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Natural and anthropogenic factors of landslide processes within the slopes of the loess plateau

Vynnykov Yuriy[1], Kharchenko Maksym[2], Yaholnyk Andrii[3], Lystopad Serhii[4*]

[1] National University «Yuri Kondratyuk Poltava polytechnic» https://orcid.org/0000-0003-2164-9936
[2] National University «Yuri Kondratyuk Poltava polytechnic» https://orcid.org/0000-0002-1621-2601
[3] National University «Yuri Kondratyuk Poltava polytechnic» https://orcid.org/0000-0003-4792-1934
[4] National University «Yuri Kondratyuk Poltava polytechnic» https://orcid.org/0000-0002-6743-1257
*Corresponding author E-mail: serzhlistopad@gmail.com

The authors of the article analyzed the geomorphological, geological and hydrogeological features of the structure of the slopes of river valleys within the boundaries of the loess plateau under anthropogenic influence. The main factors of the occurrence of landslide processes were highlighted. The geomorphological structure of the slope was analyzed taking into account the dynamics of landslide processes. The influence of the hydrogeological regime on the reduction of the mechanical properties of soils within the basins was evaluated. The authors analyzed the genesis of loess, loess, and deluvial-proluvial deposits. A spatial information model of the slope array has been compiled. Its stability of the massif of the slope was evaluated taking into account the geological structure, hydrogeological factor, structural parameters of soils and their changes within the basins

Keywords: relief, genesis, loess rock, slope, landslide, basin, soil strength, structural cohesion, stress-deformed state, stability

Природні та антропогенні чинники зсувних процесів у межах схилів лесового плато

Винников Ю.Л.[1], Харченко М.О.[2], Ягольник А.М.[3], Листопад С.М.[4*]

[1, 2, 3, 4] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
*Адреса для листування E-mail: serzhlistopad@gmail.com

Проаналізовано геоморфологічні, геологічні та гідрогеологічні особливості будови схилів річкових долин у межах Полтавського лесового плато за значного антропогенного впливу. Виділено основні чинники виникнення зсувних процесів, зокрема, особливості геологічної будови та гідрогеологічного режиму схилу, генезис і фізико-механічні властивості відкладів, які складають масив, зміна наведених параметрів під впливом природних або антропогенних факторів. Виділено типи рельєфу та механізм формування лесових порід у межах лесового плато, поверхня якого прорізана долинно-ерозійною мережею. Досліджено геоморфологічну будову схилу з урахуванням динаміки зсувних процесів. Виявлено стародавні заглиблення у водотривких або слабко проникних ґрунтах – улоговини, які визначають будову схилу. Оцінено вплив гідрогеологічного режиму, що має складну структуру й динаміку, на зміну напружено-деформованого стану (НДС) масиву та, як наслідок, виникнення локальних зсувних явищ. Доведено зниження механічних властивостей ґрунтів улоговин. Проаналізовано генезис лесових, лесованих і делювіально-пролювіальних відкладів, які на схилах переходять у нестійкий стан. Розглянуто властивості міцності ґрунтів, їх формування, методи визначення. Встановлено локальні негативні інженерно-геологічні процеси на схилі, зокрема, антропогенний вплив на НДС масиву. Обґрунтовано механізм і динаміку виникнення та розвитку зсувів. Складено просторову інформаційну модель схилу, в якій враховано геологічну його будову, улоговини, гідрогеологічний режим, зсувні масиви. Оцінено стійкість цієї моделі схилу з урахуванням її просторової геологічної будови, гідрогеологічного фактору, структурних параметрів порід та їх змін у межах улоговин. На базі результатів оцінювання стійкості схилу з урахуванням впливу каналізаційного колектору для його подальшої безаварійної експлуатації рекомендовано комплекс відповідних протизсувних заходів

Ключові слова: рельєф, генезис, лесова порода, схил, зсув, улоговина, міцність ґрунту, структурне зчеплення, напружено-деформований стан, стійкість

Introduction

The central part of Left Bank Ukraine is located within the Dnieper Lowland. The modern topography of the Poltava region was formed under the influence of endogenous and exogenous processes mainly in the Cenozoic era.

The main geomorphological features were laid down in the Neogene period during the formation of a branched river system. The final formation of the relief and geomorphological structure took place due to the active erosive activity of surface waters during several cyclic glaciations in the Quaternary period. Within the accumulative plain, river valleys, floodplain terraces and loess plateaus were formed as a result of these active geological processes [1-3].

Within the plain, the geological structure with several horizons of Quaternary soils is characterized by a wide distribution of loess and loess rocks. They are covered with heavy loams and clays. These soils have eolian-deluvial and eluvial genesis.

The geomorphology of the slopes of river valleys in the Poltava Region was formed by the active development of landslide, erosion, and suffusion processes and phenomena. The peculiarity of the geological structure is the uneven accumulation of loess and loess soils along ancient depressions in water-resistant or poorly permeable soils - "basins" [1-7].

Such slopes are classified as landslide or landslide-prone areas [4-9].

Review of the latest research sources and publications

When developing these territories, one should take into account the peculiarities of the geological and hydrogeological structure, the change in soil properties, the development of negative processes, etc. This determines the necessity and complexity of research that analyzes the causes of landslides when the stress-strain state (SSS) of the soil massif changes [4-14].

The analysis of the causes of landslides, the dynamics of the development of landslide processes, the peculiarities of the physical and mechanical properties of soils within the slopes of river valleys and the peculiarities of the protection of territories from landslides are described in the works of I. Boyko, Yu. Velikodnyi, L. Ginsburg, M. Goldshtein, M. Demchyshyn, A. Drannikova, M. Zotsenko, M. Kornienko, V. Kraeva, M. Maslova, S. Meschyana, H. Strizhelchyk, V. Shvets, O. Shkola, A. Bishop, A Casagrande, J. Duncan and others.

Insufficient study of the features of engineering and geological structure, inaccuracies in determining soil properties and methods of determining slope stability lead to errors in design and operation in landslide and landslide-prone areas.

These errors cause the destruction and damage of buildings and structures, engineering communications and have other negative consequences. Large-scale landslide processes and phenomena can be the cause of technogenic and environmental disasters [6, 7, 11-14].

There is a significant number of classifications of landslides, which are developed on the basis of geological structure, dynamics of landslide masses, nature of landslide processes, etc. These classifications are in constant development and expansion to take into account as many features of the engineering-geological and hydrogeological structure as possible. [5].

A special place is occupied by the assessment of slope stability. It is necessary to take into account the classification of the slope and the features of the engineering and geological structure, use the data of laboratory and field tests, monitoring of landslide processes, take into account changes in the physical and mechanical properties of soils and other factors during the calculation. [15-20].

An important place in the complex approach to the study of the causes of the occurrence and development of landslide processes is the genesis of soils on the slope. Features of the origin and formation of the soil massif significantly affect the formation of landslides, physical and mechanical properties of soils, hydrogeological regime, etc. [2, 5-7, 10-12].

The hydrogeological factor exerts a significant influence on the dynamics of landslide masses on the slopes. Features of the hydrogeological structure exert a significant influence on the stress-strain state of the soil massif of the slope. This especially affects the change in soil properties. The regime of groundwater is characterized by the occurrence of a waterproof layer, on the roof of which their movement occurs. The peculiarities of the hydrogeological regime include a relatively rapid change under the influence of natural and anthropogenic factors [21-26].

Definition of unsolved aspects of the problem

It is necessary to take into account a wide range of variable factors and initial data for a qualitative assessment of slope stability and the design of effective anti-slide measures. The most effective are the methods of modeling shear processes. They take into account the spatial effects of soil layers and the movement of groundwater, soil characteristics and the forecast of their change, anthropogenic factors.

The results of slope stability analysis depend significantly on soil strength characteristics and their physical condition.

However, the methods of soil testing recommended by the standards often give overestimated values of the strength characteristics. Since they do not take into account the actual condition of the soil in the massif of the slope [15]. When physical properties change, soil strength parameters also change. [4].

Therefore, when determining the characteristics of soils to assess stability, it is necessary to use methods that maximally reproduce the stressed state of soils in the massif within the slope. The characteristics determined by such methods often have lower values compared to standard methods. At the same time, the calculated stability coefficients showed that the use of such parameters allows for more reliable evaluations that are correlated with field observations [6, 7].

Problem statement

Therefore, the purpose of the work is to research the causes of landslide processes of the soil massif, taking into account the features of the engineering-geological and hydrogeological structure of the slope, physical and mechanical properties of soils, dynamics of landslide masses, technogenic influence and assessment of stability taking into account these factors.

Accordingly, in order to achieve the purpose, the following tasks are selected: engineering-geological and hydrogeological studies of the territory; determination of features of the genesis of the soil massif; laboratory studies of soil characteristics taking into account their structural strength; forming the initial data of the calculation model of the slope; making an assessment of slope stability with recommendations for stabilization of landslide processes on the slope

Basic material and results

Actual scientific work is based on the results of a natural objects studies (Fig. 1) - the slope of the Poltava loess plateau (on the outskirts of the city of Poltava) with significant anthropogenic influence. An analysis of the causes of landslide processes and phenomena under the conditions of the slopes of river valleys was carried out. Therefore, it is determined that it makes sense to highlight several main factors of the occurrence of landslide processes, which include:

1) peculiarities of the geological structure of the slope territory;
2) hydrogeological regime on the territory of the slope;
3) genesis and physical and mechanical properties of the soils that make up the massif of the slope;
4) change of the above parameters under the influence of natural or anthropogenic factors.

According to the first factor, places where landslides occur on the slopes depend on the features of the geological structure, which was formed in a certain geological period.

Figure 1 – A characteristic view of the research site at the top of the slope

In general, the territory of the Poltava region is a plain. Within its boundaries there are the following types of relief (Fig. 2): eolian-deluvial accumulative, accumulative-denudation and accumulative-terrace plain [1-5].

In the Middle Quaternary, the Dnieper glaciation had a significant impact on the development of the relief and its forms. It covered about 80% of the territory of the region. Glaciation is associated with the formation of numerous through valleys in glacial and periglacial zones.

The territory of the Poltava region is characterized by a wide development of loess rocks with several horizons of fossil soils of lower, middle and upper Quaternary age. They were formed as a result of eolian deluvial and eluvial processes.

Loess Middle and Upper Quaternary rocks cover almost the entire territory of the region, with the exception of the first floodplain terraces and river floodplains. They participate in the formation of the modern relief and its forms [1, 4, 5] (Fig. 3).

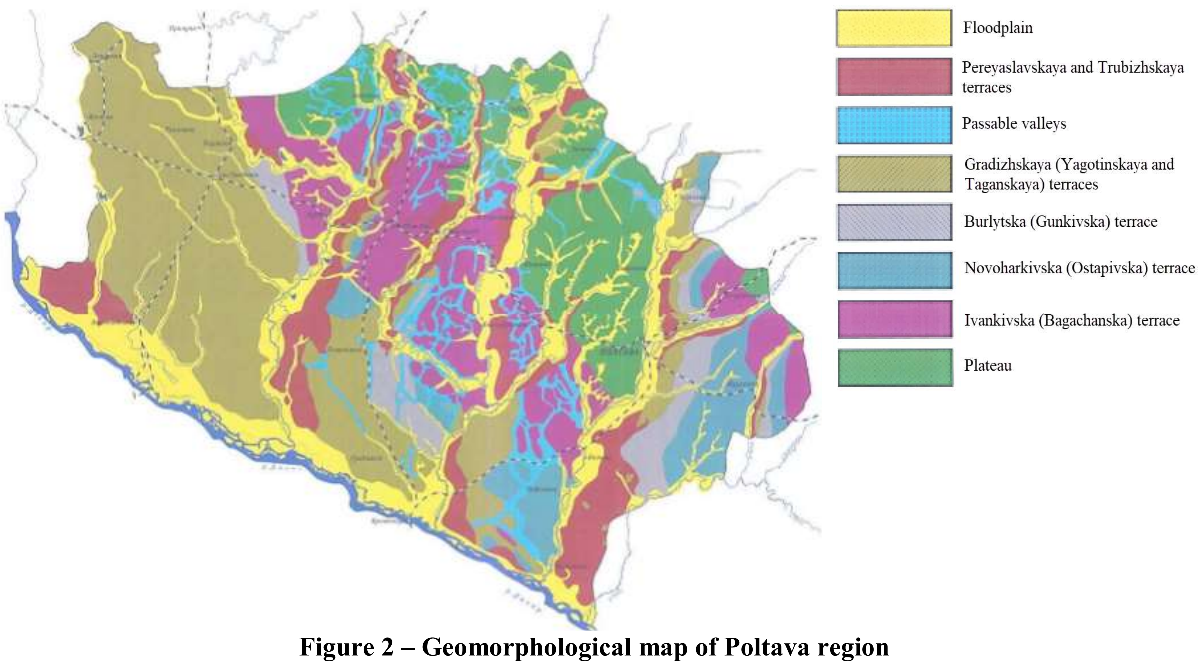
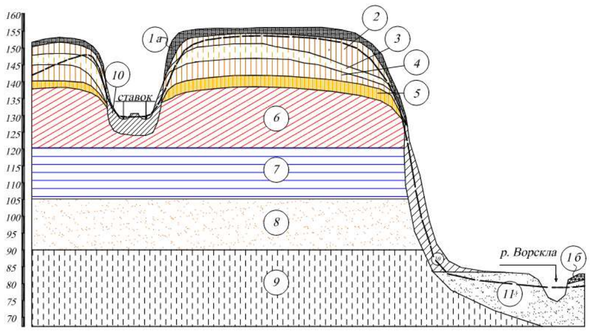


Figure 2 – Geomorphological map of Poltava region



IGE-2...5 - loess loams; IGE-6, 7 – clays; IGE-8 – sand; IGE-1, 10 – deluvium, IGE-9 – clays

Figure 3 – A characteristic geological section of the Poltava Loess Plateau

Under these geological conditions, the slope was formed under the conditions of a relatively elevated formation - a loess plateau. Its surface is cut by a valley erosion grid.

As a result of such dismemberment, a branched ravine-gully system with a certain geological structure and a cascade of ponds was formed.

Lithologically, the section is represented by Paleogene, Neogene and Quaternary systems. Paleogene deposits are represented by Paleocene, Eocene, and Oligocene formations. Oligocene sediments in the Neogene and Quaternary times underwent significant destruction. The upper part of these deposits is covered by a deep erosion grid within the Pliocene terraces and plateaus.

The Neogene system consists of deposits of the Poltava Formation, mainly clays and alluvial formations, Miocene and Pliocene systems.

Quaternary sediments are represented by sediments of different ages of eluvial genesis: aeolian-deluvial, eluvial, and lake-swamp complexes.

The listed deposits are indigenous. Under natural conditions on the slopes, they are in a stable state. From the surface, the slopes are covered with bulk and deluvial-proluvial deposits.

Under certain conditions, these rocks can go into an unstable state, which will lead to the occurrence of landslide phenomena.

The geomorphological structure of the slope changes dynamically over a long period of time as a result of active sliding processes.

The slope has areas with different slopes, landslides cirque, terraces, brow of failure, bulk soil and anthropogenic soils, cracks in the bulk massif, etc. (Fig. 4).

The features of the geological structure of the experimental slope, as well as most of the slopes of river valleys, include the uneven thickness of loess, loess, deluvial, anthropogenic and other deposits. This is explained by the presence of ancient depressions in water-resistant or poorly permeable soils, so-called "basins".

They determined the topography of the slopes [4] (Fig. 5).

Basins in the water-resistant layer are covered by anthropogenic, deluvial and indigenous loess or loess soils under the influence of various relief-forming factors.

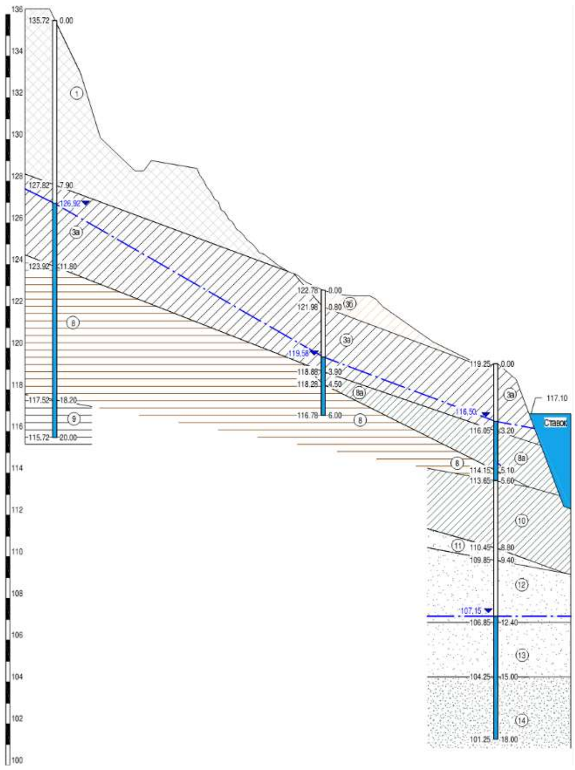


Figure 4 – Longitudinal engineering geological section

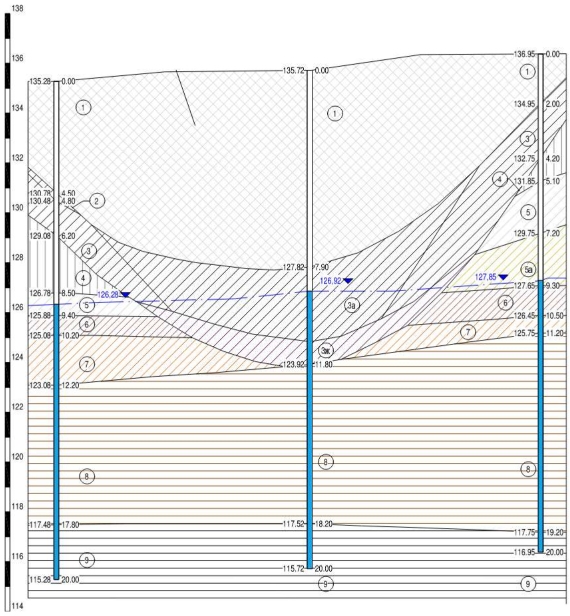


Figure 5 – Transverse engineering and geological section

In these places, local areas with a complex stress-strain state are formed on the slope, which determines potential landslide arrays.

The factor of the hydrogeological regime has a significant influence on the dynamics of landslide processes.

It is connected with the hydrographic grid (Fig. 6) on the territory of the region, which existed already in the Neogene.

This is recorded by Pliocene terraces located in the basins of the Dnipro, Sula, Psel and Vorskla rivers [1, 4].

Figure 6 – Hydrographic grid of Poltava region

In addition to the Pliocene terraces, in the basins of these rivers, in the upper and lower Quaternary ages, supraflood terraces were formed. Modern floodplains were formed in the Holocene. In the Quaternary age, the intensive formation of river valleys took place in the Lower Quaternary and Upper Quaternary ages, as well as in the modern era during the formation of supraflood terraces and floodplains.

In terms of hydrogeology, the site is part of the Dnipro-Donetsk artesian basin. The hydrogeological structure is characterized by the presence of two soil-type aquifers.

The waterproof layer of the first horizon is Zavadi or Neogene clay.

At the same time, this aquifer has a complex structure and dynamics.

Groundwater discharge from the plateau to the slope occurs locally in the form of springs and streams (Fig. 7).

Figure 7 – Unloading of groundwater from the plateau

These processes are carried out due to the structure of the waterproof layer, due to the presence of a basin on the slope. [6].

Then the phenomena of erosion, suffusion, creep develop, and at the same time the pressure gradient increases. The result of such influence is a decrease in the mechanical properties of soils within the basins, an increase in their deformability. These phenomena have the most negative effect on loess, loess or deluvial soils, which are formed above a waterproof layer. In such places, sliding surfaces often occur. According to which shifting processes take place in the future (Fig. 8).

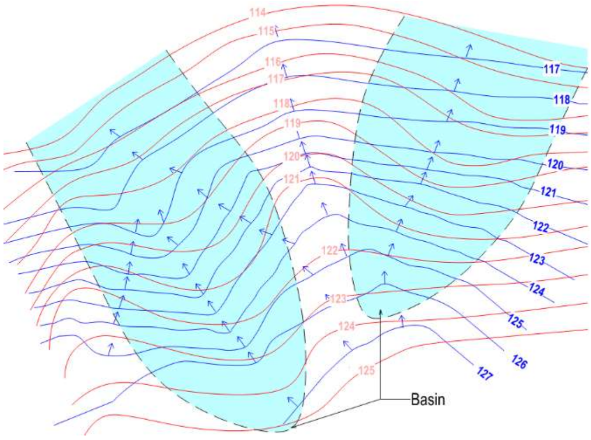
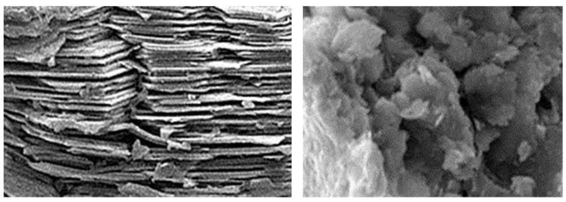


Figure 8 – The scheme of placing basins on the slope

These processes are in constant dynamics. Systems of natural drains are disturbed as a result of landslide processes. Then the bulk mass and the upper layers of the massif of the slope are saturated with water. After that, the soil loses part of its strength, the strained state of the soil massif changes. This contributes to the occurrence of local landslide phenomena and processes.

The third factor includes the origin of soils, which affects the formation of their special physical and mechanical properties. Loess, loess, weak, and deluvial-proluvial soils are the soils that most often become unstable on slopes under certain conditions. This is due to the peculiarities of their eluvial genesis. At the same time, there are aeolian, aeolian-deluvial, eluvial and lake-swamp complexes. (Fig. 9).



a) b)

Figure 9 – The structure of clays (a) and loess loams (b)

This feature determines the physical and mechanical properties of soils and their change due to various natural and anthropogenic phenomena.

Soil strength parameters include the angle of internal friction φ and the total specific adhesion p. These parameters determine the stability of the soil massif on the slope. The general specific adhesion can be divided into two components - structural adhesion and cohesion adhesion $c = c_{st} + \Sigma_w$ [4, 7].

The strength of loess and loess rocks is determined by the influence of both types of adhesion, but their importance is different. Structural cohesion has the main influence on stability. It gives the breed a certain rigidity, hardness. This type of coupling is due to the presence of some rigid bonds that act between the particles. Structural connections are to a certain extent elastic in nature, which determines the degree of deformation of rocks and their density. However, when the soil structure is disturbed, rigid structural connections are irreversibly destroyed.

Structural cohesion in deluvial or weakly degraded soils due to the conditions of formation of such deposits is practically absent. Therefore, such soils on the slope are considered unstable, and their strength is determined by cohesion. Cohesion connectivity is characteristic of clayey soils of any consistency, together with structural connectivity, it determines their strength. Cohesion of connectivity has a somewhat different character than structural cohesion. In loess sands and light loams, cohesion is of little importance and depends on the density of the soil.

When determining the strength characteristics of soils on landslide and landslide-prone slopes, it is necessary to use a specialized method of processing the results of the soil displacement test. It would make it possible to determine both components of adhesion. [4] (Fig. 10).

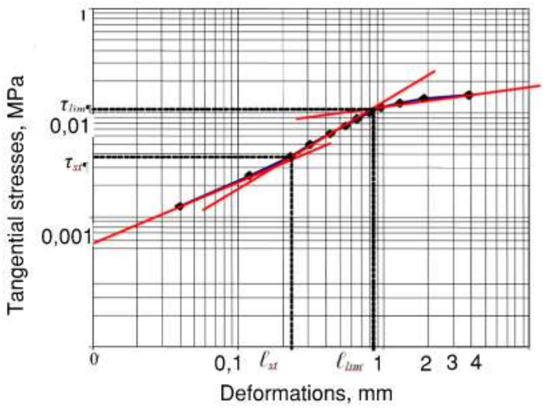


Figure 10 – Methods of determining structural cohesion

The formation of landslide masses most often occurs in places where the strained state of the soil massif of the slope is close to the limit. At the same time, the shear stresses are equal in value to the retaining stresses. Such places on the slope are characterized by a special geological and hydrogeological structure, differences in physical and mechanical properties of the same type of soil, anthropogenic influence, etc. That is, locations are formed that are potentially the most favorable for the occurrence of landslide processes and phenomena.

But at the same time, the slopes are in a stable state. This happens due to the formation of a relatively balanced system on the slope. The system is characterized by a certain geological structure, stable hydrogeological regime and stable soil properties. It consists of a system of natural drains. Such slopes are classified as landslide-prone [8, 9].

Therefore, the occurrence and development of landslides are significantly influenced by the given parameters under the influence of natural or anthropogenic factors. Changes from natural factors occur due to the presence of basins in the geological structure. At the same time, it is important that atmospheric and ground water are unloaded through them. As a result of the long-term movement of water in the basin, soils significantly lose their mechanical properties. Then the processes of suffusion and erosion begin, creeping and other processes develop.

In addition to natural processes, processes associated with anthropogenic changes play a major role on the slopes. Significant anthropogenic influence leads to changes in the relief, the appearance of bulk soils, disruption of the hydrogeological regime, etc. This leads to a violation of the natural balance due to changes in the strained state of the soil massif, soil properties. The result is the occurrence of landslide processes.

Such a violation of the existing balance of the massif is accompanied by soil sliding down the slopes. And it is also possible by pushing them out from under the foundations of buildings with significant subsidence, displacements and deformations of structures. Such slopes pass from the category of landslide-prone to landslide.

All factors of the occurrence and development of landslide processes are in constant interaction and dynamics. At the same time, such interaction has a very complex nature. It requires large-scale analyzes to assess the stability of slopes. Such an example is researching the slope in Poltava. At the bottom of this slope, a sewage collector is laid, which is constantly destroyed due to landslide processes and soaks the soil massifs at the foot of the slope.

The modern topography of the site is stepped and complex in structure. At the time of the research, the slope had repeatedly undergone significant anthropogenic changes. A collector was built in the lower part of the slope, and power grid supports were built in the middle part of the slope. Engineering facilities, garage buildings are built on a plateau that directly borders the slope. There will be long-term dumping of soil from the plateau on the slope without planning and compaction.

As a result of anthropogenic changes and natural factors, development occurred on the slope of landslide processes.

They passed locally along the most favorable parts of the slope - the basins (Fig. 11).

Groundwater discharge from the plateau to the slope occurs locally in the form of springs and streams. Dumped and displaced soils blocked the natural exits of underground water to the earth's surface. As a result, bulk deposits and upper layers of the massif of the slope are additionally saturated with water. At the same time, soils lose their strength properties and the load on the slope changes.

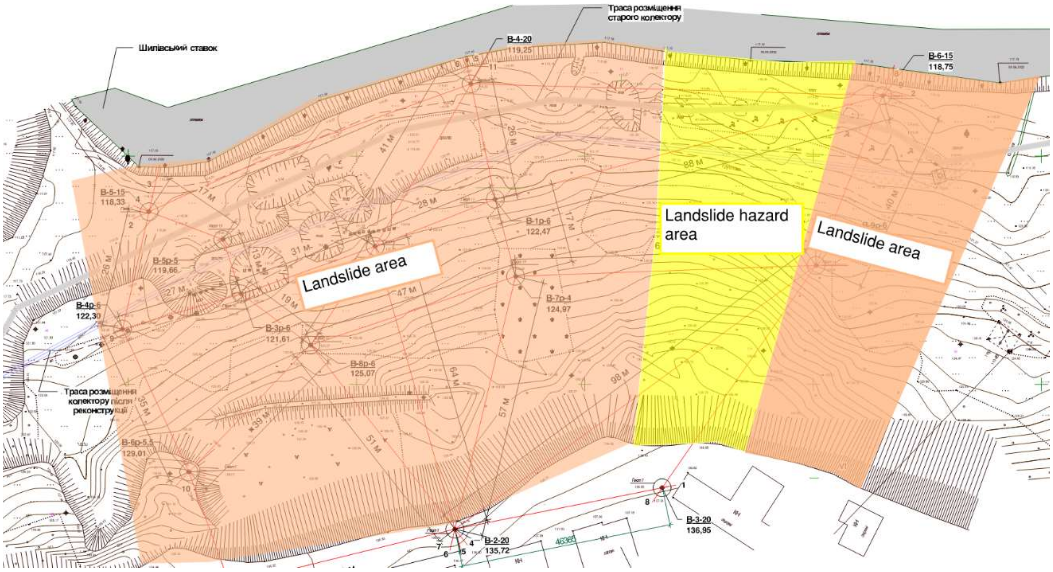


Figure 11 – The scheme of placement of landslide and landslide-prone areas on the slope

This leads to the occurrence of local shear processes and phenomena.

The geological structure of the slope was assessed in detail, and landslide and landslide-prone areas were found.

The evaluation was carried out based on the results of field research, the construction of longitudinal and transverse engineering-geological sections (Fig. 12) and the spatial calculation model (Fig. 13).

Special attention is paid to the study of the hydrogeological regime. The movement of groundwater, especially within basins, has a significant impact on the physical and mechanical properties of soils on a slope.

This problem is especially relevant for loess, loess or deluvial soils above the waterproof layer.

We can analyze the peculiarities of groundwater movement on the site and their influence on the development of landslide processes using the constructed map of the groundwater surface in hydroisogypsums.

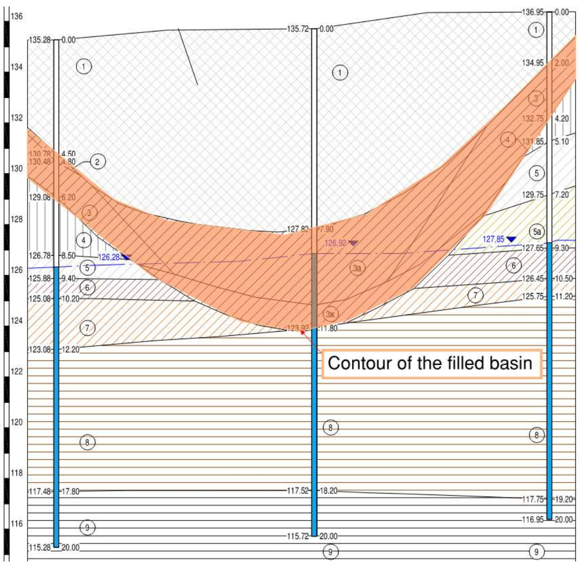


Figure 12 – Contour of the filled basin

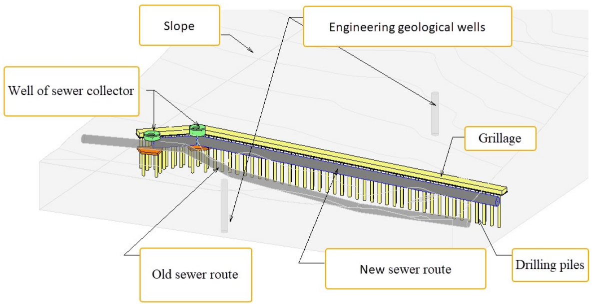


Figure 13 – Spatial calculation model

The process of occurrence of landslides on the site is as follows: in the upper part of the slope, construction debris is dumped uncontrollably.

The consequence is additional loading of the soil massifs of the slope. This blocks the natural drains of surface and ground water and additionally saturates the landslide massifs with water.

At the bottom of the slope due to leaks from the sewage collector, water saturation and weakening of the soil mass at the foot of the slope occurs. As a result, in areas of the slope due to the imbalance of the upper part of the slope, the displacement masses in the middle of the slope are pushed out.

Then landslide processes develop both in the middle and in the lower parts.

In this way, the formation of sliding surfaces takes place, following which landslide processes take place (Fig. 14).

The conducted research made it possible to generate initial data for assessing the stability of the slope, taking into account the spatial geological structure. They also take into account the hydrogeological factor, structural characteristics of soils and their change within the basins.

Calculations can be checked by finite element modeling (FEM) using an elastic-plastic soil model with the Mohr-Coulomb strength criterion.

In the article, calculation schemes (Fig. 15) are made for assessing slope stability and shear pressure values.

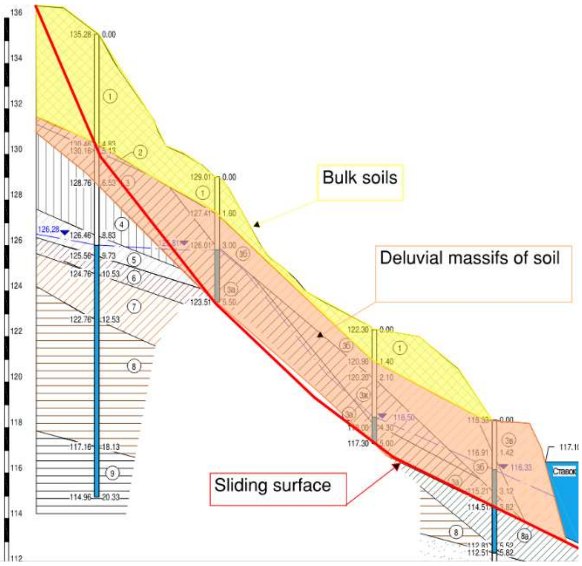


Figure 14 – Sliding surface

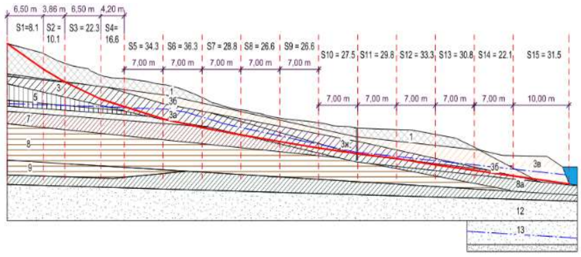


Figure 15 – Calculation scheme of slope stability

Calculation algorithms and mathematical models of slopes were also made.

These factors made it possible to take into account natural and man-made loads and influences, their change, and possible changes in soil strength characteristics.

The degree of stability of the slope is estimated by the value of the stability margin coefficient (k_{st}).

When $k_{st}>1$, the soil massif of the slope is considered stable.

When $k_{st} <1$, this stability is lost.

When $k_{st} \approx 1$, the state of ultimate equilibrium of the soil mass occurs, which, as a rule, leads to the occurrence of a shift.

A complex for landslide events was recommended based on the results of the slope stability assessment for its further safe operation. The stability of the slope was evaluated taking into account the influence of the sewage collector.

Table 1 – Stability assessment table

Total shear forces, kN	1246,6
Total resistance to displacement, kN	1283,2
Actual stability coefficient	**1,03**
Safety factor	**1,25**
Equivalent value of shear pressure at the end of the slope, kN	-36,6
Equivalent value of shear pressure at the end of the slope with the stability coefficient 1,25, kN	220,0

Conclusions

So, according to the results of research on a natural object within the slope of the Poltava loess plateau with significant anthropogenic influence, it was determined.

1. The following main factors of the occurrence of landslide processes and phenomena under the conditions of the slopes of river valleys have been determined: peculiarities of the geological structure and hydrogeological regime of the slope; genesis and physical and mechanical properties of massif deposits; change of these parameters under the influence of natural or anthropogenic factors.

2. The geological structure of the territory of Poltava Region was analyzed. It is characterized by a wide development of loess rocks with several horizons of fossil soils of lower, middle and upper Quaternary age. The peculiarity of their genesis is their formation as a result of eolian deluvial and eluvial processes.

3. The geological structure of the slopes of river valleys forms a special hydrogeological regime on them. This regime is characterized by the unloading of groundwater in basins formed in watercourses. The formation of landslides most often occurs precisely in such places on the slope. Also, the highly deformed state of the soil massif depends on the physical and mechanical properties of the soil, anthropogenic influence and other factors.

4. The peculiarities of the hydrogeological regime and discharge of groundwater within basins on a sliding slope are determined. The constructed map of the groundwater surface in hydroisogypsums was made to analyze the features of groundwater movement and their influence on the development of landslide processes.

5. It was determined that landslide processes on the slope occur when the hydrogeological regime changes and the natural exits of groundwater to the surface are closed. At the same time, the soil massif is saturated with water, the soil loses part of its strength, and the load on the slope increases. This leads to the formation of local landslide phenomena and processes.

6. The results of the research made it possible to correctly form the initial data for assessing the stability of the slope from the standpoint of the spatial geological structure. And also take into account the hydrogeological factor, structural characteristics of rocks and their changes within the basins. The obtained calculation results are confirmed by finite element modeling using an elastic-plastic soil model with the Mohr-Coulomb strength criterion. This approach made it possible to fairly reliably assess natural and technogenic loads and influences, their changes, as well as possible changes in soil strength characteristics.

7. The results of research and assessment of the stability of the slope, taking into account the influence of the sewage collector, were used to effectively substantiate the recommendations for the design of the complex of anti-slide measures for its further safe operation.

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