Збірник наукових праць. Галузеве машинобудування, будівництво
Academic journal. Industrial Machine Building, Civil Engineering
http://journals.nupp.edu.ua/znp
https://doi.org/10.26906/znp.2020.54.2272

UDC 624.131.537: 624.137

Change of stress-deformed mode of the slope masses during developing and operation of excavations in it

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

Peculiarities of structure geomorphological and engineering-geological features on the site with artificial excavation in the water basin form, the surface water valley runoff into the reservoir, and the soils properties are determined. Negative engineering-geological processes on the site and the reasons for the activation of landslide processes are considered. A slope spatial model is compiled. The slope stability was assessed taking into account the peculiarities of geological and hydrogeological structure using the structural soil strength. Sliding planes and shear pressures on possible landslide protection structures are determined. A "reverse" calculation of the slope stability was also performed to clarify the characteristics of soil strength. It is established that when arranging excavations in the slope array, its SDM changes, which activates landslides.

Keywords: slope, artificial excavation, landslide, comb, soil strength, cohesion, stress-deformed mode, finite element method, ultimate equilibrium method, one plane shear testing, «plate-by-plate» method

Зміна напружено-деформованого стану масиву схилу при влаштуванні та експлуатації у ньому виїмок

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 та інженерно-геологічні особливості будови ділянки розміщення штучної виїмки у вигляді ставка-накопичувача. Виявлено улоговину стоку поверхневих вод до водойми та визначено фізико-механічні властивості ґрунтів. Розглянуто негативні інженерно-геологічні процеси на ділянці й причини активізації зсувних процесів. Складено просторову інформаційну модель масиву схилу, до якої результати лабораторних досліджень ґрунтів внесено шляхом присвоєння її елементам відповідних властивостей. Виконано оцінювання стійкості схилу з урахуванням особливостей його інженерно-геологічної та гідрогеологічної будови і з використанням структурної міцності ґрунтів. Визначено можливі площини ковзання та зсувні тиски на потенційні протизсувні споруди. Проведено «зворотній» розрахунок стійкості схилу для уточнення значень характеристик міцності ґрунтів. Для оцінювання напружено-деформованого стану (НДС) масиву дослідного схилу використано математичне моделювання методом скінченних елементів з використанням пружно-пластичної моделі ґрунту за критерієм міцності Мора – Кулона. При цьому розрахунок методом скінченних елементів виконано шляхом ітераційного зменшення міцності ґрунтів до моменту настання граничної рівноваги. Встановлено, що при влаштуванні виїмок в масиві схилу відбувається зміна його НДС, що в свою чергу активізує зсувні процеси. Доведено, що для комплексного оцінювання впливу виїмки на НДС схилу доцільно використовувати технологію геотехнічного інформаційного моделювання. За результатами моделювання розроблено заходи щодо подальшої безпечної експлуатації схилу з виїмкою шляхом зменшення навантаження на верхню частину масиву та влаштування протизсувної споруди.

Ключові слова: схил, штучна виїмка, зсув, улоговина, міцність ґрунту, зчеплення, напружено-деформований стан, метод скінченних елементів, метод граничної рівноваги, одноплощинне зрушення, методика «плашка за плашкою»

Introduction

The task's urgency related to ensuring the slopes' soil masses stability is due to the need to operate building structures and MEP on landslide hazard areas.

Insufficient study of such areas engineering geological conditions features within the river valleys slopes leads to errors in the design, construction and operation of various building structures and MEP. Such consequences, in particular, are natural landscape disturbance characteristics, which occur during the installation of various artificial excavations, embankments, building pits, cutting slopes, etc. [1 - 4].

Using generally accepted slopes classifications, methods for determining the soils' mechanical characteristics and methods for assessing the soil masses stability and deformability does not make it possible to predict the landslides occurrence and determine the factors that cause them. The landslides occurrence is most often associated with the engineering-geological structure peculiarities and with changes in the slope masses stress-deformed mode (SDM). During the site development of such areas, and especially during the artificial excavations construction, there are additional influences, changes in soil properties, hydrogeological regime and relief [2, 4, 5].

The slopes soil masses SDM study, in particular significant anthropogenic impact, is a complex scientific and practical task. Therefore, to assess the slope stability, it is advisable to build spatial information models (BIM), as well as apply the finite element method (FEM) using elastic-plastic model and appropriate strength criteria, which allows to automate calculations, discretize the calculation area, take into account more factors, reduce time on cyclic operations taking into account changes in engineering-geological and hydrogeological conditions, etc. [6, 7].

This approach allows the development of effective landslide prevention works set at the stages of design, construction and operation of landslide hazard areas.

Review of the research sources and publications

Issues related to the landslides occurrence and dynamics peculiarities within the river valleys slopes are considered in the works of the Poltava geotechnical school, in particular, Yu. Velykodny and M. Zotsenko. The landslide processes formation conditions on the slopes in the presence of groundwater runoff basins are investigated. Using data from laboratory and field tests, landslides monitoring, of geological structure and slope stability assessment analysis, changes in the physical and soils mechanical properties within the basins were studied [2, 6, 7].

To improve the slope stability calculations, the normative standards [8, 9] provide for calculations taking into account the slopes typification. Existing typification is scale-related to geomorphological, geological, hydrogeological conditions, etc.

However, the typification takes into account only the slope destruction nature and the soil masses movement peculiarities, which incompletely allows assessing the landslides causes, which depend on the groundwater regime.

In turn, the groundwater regime is due to the waterproof layer nature, which roof they move in streams with different pressure gradients.

In addition, the existing landslides models do not take into account the spatial effects of soil layers and groundwater movement, which can be taken into account when using information modeling. Similar trends were noted in [12 - 15].

Therefore, based on the existing landslides typification and landslide processes dynamics F. Savarensky, A. Pavlov, I. Popov, Z. Ter-Martirosyan and others developed a classification of depressions and landslides on the slopes, which takes into account the soil mass geological structure.

The slope stability in many cases depends on the characteristics of soil strength and their physical condition. There are a number of methods for determining the mechanical parameters, which are included in the normative standards. Recommended processing test results methods often give unreasonably high strength characteristics values, because the experimental conditions do not correspond to the actual soil state in the slope masses [10, 11].

The landslides causes and development studies, soil strength reliable characteristics determination, the choice of correct calculation schemes for calculation, slope stability assessment and their modeling are exposed in the works of I. Boyko, L. Ginzburg, M. Goldstein, A. Gotman, N. Gotman, M. Demchyshyn, V. Kazarnovsky, M. Kornienko, V. Krayev, M. Maslov, S. Meschyan, D. Shapiro, V. Shvets, O. Schkola A. Bishop, A. Casagrande, J. Duncan and others.

Currently, it is proved the necessity to take into account the violation of soil structure, especially for loessial soil. Because of such violations, the soil strength characteristics are reduced, they should be determined by the «plate-by-plate» method. The characteristics obtained by this method are less compared to the standard method of one plane shear testing, as only the soils structural strength is taken into account, and the calculated slope stability coefficients showed that the use of such parameters allows more reliable slope stability assessment.

In some applications, the reducing procedure the strength properties values are implemented to find such critical values at which loses the slope stability, which helps to establish the actual experimental slope stability coefficient [12].

Definition of unsolved aspects of the problem

The normative standards [8, 9] regulate the slope stability calculation at the first limit state, taking into account both complete and structural soils adhesion. Appropriate techniques for determining complete and structural adhesion give inflated results. As a result, slopes with active displacements are defined as stable when assessing stability. Therefore, obtaining reliable initial data requires improvement of methods for their determination, adapted directly to the soil masses SDM features and slopes engineering-geological structure.

In addition, traditional methods for slope stability assessment often do not take into account the presence of depressions in waterproof layers. As a soil feature result in the geological structure is constantly under the more intense movement influence of groundwater flow. This negatively affects their mechanical properties and requires a specific approach to research methods. These factors and the forecast of their changes should be taken into account when assessing the soil mass SDM and the slopes stability.

Problem statement

Therefore, the purpose of the work is: to study the soil slope SDM with an artificial excavation (water basin); slope stability assessment of this array, taking into account the engineering-geological structure peculiarities, changes in the soils physical and mechanical properties in the depression; development of recommendations to protect the array from landslides.

To achieve it, the following tasks: engineering-geodetic and engineering-geological studies of the territory; laboratory studies of soil characteristics to assess the stability of the slope; slope information model construction, slope engineering-geological profiles and calculation schemes; possible lines (planes) determination of sliding and estimation of all slope and its separate sites stability; development of recommendations to stabilize landslide processes during operation on the structures slope.

Basic material and results

The site is situated in Azov-Pridniprovska geomorphological region of Kozyatyn structural-denudational watershed and is dated to the slope of the right tributary of the Kamyanka River. The region's river valley characteristic feature structure is formation in wide water-glacier descents and valleys with wide wetlanded bottoms.

By the analysis of toposurface, which was plotted before the embankment construction for the territory, it can be argued that the territory had general surface slope in the southwest direction–to the river (the right slope of valley of unnamed river, which is the right branch of Kamyanka river).

The slope surface was cut by the valley-erosion net. The most characteristic example of the network landforms is the depression (fig. 1), which was covered up in the construction process and constructed a water basin (fig. 2).

In the natural state (prior to the territory construction), the depression was the flow path of surface water into the river (the basin area from which surface water was collected is about 110,000 m2). At the top of the depression is an abandoned loam pit 2,5 - 6,5 m deep. On the bottom of the coombe, there are occasional deposits of dusty sand 1 – 5 cm.

The water ground level is about 9,7 – 13,1 m from the ground surface. Sands and sandy loams are water-bearing soils.

The geological structure of the site up to a depth of 30 m involves the thickness of Quaternary sediments: silty sands, small and medium size, as well as sandy loam and loam, which are covered with loose soil, soil-vegetative layer and humidified loam with total thickness 2,5–6,3 m (fig. 3, 4).

According to geological surveys, the depression geological structure presents soils that have genetic differences from the surrounding area soils (deluvial and alluvial soils). This feature is due to the processes associated with surface and groundwater runoff (flushing, erosion, filtration), which contributed to the formation of deluvial and alluvial deposits on the slopes and in the lower part of the basin.

Note, that the atmospheric water discharge to vertical planning occurred along this buried depression in the southwest direction. Because of such a long water movement impact in the depression, the soil has significantly lost its mechanical properties. From a hydrogeological point of view, the "buried" by embankment coomb continues to be a path of groundwater flow in the direction of the slope.

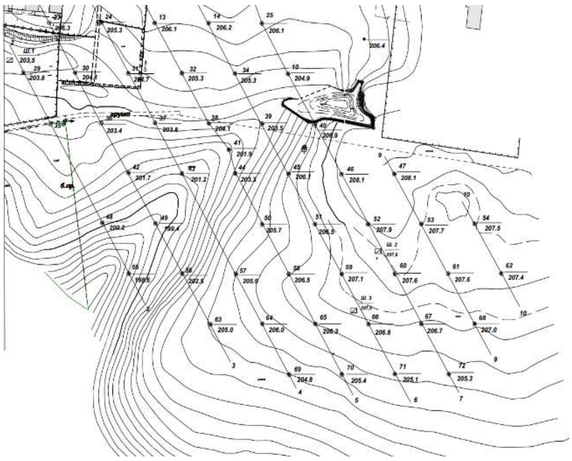

Figure 1 – Depression layout scheme (before construction in the territory)

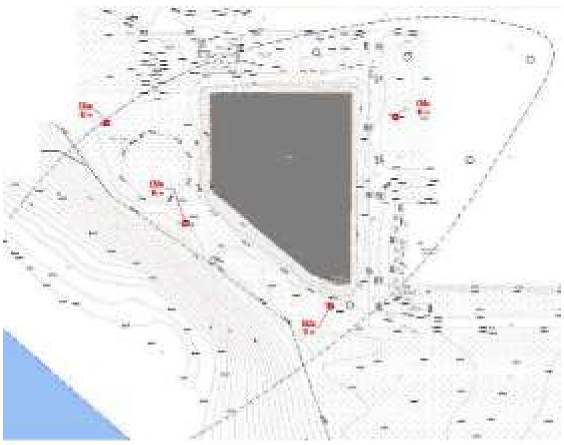

Figure 2 – Slope layout scheme with water basin

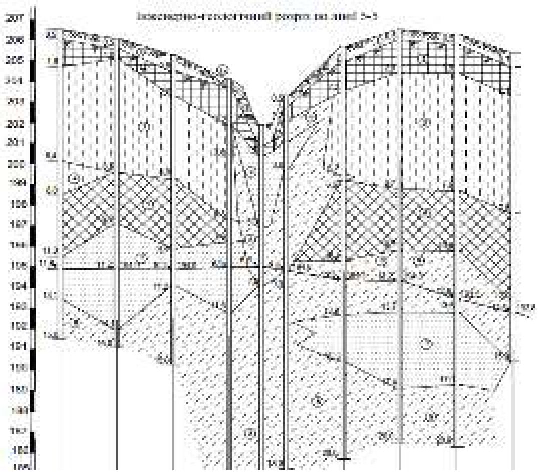

Figure 3 – Engineering-geological section before the slope construction

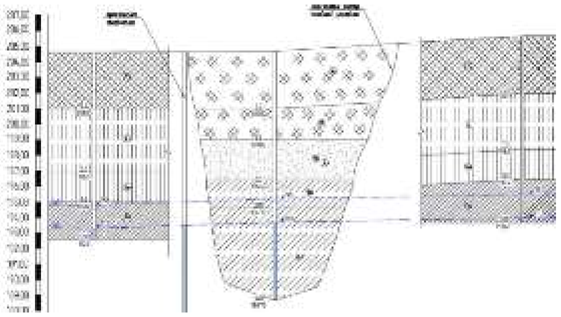

Figure 4 – Engineering-geological section after the slope construction

Unfavorable physical-geological processes within the site include:

– significant soil array heterogeneity both in area and depth: the presence of numerous layers, lenses, wedges, etc.; separate layers of soil encountered only by one or two wells; such array structure features indicate, among other things, the different soil sediments origin;

– presence soils with specific properties (collapsing, soft, backfills) particularly IGE-4 (loess sandy loam, silty, stiff, in saturated state – liquid, macroporous) and IGE-4 (loess loam, silty, macroporous, stiff, in saturated state – soft-plastic, macroporous) with collapsible properties due to loess strata saturation from surface mainly by atmospheric water infiltration;

– silty sand (IGE-5b) and silty sandy loams (IGE-6 and IGE-6a) with liquefied properties;

– site surface water erosion;

– presence of buried depression on the water basin site;

– presence of abandoned loam pit at the depression top;

– presence of landslide processes on the slope.

These negative processes led to the partial water basin slopes destruction, which were confirmed by the monitoring results. This deformation type can indicate the soil mass displacement and its pressure on the north side of the pond, resulting in a slight lifting of its sides - up to 30 mm.

On the southwest side of the basin, due to the soil mass displacement down the slope, the sides of its basin the slab lowering occurs (up to 250 mm), as well as the basin slope subsidence in the middle part (fig. 5). These deformations are the result of the landslide processes activation. The local transverse (latitudinal) fissures in the embankment massive from the riverside, water basin banks destruction should be highlighted among them.

Landslide processes activation is influenced by:

– depression territory usage, through which water flow to river was, for water basin construction; after water basin construction this water flow was partially blocked leading the slope soil massive additional saturation;

– territory releveling in the water basin construction process (excavation / mound) of soil mass contribute for atmospheric water accumulation in this manmade massif;

– active releveling of territory relief on the slope without layer by layer compaction and control of this process, turf cutting, activated landslides, erosion processes, mechanical suffusion, subsidence, etc;

– collapsible loess soils saturation (as a result of drainless areas, not enough organized surface drainage) contribute to soil mechanical properties decreasing;

– natural slope massif additional loading by soil embankment and constructions and water basin content.

Figure 5 – Soil slope subsidence of south-west side of water basin

Therefore, the visual surveys, topographic survey of the territory, as well as based on the archival data generalization in the existing water basin area can summarize the following.

1) Soil massif displacement processes occur at the investigated site.

2) The soil masses displacement affects the structures and the technical condition of the water basin and other surrounding buildings and structures.

3) As the territory made up of artificial embankment, and the water basin territory is in the place buried by the natural depression embankment, two variants of the landslides are possible:

- soil masses displacement occurs only within the bulk soils limits on the natural depression surface;

- soil displacement occurs on sliding surfaces within the natural soils of alluvial and delluvial genesis.

To assess the slope stability, engineering-geological profiles (sections) are constructed both in the longitudinal and transverse directions.

This importance is given to the origin (genesis) of each soil layer (IGE).

To evaluate soil properties, the characteristics of several groups are used: classification; basic; derivatives. For this purpose, soil samples of the undisturbed (natural) structure selected from the boreholes were used.

For strata above or at the level of the sliding surface, an additional test was performed using the method «plate-by-plate».

To analyze the groundwater level, a groundwater surface map in hydroisogips was drawn up (fig. 6).

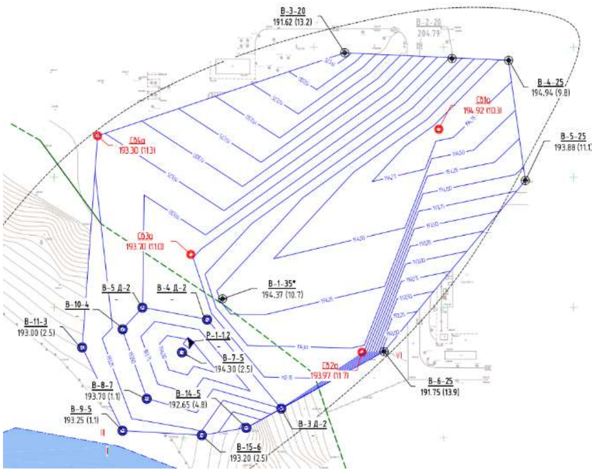

Figure 6 – Hidroisohypsis scheme on a site survey

As a result, the groundwater movement intensity increases, the hydraulic gradient increases, which leads to the soils weakening in the basin, their partial destruction

As a result of the natural place overlapping of ground water unloading by filling soil and the water basin construction, the groundwater level rose locally.

It is enhanced by leakage from the water basin and storm water drainage system.

The rise of groundwater around the water basin is confirmed by the hydroisogip scheme (fig. 6). It is marked by a "dome" and a change in the place of unloading groundwater on the slope.

Changing the hydrogeological regime and increasing the hydraulic gradient in the soils massif results in their considerable weakening, suppositional destruction and decrease of slope stability.

Generally, slope stability breach is associated with overcoming soil resistance forces by shear stresses acting on some planes.

Shear stresses in slope massif appear under the self-weight influence of soil mass and additional loading to slope from structures and filtration water pressure.

Soil shear resistance exists due to forces of internal friction and cohesion acted in soil massif. If the friction is present ($\varphi>0°$) forces of friction arise under influence of soil self-weight and additional load from structures.

After generating the initial data to assess the slope stability, calculations by combined slip surface, which position was chosen in most weak soil stratum along contact surfaces based on creation of maximal acting to retaining structures, were used and those calculations were checked by numerical modeling by FEM.

In such a case, the rate of slope stability is evaluated by value of safety factor (SF or k_{st}). In the case of $k_{st} > 1$, the slope is considered stable. In the case of $k_{st} < 1$, the slope stability loss is occurs. In the case of $k_{st} \approx 1$ the equilibrium limit state comes which leads to landslide.

Slope stability assessment consists in equilibrium condition consideration of soil massif 1 m width (two dimensional problem) with vertical lateral faces, conditionally cut from slope massif in the landslide direction (forces acted to lateral faces are not taken into account).

Its position is influenced by the peculiarities of the engineering-geological structure and hydrogeological regime on the site.

The sliding surfaces position was specified on the basis of a stability calculations series and the most probable sliding surface selection, where the stability coefficient value is minimal.

To clarify the soil strength characteristics (internal friction angle φst and structural specific cohesion c_{st}), a "reverse" calculation is performed.

It is performed with stability factor is equal to one ($k_{st} = 1$), because the slope is in a landslide condition (cracks, slopes, trees inclination towards the slope fall, etc.).

Inverse calculations for slope stability assessment are based on the analysis of their actual and forecast state, taking into account the action of all possible adverse factors and changes in engineering and geological conditions. This takes into account the change in hydrogeological conditions (surface and underground flown) by increasing the actual groundwater level, as well as changing the massive soil strength characteristics (using the smallest values obtained in the "reverse" calculation).

The aquifers influence that drain on the slopes' stability is taken into account in the conditions of rocks wetting, weighing, filtration pressure, removal by piping.

Water causes a weighing effect on the deposits that make up the slope. By saturating the soils, the water changes their physical and mechanical characteristics, and especially reduces the shear resistance value.

In addition, groundwater, wetting possible sliding surfaces, reduces friction. In doing so, the water, by weighing the soil skeleton, reduces the normal stresses in the displacement plane due to the pore pressure and can lead to almost complete removal of the internal friction in the soil.

According to the above methods and prerequisites, the calculation of the water basin dam slope stability were realised (table 2).

The slope calculation diagram is shown in fig. 7.

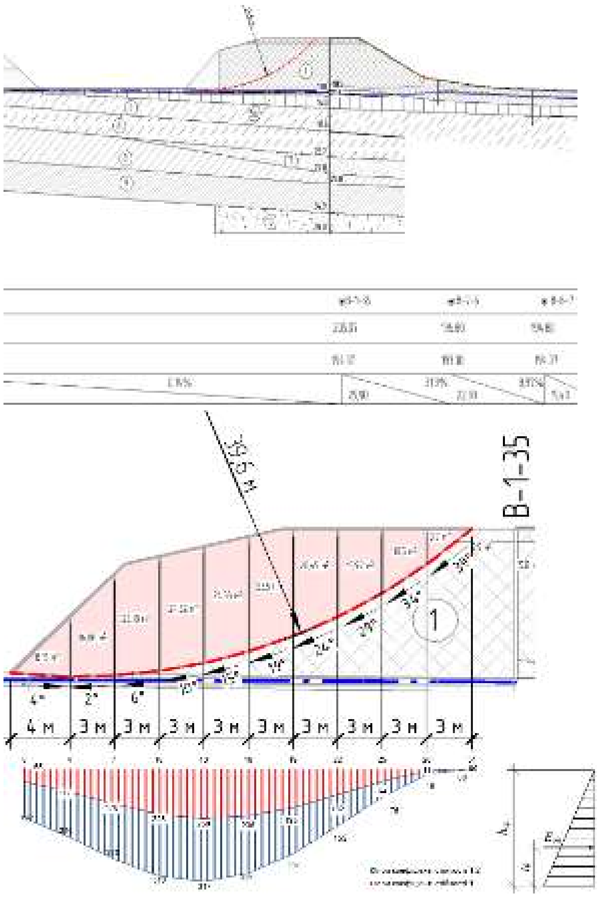

Figure 7 – Calculation schemes:
from above - placement of the sliding line on the engineering-geological section of the slope massif;
bottom - distribution diagram of equivalent shear pressure (kN / m.p.) at stability coefficient 1 and 1.2

FEM modeling was used to estimate the SDM of soils on the slope.

Slope stability modeling was performed using an elastic-plastic model with the Moore-Coulomb (MK) strength criterion. The following preconditions are accepted in the elastic-plastic problem formulation:

- the considered nonlinearity manifestations include plastic deformation of forming under a complex stress state, unimpeded deformation under tension;

- in a complex stress state (compression with shear), the total deformation contains a linear (elastic) and plastic parts, and the plastic deformation component occurs after the stress state reaches the tensile strength in accordance with the condition MK for the plane problem

$$\frac{1}{2}(\sigma_1-\sigma_2)+\frac{1}{2}(\sigma_1+\sigma_2)\sin\varphi-c\cdot\cos\varphi=0\,. \qquad (1)$$

The computational domain discretization while solving a nonlinear problem is performed by FEM.

The modeling was performed according to the method of soil strength reduction. It consists in reducing the strength characteristics until the onset of ultimate equilibrium.

This approach determines the slope stability coefficient as the specified characteristics ratio to their limit values

$$k_{st}=\frac{c+\sigma\cdot\tan\varphi}{c_r+\sigma\cdot\tan\varphi_r}\,, \qquad (2)$$

where c and φ are the initial strength characteristics;
r – normal voltage component;
c_r and φ_r are the limit values of strength characteristics

Accepted in the physical and mechanical properties calculations of engineering-geological elements and the structures properties are summarized in table. 1.

The geometric model with a finite elements grid for calculation and simulation results are shown in fig. 8.

It is used to determine possible sliding lines (planes) and to assess the entire slope stability and its individual sections, to develop measures to stabilize landslide processes during operation on the structures' slope, and so on.

In particular, according to the calculations results, the soil mass stability coefficient was 0.91. The artificial recess and the slope are in unsatisfactory technical condition. The actual soil mass state is approaching the limit, it is possible to intensify landslides.

Table 1 – Calculated Values of physical and mechanical properties of soils

Parameter	Unit	Number of soil strata				
		1	1a	1б	2	3
γ_I/γ_{II}	kN/m^3	16,8 17,0	18,4 18,6	16,5 16,7	16,7 16,9	17,5 17,6
The angle of internal friction φ_I/φ_{II}	deg.			11/ 13	24/25	17/18
Unit cohesion c_I/c_{II}	kPa			10,2/ 11,6	0,0/ 0,0	15,3/ 16,7
Unit cohesion structural	kPa			1,0	0,0	5,2

Table 2 – Shear forces calculation of the water basin dam soil massif

Block No.	Block length	Soil layer No.	Block Area, m^2	Block Volume, m^3	Unit weight of soil, kN/m^3	Block weight, kN	Slope angle of block	Internal friction angle φ_I, °	Unit effective cohesion c, kPa	Shear stress, kN	Shear resistance, kN		Shear stress (pressure), kN	Diagram of shear pressure by safety factor 1, kN	Diagram of shear pressure by safety factor 1.2, kN
											Fiction resistance, kN	Cohesion resistance, kN			
1	3	1	3,70	3,70	17	62,9	39,00	11,0	5	39,6	9,5	19	10,8	10,8	15,6
2	3	1	10,50	10,5	17	178,5	34,00	11,0	5	99,8	28,8	18	53,0	63,7	76,3
3	3	1	15,97	15,97	17	271,5	29,00	11,0	5	131,6	46,2	17	68,3	132,1	155,2
4	3	1	20,45	20,45	17	347,7	24,00	11,0	5	141,4	61,7	16	63,2	195,3	231,5
5	3	1	23,57	23,57	17	400,7	19,00	11,0	5	130,5	73,6	16	40,9	236,2	287,4
6	3	1	24,38	24,38	17	414,5	15,00	11,0	5	107,3	77,8	16	13,9	250,2	316,8
7	3	1	24,32	24,32	17	413,4	10,00	11,0	5	71,8	79,1	15	-22,6	227,6	310,0
8	3	1	23,18	23,18	17	394,1	6,00	11,0	5	41,2	76,2	15	-50,1	177,5	275,1
9	3	1	16,88	16,88	17	287,0	2,00	11,0	5	10,0	55,7	15	-60,7	116,8	226,2
10	2	1	8,15	8,15	17	138,6	-4,00	11,0	5	-9,7	26,9	15	-51,6	65,2	181,6
									Total	763,5	535,5	163			
										763,5	698,3				

Safety factor 0,91

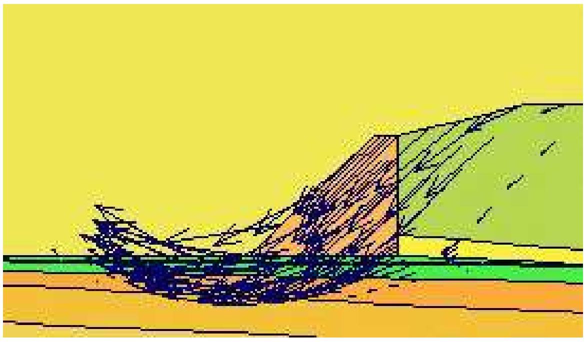

Figure 8 – Geometric model and results of SDM slope modeling

Modeling of the FEM using a comprehensive approach to determining the initial data confirms the calculations results and the actual slope soil massif state. Based on the results of assessing the slope stability with an artificial excavation for its accident-free operation, it is advisable reducing load on the slope (embankment) by cutting loose soil on the slope (minimum 2 m).

It is expedient to plan the territory for organized drainage of atmospheric water from the slope towards the river, as well as the landslide protection structures arrangement.

Conclusions

1. As a result of engineering-geodetic and engineering-geological survey of the territory there is a possibility of slope spatial information model geometry construction. The soils laboratory studies results are included in this model by assigning its elements the appropriate properties.
2. As a result of slope stability assessment analytically and by modeling the SDM according to the methods described above, the possible sliding planes and shear pressures on potential landslides were determined.
3. It is established that when arranging excavations in the slope array, its stress-strain state changes. This in turn affects the landslides activation. For a comprehensive assessment of the excavations' impact on the stress-strain state, it is advisable to use the technology of geotechnical information modeling.
4. Procedures have been developed for further slope operation with a recess by reducing the load on the upper slope part and the landslide protection structure installation.

References

1. Briaud J.-L. (2013). *Geotechnical Engineering: Unsaturated and Saturated Soils*. Wiley

2. Великодний Ю.Й., Біда С.В., Зоценко В.М., Ларцева І.І., Ягольник А.М. (2016). *Захист територій від зсувів.* Харків: «Мадрид».

3. Гинзбург Л.К. (2007). *Противооползневые сооружения.* Днепропетровск: «Лира ЛТД»

4. Біда С.В. (2011). Особливості зсувних процесів на схилах річкових долин. *Будівельні конструкції: міжвід. наук.-техн. збірник*, 75-2, 371-377

5. Lim K., Li A. & Lyamin A. (2015). *Slope stability analysis for fill slopes using finite element limit analysis.* Proc. of the XVI ECSMGE Geotechnical Engineering for Infrastructure and Development. Edinburgh: ICE Publishing, 1597-1602.
https://doi:10.1680/ecsmge.60678

6. Зоценко М.Л., Винников Ю.Л., Харченко М.О., Марченко В.І., Титаренко В.А. (2013). Заходи зі стабілізації зсувного схилу. *Будівельні конструкції: Міжвід. наук.-техн. зб. наукових праць (будівництво)*, 79, 256-264.

7. Aniskin A., Vynnykov Yu., Kharchenko M. & Yagolnyk A. (2019). *Calculation of the slope stability considering the residual shear strength.* Proc. of the 4th Regional Symposium on Landslides in the Adriatic Balkan Region. Sarajevo: Geotechnical Society of Bosnia and Herzegovina, 209-216.
https://doi.org/10.35123/ReSyLAB_2019_35

8. ДБН В.1.1-46:2017 (2017). Інженерний захист територій, будинків і споруд від зсувів та обвалів. Основні положення. Київ: Мінрегіонбуд України.

9. ДБН В.1.1-24:2009 (2010). *Захист від небезпечних геологічних процесів. Основні положення проектування.* Київ: Мінрегіонбуд України.

10. ДСТУ Б В.2.1-4-96 (1997). *Ґрунти. Методи лабораторного визначення характеристик міцності і деформативності*. Київ: Державний комітет України у справах містобудування і архітектури.

11. Tschuchnigg H.F. (2015). *Performance of strength reduction finite element techniques for slope stability problems*. Proc. of the XVI ECSMGE Geotechnical Engineering for Infrastructure and Development. Edinburgh: ICE Publishing, 1687-1692.
https://doi:10.1680/ecsmge.60678

12. Kopecký M. & Frankovská J. (2017) *Geotechnical problems of expressway construction in landslide area in East Slovakia*. Proc. of the 19th Intern. Conf. on Soil Mechanics and Geotechnical Engineering. Seoul, 2167-2170.

13. Kudla W., Szczyrba S., Rosenzweig T., Weißbach J., Kressner J., Grosser R. & Lucke B. (2015). *Flow-liquefaction of mine dumps during rising of groundwater-table in Eastern Germany – reasons and model-tests*. Proc. of the XVI ECSMGE Geotechnical Engineering for Infrastructure and Development. Edinburgh: ICE Publishing, 1585-1590.
https://doi:10.1680/ecsmge.60678

14. Silvestri V. & Abou-Samra G. (2017) *Re-assessment of stability of the experimental excavation in the sensitive clay of Saint-Hilaire (Quebec)*. Proc. of the 19th Intern. Conf. on Soil Mechanics and Geotechnical Engineering. Seoul, 2211-2214.

15. Allahverdizadeh P., Griffiths D.V. & Fenton G.A. (2015). Influence of different input distributions on probabilistic outcomes in geotechnical stability analysis. *Proc. of the XVI ECSMGE Geotechnical Engineering for Infrastructure and Development*, 1549-1554.
https://doi:10.1680/ecsmge.60678

1. Briaud J.-L. (2013). *Geotechnical Engineering: Unsaturated and Saturated Soils*. Wiley

2. Velykodnyi Yu.Y., Bida S.V., Zotsenko V.M., Lartseva I.I. & Yaholnyk A.M. (2016). *Protection of territories from landslides.* Kharkiv: "Madrid"

3. Hynzburh L.K. (2007). *Landslide protection structures*. Dnipropetrovsk: «Lyra LTD»

4. Bida S.V. (2011). *Features of landslide processes on the slopes of river valleys*. *Budivelni konstruktsii: mizhvid. nauk.-tekhn. zb.* , 75-2, 371-377

5. Lim K., Li A. & Lyamin A. (2015). *Slope stability analysis for fill slopes using finite element limit analysis.* Proc. of the XVI ECSMGE Geotechnical Engineering for Infrastructure and Development. Edinburgh: ICE Publishing, 1597-1602.
https://doi:10.1680/ecsmge.60678

6. Zotsenko M.L., Vynnykov Yu.L., Kharchenko M.O., Marchenko V.I. & Tytarenko V.A. (2013). Landslide stabilization measures. *Budivelni konstruktsii: Mizhvid. nauk.-tekhn. zb. naukovykh prats (budivnytstvo)*, 79, 256-264.

7. Aniskin A., Vynnykov Yu., Kharchenko M. & Yagolnyk A. (2019). *Calculation of the slope stability considering the residual shear strength.* Proc. of the 4th Regional Symposium on Landslides in the Adriatic Balkan Region. Sarajevo: Geotechnical Society of Bosnia and Herzegovina, 209-216.
https://doi.org/10.35123/ReSyLAB_2019_35

8. DBN V.1.1-46:2017 (2017). *Engineering protection of territories, buildings and structures from landslides and collapses. General principles.* Kyiv: Minrehionbud Ukrainy.

9. DBN V.1.1-24:2009 (2010). *Protection against dangerous geological processes. Basic design principles.* Kyiv: Minrehionbud Ukrainy.

10. DSTU B V.2.1-4-96 (1997). *Soils. Methods of laboratory determination of strength and deformability characteristics.* Kyiv: Derzhavnyi komitet Ukrainy u spravakh mistobuduvannia i arkhitektury.

11. Tschuchnigg H.F. (2015). *Performance of strength reduction finite element techniques for slope stability problems.* Proc. of the XVI ECSMGE Geotechnical Engineering for Infrastructure and Development. Edinburgh: ICE Publishing, 1687-1692.
https://doi:10.1680/ecsmge.60678

12. Kopecký M. & Frankovská J. (2017) *Geotechnical problems of expressway construction in landslide area in East Slovakia*. Proc. of the 19th Intern. Conf. on Soil Mechanics and Geotechnical Engineering. Seoul, 2167-2170.

13. Kudla W., Szczyrba S., Rosenzweig T., Weißbach J., Kressner J., Grosser R. & Lucke B. (2015). *Flow-liquefaction of mine dumps during rising of groundwater-table in Eastern Germany – reasons and model-tests*. Proc. of the XVI ECSMGE Geotechnical Engineering for Infrastructure and Development. Edinburgh: ICE Publishing, 1585-1590.
https://doi:10.1680/ecsmge.60678

14. Silvestri V. & Abou-Samra G. (2017) *Re-assessment of stability of the experimental excavation in the sensitive clay of Saint-Hilaire (Quebec)*. Proc. of the 19th Intern. Conf. on Soil Mechanics and Geotechnical Engineering. Seoul, 2211-2214.

15. Allahverdizadeh P., Griffiths D.V. & Fenton G.A. (2015). Influence of different input distributions on probabilistic outcomes in geotechnical stability analysis. *Proc. of the XVI ECSMGE Geotechnical Engineering for Infrastructure and Development*, 1549-1554.
https://doi:10.1680/ecsmge.60678