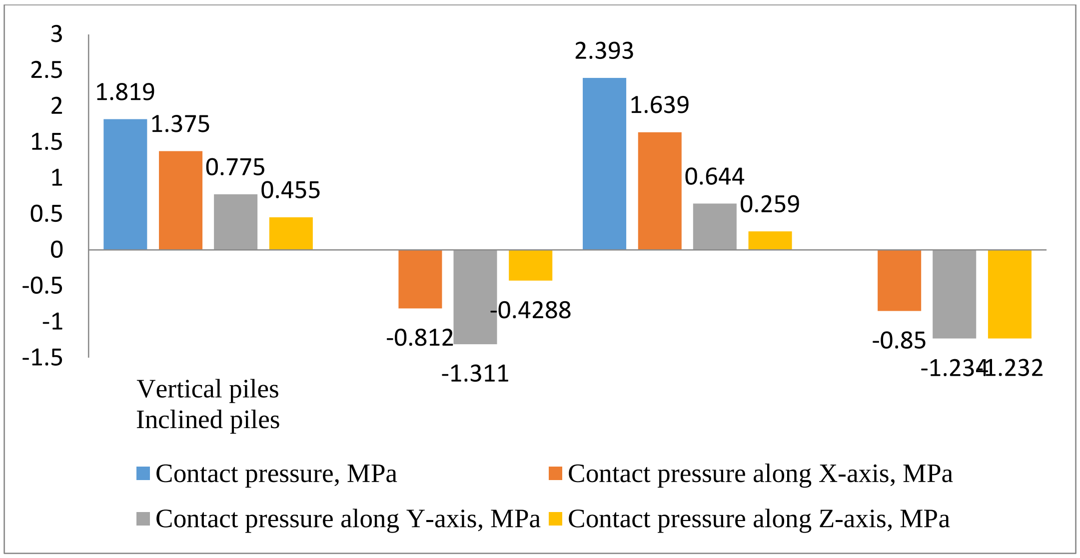

Fig.9. Comparison of contact pressure values in a concrete grillage in models with vertical and inclined piles.

The comparison of values of safety factors in concrete grillages visually demonstrates the difference in values for 55.1%. In case of vertical piles, the safety factor is less than 1.0, which is completely unacceptable for normal operation of the structure.

The comparison of stress values in soil-cement piles is shown in Fig. 10. The maximum difference in values according to von Mises stresses between inclined piles without a grillage and inclined piles joined with a concrete grillage is 53.8%. The least stresses are in the structure with inclined piles joined with a grillage.

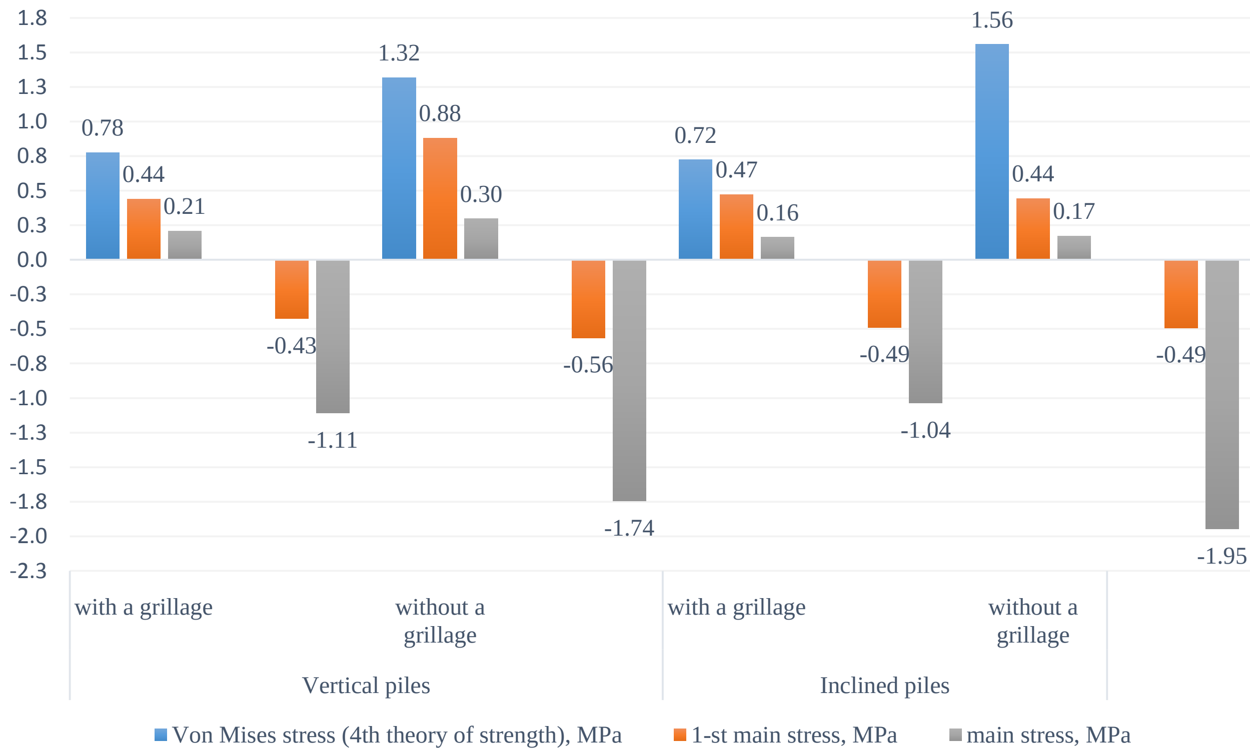

Fig.10. Comparison of stresses in soil-cement piles

The comparison of absolute displacements in soil-cement piles is shown in Fig. 11. The greatest difference in relative deformation in structures with inclined piles joined with a concrete grillage and in vertical piles joined with a concrete grillage is 55.3%.

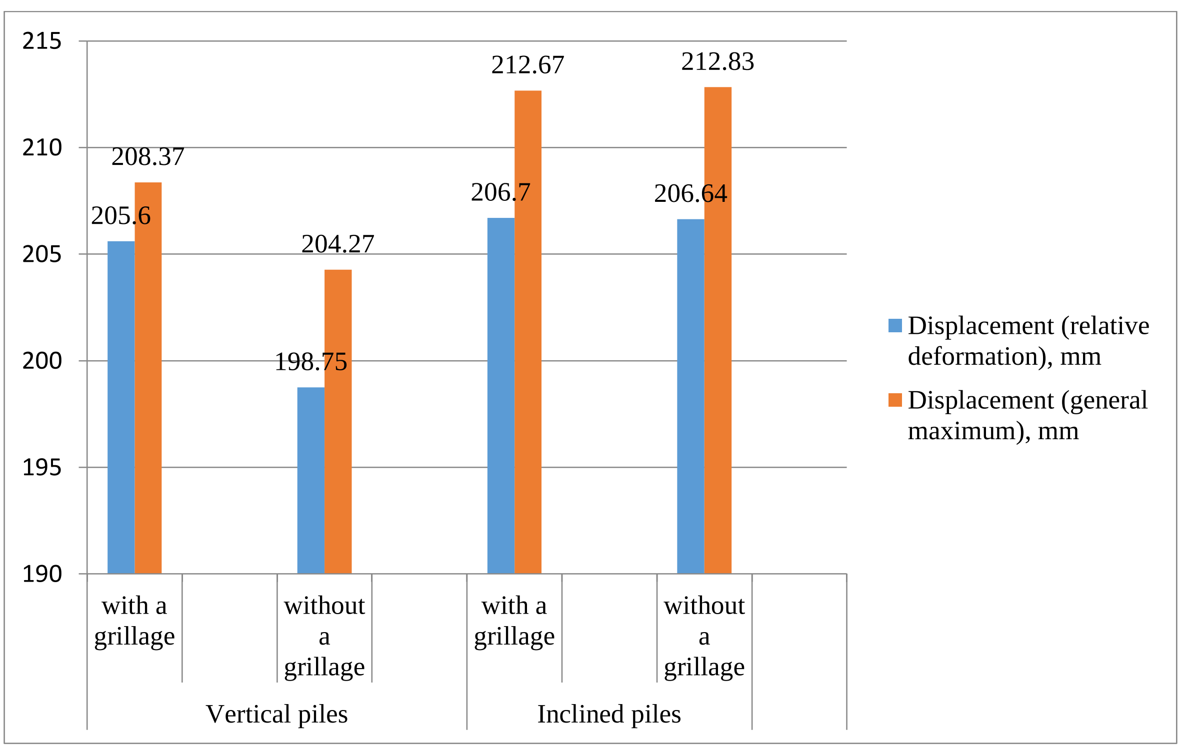

Fig.11. Comparison of absolute displacements in soil-cement piles.

The comparison of values of safety factors for soil-cement piles shows that the greatest difference in values is 53.6% between inclined piles joined with a grillage and those that are not joined with a grillage.

The most identical values of obtained results are vertical displacements of soil-cement piles in all 4 cases. The maximum difference of values was 3.0% – relative deformation. This suggests that the configuration of the supporting structure has almost no effect on this comparison parameter.

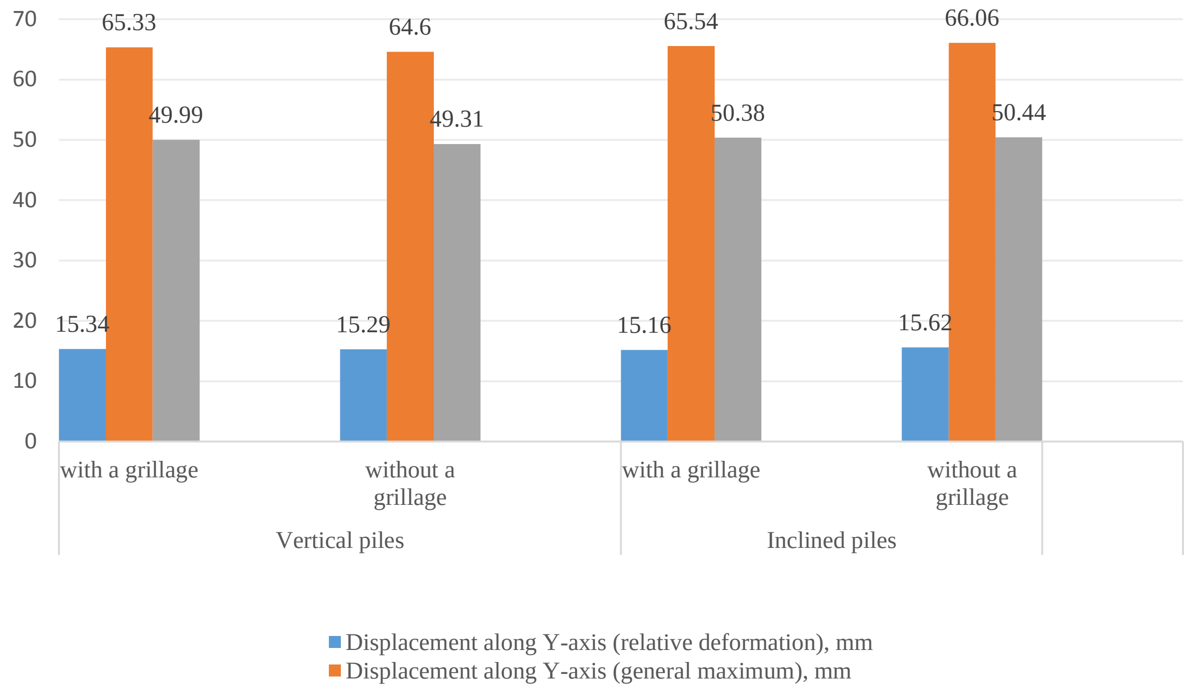

Fig.12. Comparison of soil-cement piles displacement along Y-axis in various models.

The comparison of transverse displacements of soil-cement piles is shown in Fig. 13. The greatest difference of values is 89% – relative displacement along Z-axis. Vertical piles joined with a grillage have the smallest displacement values compared to other configurations of supporting structures.

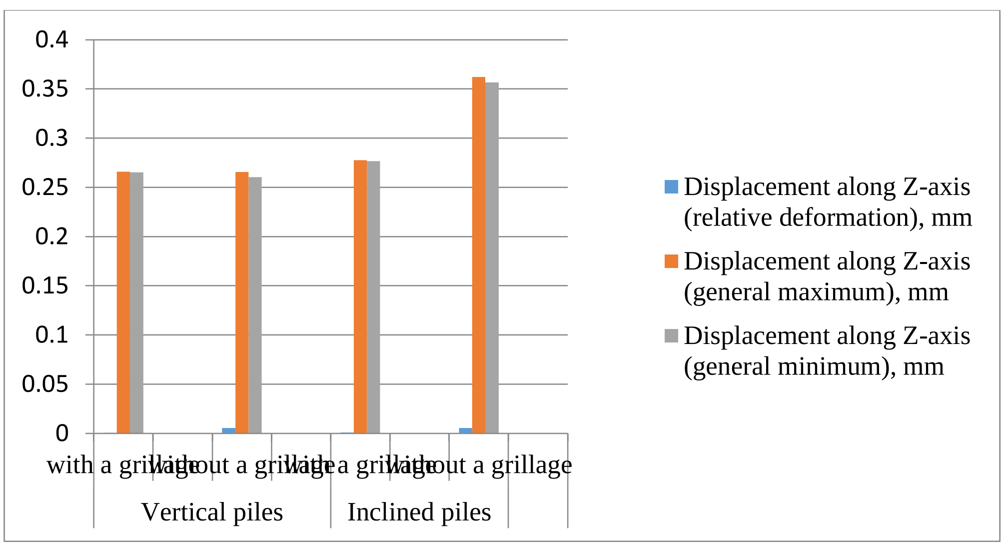

Fig.13. Comparison of soil-cement piles displacement along Z-axis in various models.

Comparison of contact pressures in soil-cement piles is shown in Fig. 14. According to comparison graphs, the smallest contact pressure is in inclined piles joined with a concrete grillage. The difference with the maximum value is 36.6% compared with inclined piles without a grillage.

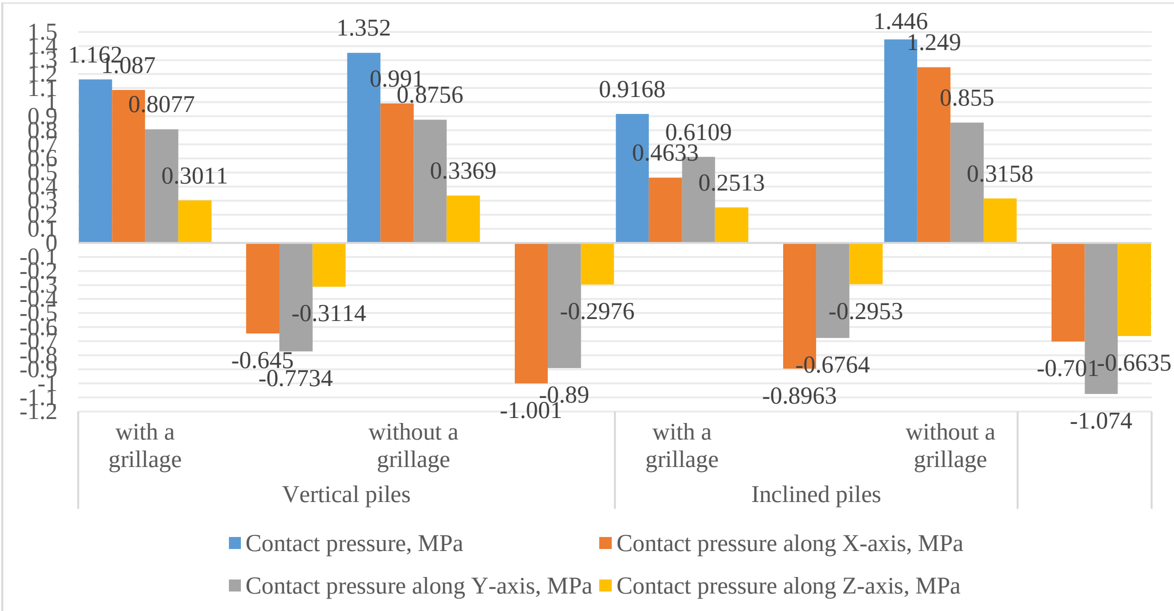

Fig.14. Comparison of contact stresses in soil-cement piles in various models

The comparison of calculation results for a landslide-prone body is shown in Fig. 15. According to such parameters as the displacement along X, Y axis, as well as the total displacement, the maximum difference of values in all 4 cases is practically insignificant, and does not exceed 2.0%, while the maximum difference in displacements along Z-axis in comparison of vertical and inclined piles without a grillage is 51.8%, and the minimum safety factor differs by 57.3% in the same comparison. This suggests that, according to the comparison parameters, inclined piles not joined by a grillage have better performance in comparison with other configurations of supporting structures made of soil-cement piles. But if we proceed from the fact that, in the direct analysis of slope protection, the key parameter is still the displacement, then the best option is still the structure of vertical soil-cement piles not joined with a concrete grillage, which can be clearly seen from the diagram in Fig. 15.

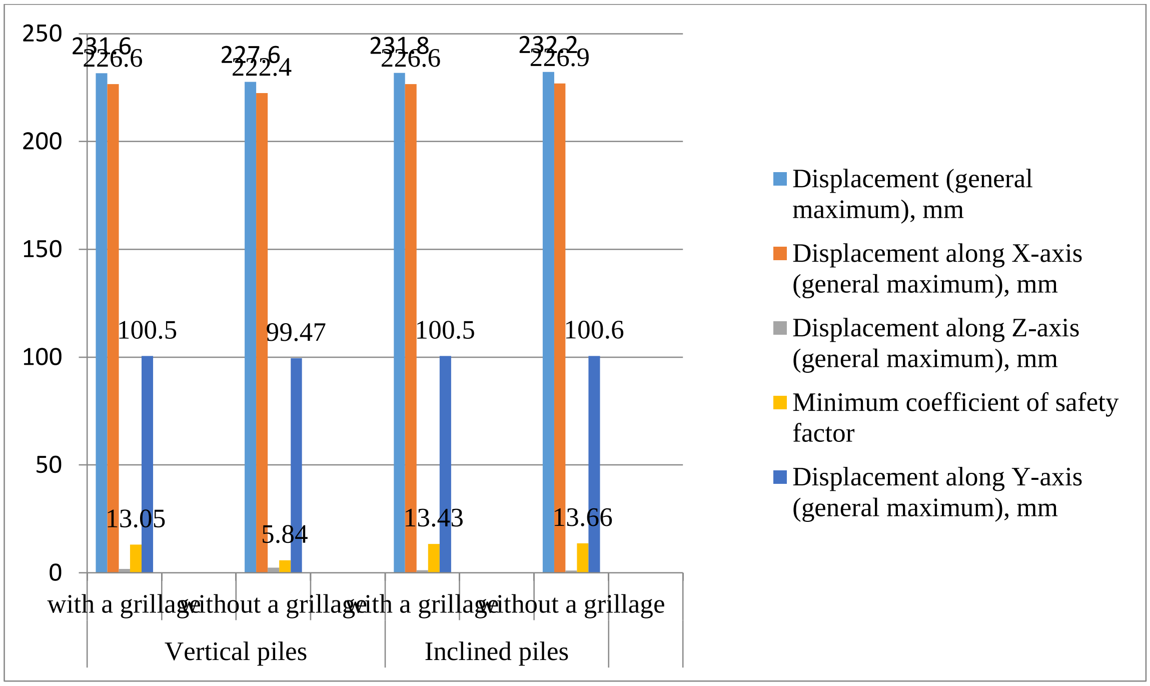

Fig.15. Comparison of calculation results of the landslide slope body

4. Calculation of the stability coefficient of a slope strengthened with soil-cement piles

The shearing force of the landslide on 1 pile is calculated by the formula:

$$F_{ls} = P_1 \cdot \frac{2\pi R}{2} \cdot h_{cut}$$

The holding force of the 1 soil-cement pile is calculated by the formula:

$$F_{pl} = P_2 \cdot \frac{2\pi R}{2} \cdot h_{cut}$$

where:

P_1 is maximum contact, active pressure on the surface of the pile from the side of landslide displacement;
P_2 is maximum contact, passive pressure on the pile surface from the opposite side of the landslide displacement;
R is the radius of the soil-cement pile;
h_{cut} is the length of the considered cut of the soil-cement pile for cut calculation;

The stability coefficient of the landslide-prone slope strengthened with soil-cement piles:

$$C_{st} = \frac{F_{pl}}{F_{ls}}$$

$$F_{ls} = 0{,}006579 \frac{\text{tf}}{cm.sq.} \cdot \frac{2\pi \cdot 30\ cm}{2} \cdot 100\ cm = 62{,}0\ t$$

$$F_{pl} = 0{,}00408 \frac{\text{tf}}{cm.sq.} \cdot \frac{2\pi \cdot 30\ cm}{2} \cdot 100\ cm = 384{,}5\ t$$

5. Conclusions

According to the results of this study, we can draw the following conclusions:

1. Grounding on the fact that the estimated length of the sliding body of the slope in the engineering-geological cut, which is considered in this study, is about 50 m (Fig. 2), it can be concluded that the use of soil-cement piles as reinforcing structures on this landslide-prone slope allows to reduce the displacement of the body of the forming landslide and stabilize it, which is confirmed by the analysis of the histogram comparing maximum displacements along X-axis (Fig. 20). The share of the maximum displacement along slide axis was 0.2318: 50 = 0.0046 that is less than 0.5%;

2. Comparing the high-quality work of retaining structures made of soil-cement piles of different configurations joined with a concrete grillage, it can be concluded that the key parameter and criterion for evaluating the work are not displacements, but stresses that arise in structural elements, since there are significant differences in safety factors of concrete grillages with different variants of soil-cement piles location relative to the vertical axis (up to 65%), as evidenced by the comparison results presented in the histogram in Fig. 13.

3. Having analyzed the comparison histograms in Fig. 9-20, it can be concluded that the most optimal variant of retaining structure configuration of soil-cement piles for effective stabilization of a particular slope is the use of vertical soil-cement piles not joined with a concrete grillage. However, in the case of using inclined piles that are not joined with a grillage, according to such parameter as the safety factor for piles themselves, more advantageous situation is created, as, in percentage, vertical piles have for 57.2% less safety factor despite the fact that they have only for 2.0% less displacement compared to inclined piles (Fig. 20).

4. In the case of a concrete grillage use, for its effective work, the only configuration of the structure that meets all requirements of landslide prevention will be the structure with inclined piles, since in the case of using vertical piles we have a critical safety factor for concrete equal to 0.53 which is unacceptable. In the case of using inclined piles joined with a concrete grillage, according to Fig. 7 and Fig. 13, the safety factor for concrete is 1.18, which is significantly more than for vertical piles.

5. Based on the presented studies, it can be concluded that the use of vertical soil-cement piles not joined with a concrete grillage with such parameters as: pile diameter – 60 cm., length – 8.3 m., spacing between piles in the clearance – 60 cm. for engineering protection of the slope will give a significant increase of its anti-landslide stability (for more than 5 times) and the overall stabilization of the natural soil object.

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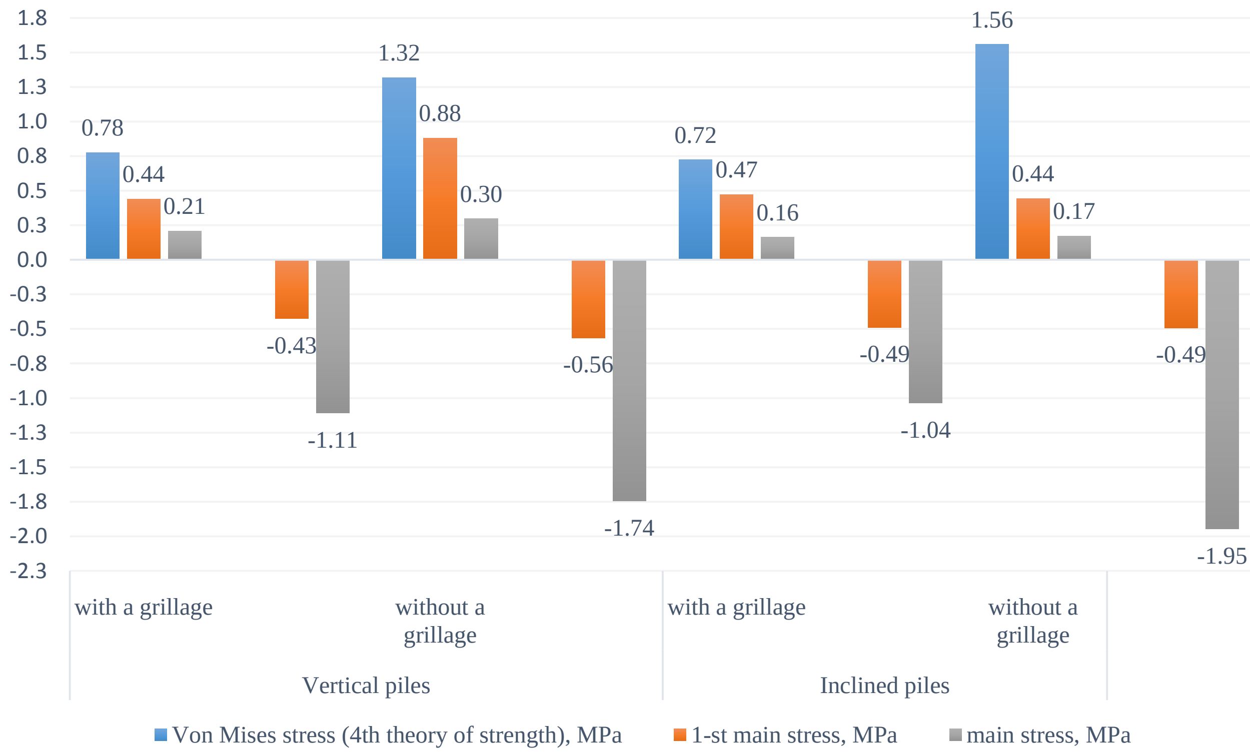
1.8
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-0.49
-1.95
with a grillage
without a grillage
Vertical piles
with a grillage
without a grillage
Inclined piles
Von Mises stress (4th theory of strength), MPa
1-st main stress, MPa
main stress, MPa