



Assessment of the Stability of the Slope of Kok Tobe Mountain

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Abstract

In this work, the stability of the slope of Mount Kok Tobe is assessed under the following three conditions: condition 1 - the soil of the slope is homogeneous and is completely in its natural state; condition 2 - the surface layer of the slope 70 cm thick is moistened by rainwater and it is assumed that the sliding surfaces are deep (below the base of the slope); condition 3 - the surface layer 70 cm thick is moistened by rainwater and it is assumed that the sliding surfaces are close to the moistened surface layer of the slope. The assessment of slope stability was carried out using the circular cylindrical sliding surface (CCSS) method. A modified CCSS method has also been developed and used in the calculations, which, together with the Terzaghi-Fellenius method, makes it possible to speed up and increase the accuracy of determining the position and characteristics of sliding surfaces. The calculation results showed that the slope is practically in a nonequilibrium (dangerous) state.

Keywords: Calculation of mountain slope stability; Circular cylindrical sliding surface method; Modified CCSS method; Precipitation.

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1. Introduction

Assessing the stability of mountain slopes is an important task in geotechnical engineering as it helps to identify potential slope failure risks and take necessary measures to prevent disasters. In this paper, the stability of one of the slopes of Mount Kok Tobe, located near the city of Almaty, is assessed. The landslide condition of the slopes of this mountain has not yet been sufficiently studied using modern geomechanical methods.

The height of Mount Kok Tobe is 250 m, and the height of the television tower, built on its western slope on loose soils, is 372 m; the total height relative to Dostyk Avenue is 622 m. Regarding the Kok Tobe TV tower, nature has already given threatening signals. For example, in 1985, the slopes of Mount Kok Tobe were washed away by rains, mudflows and dangerous processes of sliding of the soil base of the tower. In the early spring of 2004, after heavy rains on Kok Tobe, an emergency occurred on the surface of the mountain, significant cracks appeared, the soil began to slide and buildings collapse. Kok Tobe settled 2 meters down. There

was a real threat of a landslide affecting nearby residential areas. After examining the eastern slope, municipal services discovered a crack 5 m wide and 1.5 m deep.^[1]

In 2016, on May 11, in the Medeu region, due to hypothermia of the soil, a landslide descended from the Eastern slope of Mount Mokhnatka.^[2,3] A year later in 2017, in early spring, 64 cases of spontaneous landslides occurred in the eastern territory of Almaty. In May, 35 landslides were recorded due to sudden warming, melting snow and heavy rains. In 2023-2024, three large landslides occurred in the immediate vicinity of the object we studied: 1) On February 27, 2023, in the cottage town of Burabay in the village of Besagash, Talgar district, due to precipitation, the soil became waterlogged, resulting in a spontaneous flow of soil from the mountainside toward two private residential buildings on Bayanaul Street through a protective fence - a concrete retaining wall. The approximate volume of drained soil is 360 cubic meters.^[4] 2) On February 8, 2024, four people died as a result of a landslide on private residential buildings No. 3A and No. 3, located on Olimpiyskaya Street (Tau-Samal microdistrict, Medeu district of Almaty). The predicted volume of the landslide is about 3,200 m³, Kazselezaschita reported. The mountain slope consists of loess-like loams (subsidence soils), and the steepness of the slope in this area

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is approximately 45-50 degrees.^[5] 3) In the cottage town of "Burabai", due to unstable weather conditions in the period from March 21 to 23, 2024, the soil became waterlogged, as a result of which the soil spontaneously flowed from the mountainside onto the territory of two private residential buildings. The soil ran along the edge of an unfinished protective fence (a 4m high concrete retaining wall). The fallen soil damaged a window opening (glass was broken) in the house, and also partially damaged a temporary structure (outbuilding) on the territory of the house. The approximate volume of drained soil is 500 cubic meters.^[6,7]

Evaluation of mountain slope stability is an important task in geotechnics and engineering geology. In recent years, significant progress has been made in international research in this field. Modern approaches include the use of numerical modeling, laboratory testing, and remote sensing methods to analyze slope dynamics under the influence of climatic and other factors. A large number of works by researchers from different countries are devoted to the study of landslides on mountain slopes. Thus, in this area of science, the works are well known.^[8,9] There are also works that pay attention to determining the types and mechanisms of landslides, and methods for calculating slope stability have been developed.^[10-14]

Researchers in slope geomechanics have begun to successfully use special computer programs. For example, Zhong *et al.*^[15] studied the mechanisms of precipitation penetration into unsaturated soil using the SEEP/W and SLOPE/W software modules. Geo5 software was used to analyze and stabilize slope stability.^[16] The possibility of landslides occurring on mountain slopes due to precipitation was shown by the authors of the work.^[17-20] The results of the work also draw attention to the negative consequences of water saturation of slope soils.^[21] The relationship between the features of the evolution of filtration (due to the infiltration of rainwater) and the patterns of changes in the stability of granite residual soil inside a high slope is considered by the authors of the work.^[22]

Harabinová and Baimakhan *et al.*^[23,24] are devoted to assessing the stability of slopes on roads. It has been established that one of the places where landslides occur is the cut areas of mountain slopes in order to pave a road. Coccia *et al.*^[25] have shown that using the finite element method (FEM) in combination with LiDAR data allows for accurate modeling of slope behavior during soil moisture. Frodella *et al.*^[26] proposed a method for using thermal imaging data for early detection of potential landslide zones under conditions of intense snowmelt was proposed.

A comparative analysis of various slope stability

assessment methods performed Sirotkina *et al.*^[27] demonstrated that traditional limit equilibrium methods (LEM) have limitations in modeling the influence of meltwater. While methods that take into account the thermal-hydrromechanical behavior of soils, such as Coupled Thermal-Hydro-Mechanical (THM) models, show higher accuracy, but require significant computational resources.

The results of the Kopytov *et al.*^[28] showed that the integration of numerical methods with remote sensing can significantly improve the accuracy of slope stability assessment. Their work demonstrated the effectiveness of using LEM in combination with geotechnical models that take into account the degree of soil water saturation.

Bouajaj and Kasri proposed a method for assessing slope stability using the Monte Carlo method based on the Hovland method.^[29] The influence of random variables such as cohesion and angle of internal friction of a soil on slope stability is analyzed. It was shown that the proposed method yields results comparable to previous studies and can be used to analyze the stability of homogeneous slopes.

Zerkal *et al.*^[30] analyzed the limitations of deterministic approaches and considered the principles of probabilistic analysis in slope stability modeling. They demonstrated that probabilistic methods allow for more accurate consideration of geological risks and prediction of possible landslide processes.

Kundu *et al.*^[31] examined probabilistic methods for assessing slope stability, allowing for the spread of soil characteristics and uncertainties in the context of external influences. The Monte Carlo method was used to predict the probability of slope failure, which allowed for the expansion of engineering solutions in areas with a high risk of landslide processes.

The application of machine learning to predict the stability of rock slopes is shown in Arif *et al.*^[32] This work considers various algorithms, including random forests, gradient boosting, and deep neural networks. Their effectiveness in analyzing factors affecting the probability of landslides is shown.

Gael *et al.*^[33] conducted a comparative analysis of various methods for assessing slope stability (the limit equilibrium method, the finite element method, and analytical approaches). It was found that integrated models that take into account several risk factors provide more accurate forecasts.

The modified CCSS method proposed in this article combines the advantages of the classical LEM and elements of soil saturation with moisture. Unlike complex THM models, it allows for faster calculations with sufficient accuracy for engineering practice. The main advantage of the approach

used in our article is the possibility of its application in warm regions, where the surface soil layer of mountain slopes is moistened mainly by rainwater in the spring.

2. Brief description of the object

Mount Kok Tobe, whose height reaches 1130 meters above sea level, is part of the Almaty mountain range. The region is characterized by a variety of landscapes and unique flora and fauna. As a result of the processes of erosion, natural subsidence, tectonic and climatic changes, as well as anthropogenic influences (tourist activity, road construction, construction of buildings and structures, etc.), the stability and stability of mountain slopes become relevant. Studying the stability of mountain slopes makes it possible to develop sound recommendations for further ensuring their stability, which will ensure the safety of people, the normal functioning of facilities, and preserve the natural wealth of the region.

Geographical location: Kok Tobe is located on the southeastern slopes of the Zailiyskiy Alatau mountain range, in close proximity to the city of Almaty. The mountain is easily accessible both by car and by cable car, making it a popular place for walking and relaxing.

Nature and ecology: The slopes of Kok Tobe are covered with greenery, including coniferous and deciduous trees,

which contributes to the creation of a favorable microclimate and ecosystem. The area is home to various species of flora and fauna, making it an important natural site.

Tourism and recreation: Kok Tobe attracts tourists thanks to its observation deck, which offers breathtaking views of Almaty and the surrounding mountains. The mountain has various entertainment facilities such as cafes, restaurants, a play park and cultural monuments, including the My Friend the Dog statue and other art objects.

History and culture: Kok Tobe has a rich history, which, according to local legends, is connected with ancient legends and cultural traditions of the Kazakh people. The mountain also serves as a venue for various cultural events and festivals, which helps to preserve the cultural heritage of the peoples of the region.

Conservation and sustainable development: In recent years, attention to environmental protection and sustainable development of the region has become especially important. Measures to maintain the environment and prevent slope erosion and landslides are becoming increasingly important.

Fig. 1 shows Mount Kok Tobe, on which the part of the mountain we are studying is highlighted with yellow lines. Since the slopes of the mountain are symmetrical about the vertical axis, for further research we accept only the right slope.

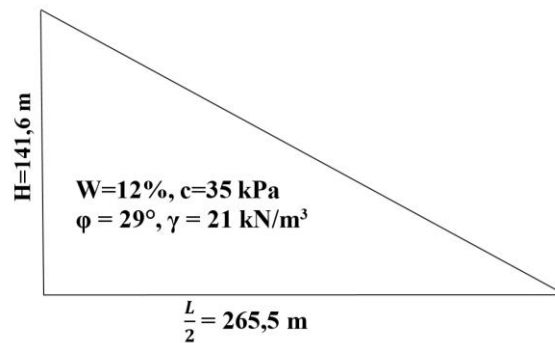
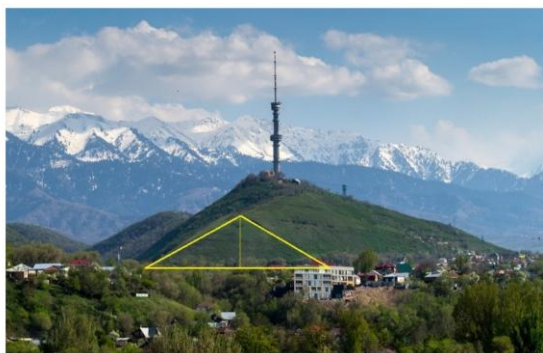


Fig. 1: South-eastern slope of Mount Kok Tobe, geometric dimensions and soil characteristics.

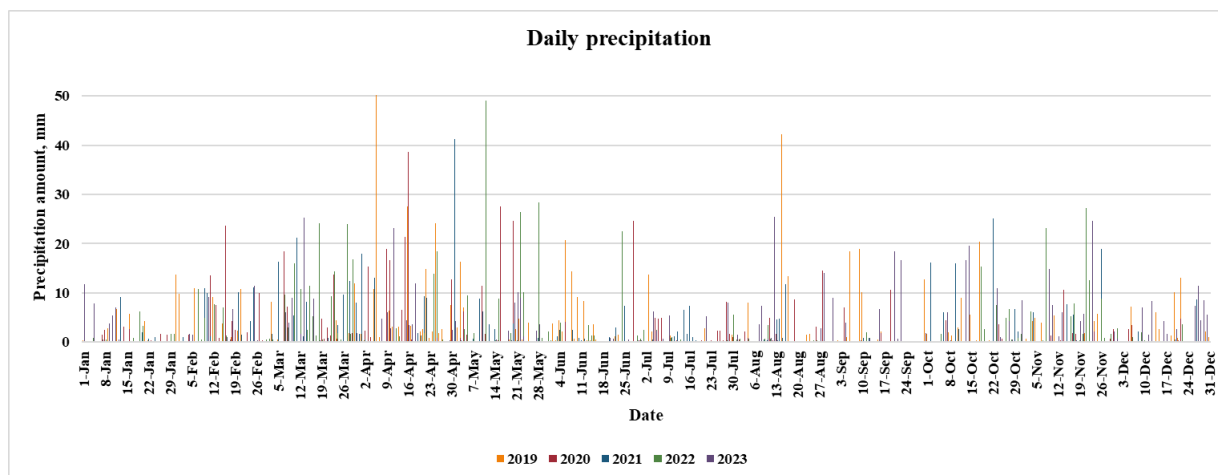


Fig. 2: Daily precipitation in the vicinity of Mount Kok Tobe.

3. Atmospheric precipitation

3.1 Precipitation distributions

Mount Kok Tobe has specific climatic and meteorological conditions that are closely related to the level of precipitation. Precipitation plays a key role in the mountain ecosystem, in its water exchange, the balance of mountain ranges, and the stability of slopes.

Data on daily amounts of precipitation in the vicinity of Mount Kok Tobe for the period from January 2019 to December 2023 were obtained by the National Hydrometeorological Service of Kazakhstan.^[34] Fig. 2 shows a histogram of the distribution of daily precipitation. The highest daily precipitation reached 50.2 mm in 2019, 38.7 mm in 2020, 41.2 mm in 2021, 49.0 mm in 2022, and 25.5 mm in 2023. The average value of maximum daily precipitation in the five-year period under review was 40.9 mm.

Average daily air temperature, precipitation amount, and snow cover height in 2022 are presented in Figs. 3 and 4. As

can be seen, in the region under consideration, the duration of the cold period is very short, the amount of precipitation during the cold period is significantly smaller compared to the warm period, and the height of the snow cover usually does not exceed 10 cm (with the exception of only one case).

A histogram of monthly precipitation amounts is shown in Fig. 5. As can be seen, the spring months, especially April 2019 and March 2022, received large amounts of precipitation (up to 165 mm per month). As can be seen from Fig. 6, total annual precipitation ranges from 489 mm (2021) to 660 mm (2019), with an average of 575 mm.

Thus, an analysis of the distribution of precipitation showed that, in the vicinity of Mount Kok Tobe, the highest and average amounts of daily precipitation are approximately 50 mm and 41 mm, respectively; the maximum monthly precipitation in spring reaches 165 mm; the highest and average amounts of total annual precipitation are 660 mm and 575 mm, respectively.

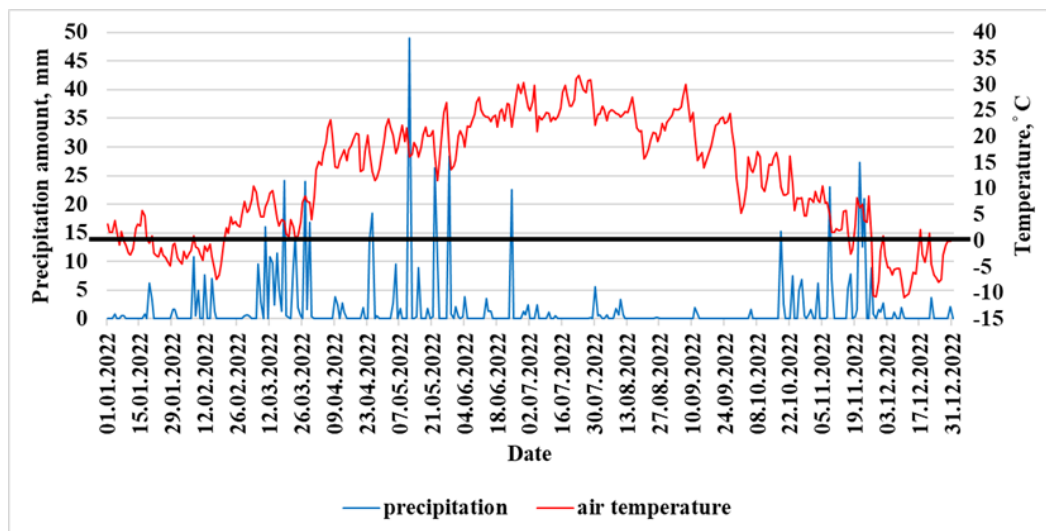


Fig. 3: Average daily air temperature and precipitation in 2022.

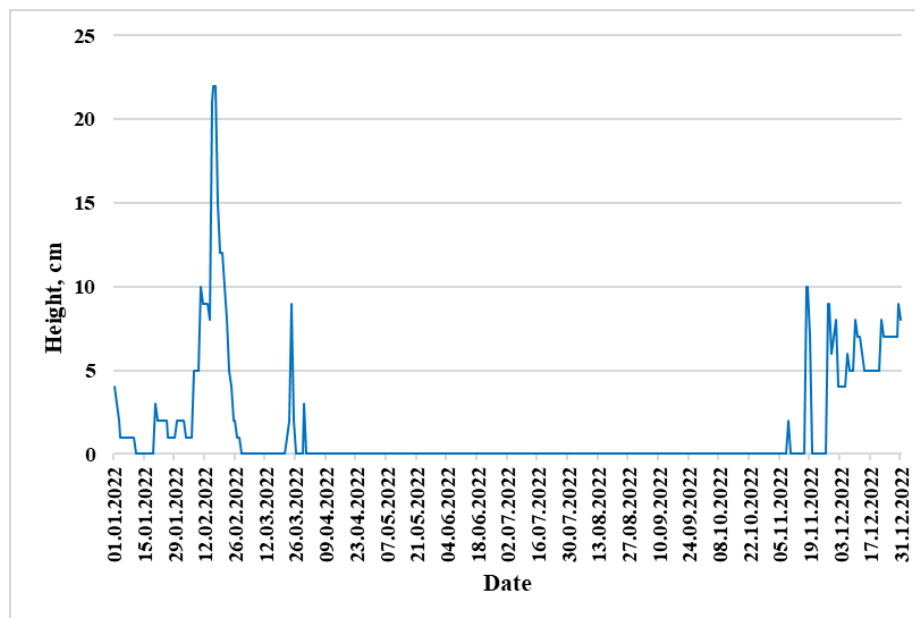


Fig. 4: Height of snow cover in 2022.

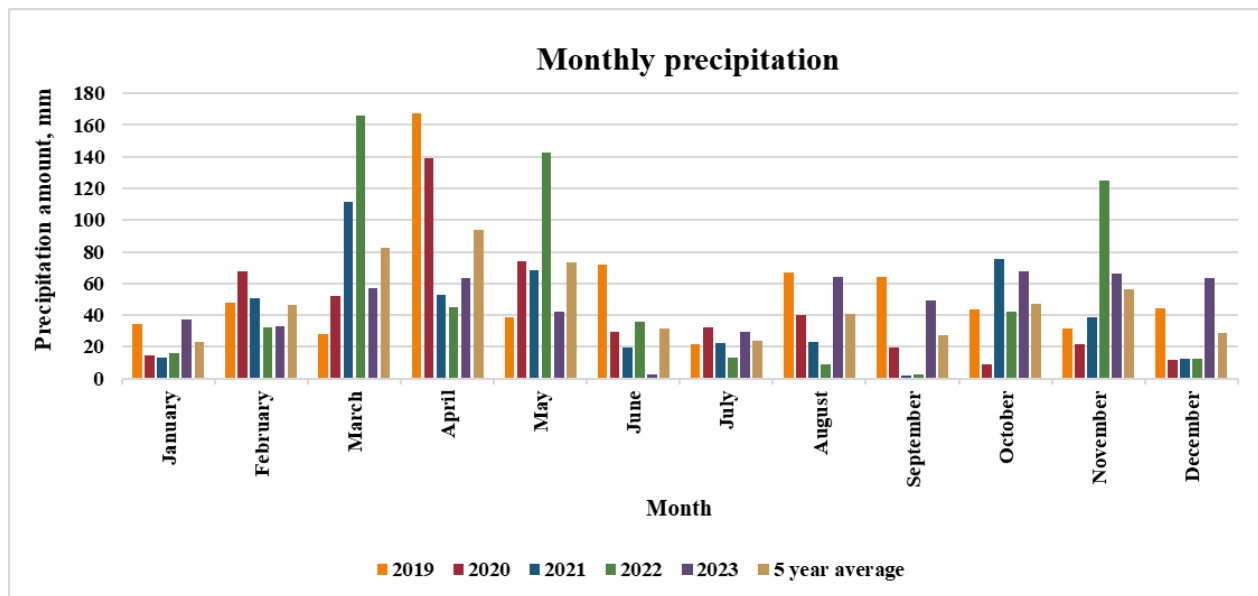


Fig. 5: Monthly precipitation in the vicinity of Mount Kok Tobe.

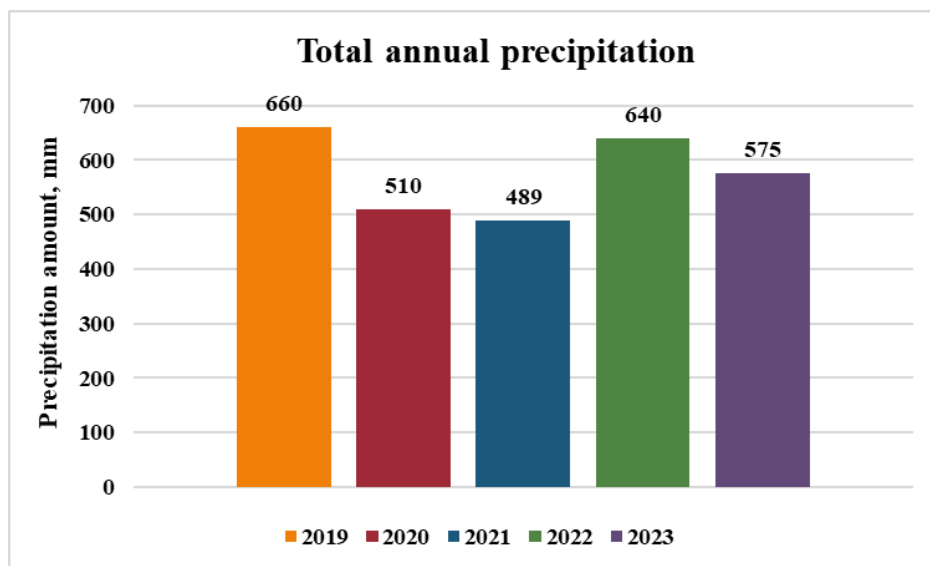


Fig. 6: Annual precipitation in the vicinity of Mount Kok Tobe.

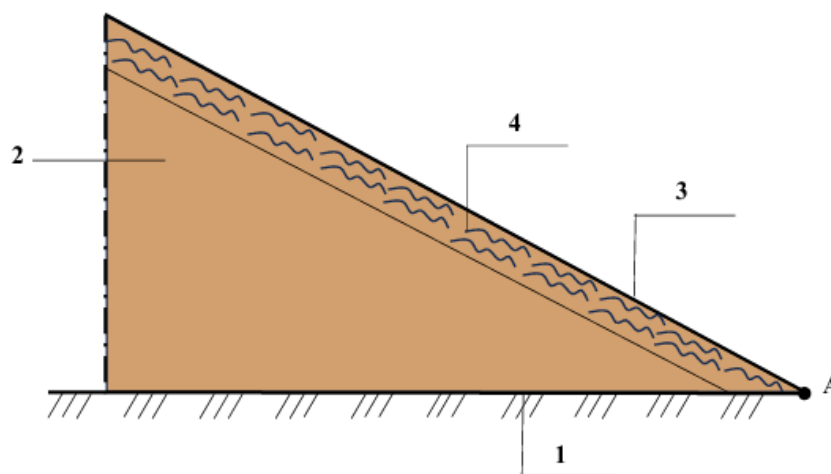


Fig. 7: A natural slope, the surface layer of which is moistened by rain and melt water: 1 - surface of the slope; 2 - slope; 3 - slope surface; 4 - moistened soil layer.

3.2 Moisturizing the surface layer of the slope

During rains and thawing of snow and ice, part of the water penetrates into the surface soil layer of the slope, and part flows down the surface. A moistened soil layer can retain water due to capillary phenomena. Fig. 7 shows a natural slope, the surface layer of which is moistened by rain and melt water.

An important issue in assessing the stability of slopes composed of clay soils is the correct assignment of the characteristics of absorption of atmospheric precipitation (rain and melt water) from the surfaces of the slopes deep into the slopes. One of the most effective ways of determining and long-term monitoring of moisture, including multiple freezing and thawing, is the use of special measuring systems with temperature and moisture sensors.^[35-37]

By analyzing the results of works,^[38-40] it was established that in the soil stratum of clayey soils (including loam) after heavy rain, the absorbed moisture for a long time (up to 20 days) is in the upper part (up to 60-70 cm) soil mass in a capillary-suspended state. The amount of moisture decreases from top (30%) to bottom (26%). The maximum amount of moisture in the upper layer of the soil column is equal to the maximum moisture capacity of the soil.

In this work, for further calculations, taking into account the above and based on the results of these works, the following moisture distribution along the depth of the selected slope is accepted: thickness $h = 0-10$ cm, moisture $W = 30\%$; $h = 10-50$ cm, $W = 28\%$; $h = 50-70$ cm, $W = 26\%$. It is also accepted that the slope is composed of only one soil (loam), which is uniform throughout the entire volume of the slope. The soil in its natural state has a moisture content of $W = 12\%$.

4. Soil characteristics

4.1 Soil in its natural state

In the calculations, it is assumed that the slope soil (loam) in its natural state has a moisture content of $W = 12\%$. At this moisture content, the characteristics of loam are assumed to be

as follows: specific cohesion $c = 35.0$ kPa, angle of internal friction $\varphi = 29.0$ degrees and specific gravity $\gamma = 21.0$ kN/m³.

4.2 Soil in the moistened surface layer

It is known that the strength and deformation characteristics of clayey soils (loam) vary significantly depending on the moisture content.^[11,12,41-43] Therefore, it is necessary to determine the values of the strength characteristics (specific cohesion c and angle of internal friction φ) of loam at the moisture values established in the previous section of the article for the moistened surface layer of the slope.

Fig. 8 shows a graph of changes in moisture in depth from the surface of the slope, constructed according to the accepted moisture distribution. As you can see, this graph is approximated with high accuracy ($R^2 = 0.82$) by a power function.

Graphs of the dependence of the specific cohesion c and the angle of internal friction φ of loam on moisture are shown in Fig. 9, which clearly shows that the established dependencies have a high degree of reliability ($R^2 \approx 1$ and $R^2 = 0.92$, respectively) and can be used in further calculations. Let's calculate the specific gravity of dry ($W=0\%$) soil:

$$\gamma_0 = \gamma_{12} - \gamma_{water} \cdot 0.12 \tag{1}$$

where γ_{12} is the specific gravity of soil in its natural state (moisture $W=12\%$); γ_{water} is the specific gravity of water equal to 9.81 kN/m³; 0.12 is the soil moisture in its natural state in fractions of unity.

According to Eq. (1) it is found: $\gamma_0 = 19.8\%$.

The specific gravity of wet soil is determined by Eq. (2):

$$\gamma_W = \gamma_0 + \gamma_{water} \cdot W_1 \tag{2}$$

where W_1 is the soil moisture in fractions of a unit.

Table 1 gives the values of the strength characteristics (specific cohesion, angle of internal friction and specific gravity) of soil (loam) at different moisture levels, obtained using the data from the previous section and the graphs in Figs. 8 and 9. As one would expect, the strength characteristics of

Table 1: Characteristics of loam at different moisture levels.

Moisture $W, \%$	Cohesion $c, \text{ kPa}$	Angle of internal friction $\varphi, \text{ degree}$	Specific gravity $\gamma, \text{ kN/m}^3$
0	-	-	19.8
12	35.0	29.0	21.0
26	2.7	11.3	22.4
28	2.2	10.4	22.6
30	1.8	9.5	22.8

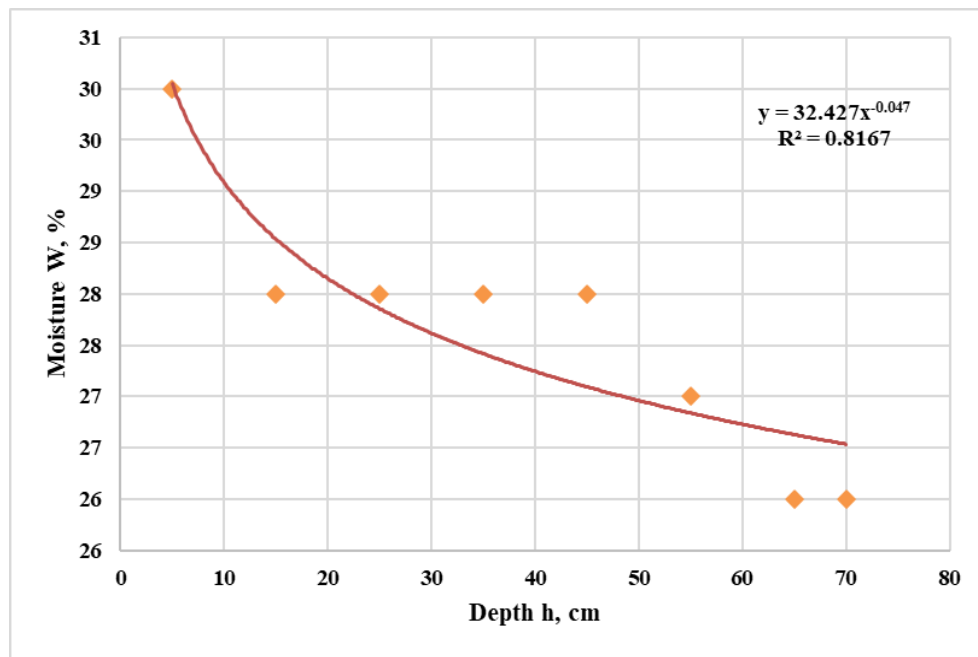


Fig. 8: Graph of changes in moisture in depth from the surface of the slope.

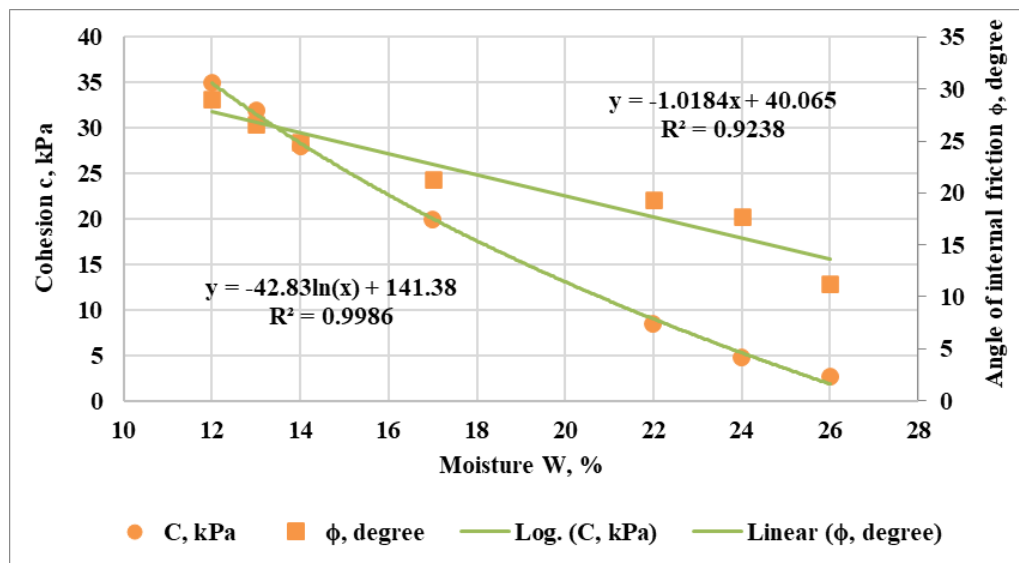


Fig. 9: Graphs of specific cohesion and angle of internal friction from moisture.

the soil vary greatly within the limits of those moisture values that are accepted for the upper part of the slope chosen for the calculation. Thus, with an increase in moisture from 12% to 30%, soil cohesion decreases from 35.0 kPa to 1.8 kPa, and the angle of internal friction decreases from 29 degrees to 9.5 degrees.

If there is an uneven distribution of soil moisture along the depth of the moistened surface layer of the slope, their weighted average values, calculated using Eqs. (3-5) are taken as the calculated values of soil characteristics:

$$c = \frac{\sum_{i=1}^m c_i h_i}{\sum_{i=1}^m h_i} \tag{3}$$

$$\phi = \frac{\sum_{i=1}^m \phi_i h_i}{\sum_{i=1}^m h_i} \tag{4}$$

$$\gamma = \frac{\sum_{i=1}^m \gamma_i h_i}{\sum_{i=1}^m h_i} \tag{5}$$

where c_i , ϕ_i , γ_i are cohesion, angle of internal friction, and specific gravity of the soil of layer i , within which the moisture is assumed to be constant, respectively, h_i is the layer thickness i .

5. Slope stability assessment

5.1 CCSS method

In this work, to assess the stability of the slope of a selected slope, the well-known engineering method, the circular cylindrical sliding surface (CCSS) method is adopted,^[8,11-14] in which it is assumed that the loss of slope stability occurs by sliding the underlying soil mass along a circular cylindrical

stability factors F_s are calculated. Since the positions of the slip curves are not known in advance, the entire calculation procedure has to be calculated many times for different proposed sliding surfaces.

In the book by Babkov V. F. and Andreeva O. V.,^[14] it is said that in the practice of road organizations, to facilitate finding the position of sliding surfaces, the Terzaghi-Fellenius method is used. In this method, it is accepted that the centers of the slip curves (surfaces) corresponding to the smallest stability factor are located near a certain straight line (Fellenius straight line). The position of the Fellenius straight line depends on the laying coefficient and the slope angle, and is determined through special geometric constructions, which for our case are shown in Fig. 10.

The degree of slope stability is assessed by the value of the stability factor, determined by the ratio of the sum of the moments of the holding forces to the sum of the moments of the shear forces relative to the center of the most dangerous sliding arc in Eq. (6):

$$F_s = \frac{\sum M_{sh}}{\sum M_h} = \frac{\sum_{i=1}^n (Q \cdot \cos \alpha \cdot \tan \varphi) \cdot R + c \cdot L \cdot R}{\sum_{i=1}^n (Q \cdot \sin \alpha) \cdot R} \quad (6)$$

where φ is the angle of internal friction of the soil, degree; c is the specific soil cohesion, kPa; L is the sliding surface length, m; R is the sliding surface radius, m; $S = Q \cdot \cos \alpha$, S is the shear force, kN; $T = Q \cdot \sin \alpha$, T is the holding force, kN; n is the

number of soil prisms.

The length of the sliding surface is determined by Eq. (7):

$$L = 2 \cdot \pi \cdot R \cdot \frac{\alpha'}{360^\circ} \quad (7)$$

The slope is considered stable if the minimum stability factor F_s is greater than 1.3.

5.2 Modified CCSS method

When taking into account the moistening of the surface layer of the slope, the question arises: it is possible that in these cases the sliding surfaces with minimal stability factors do not coincide with those considered in the case of a dry slope. It is logical to assume that they can be located much closer to the moistened surface layer.

To answer this question, we assume the following modification of the CCSS method, maintaining its basic position: loss of slope stability will occur by sliding of the underlying soil mass along a circular cylindrical surface. We also assume that the center of slip lies on the Fellenius line.

Fig. 11 shows that the position of point A of the sliding surface (curve) is always fixed. Its coordinates: $x_A = \frac{K}{2}$; $y_A = 0$. Next, using the known (accepted) coordinates of two points lying on the sliding surface, we will mathematically describe the sliding surface, i.e. calculate the radius and coordinates of the center of the sliding surface.

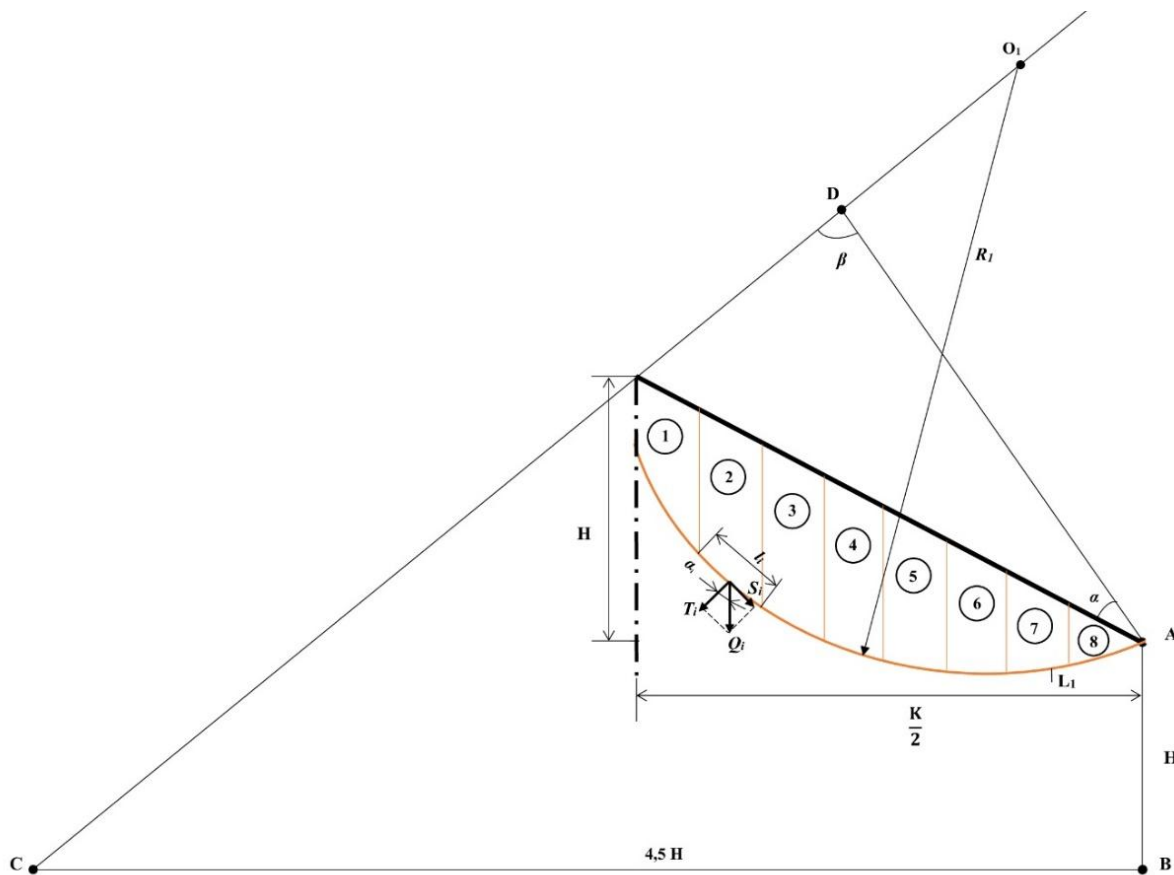


Fig. 10: Scheme for calculating slope stability using the CCSS method: O_1 - sliding center; H - slope height; R - sliding surface radius; L - sliding surface length; Q - ground prism weight; S - shear force; T - holding force.

assumed that the sliding surfaces are deep (below the base of the slope); condition 3 - the surface layer 70 cm thick is moistened by rainwater and it is assumed that the sliding surfaces are close to the moistened surface layer of the slope.

The results of slope stability calculations under the above three conditions are presented in Tables 2-4. For clarity, the values of stability factors corresponding to different sliding surfaces are shown in Fig. 12.

Table 2: Results of slope stability calculations (condition 1).

Sliding center	Radius, m	Sliding length, m	surface	Sum of forces, kN	shear	Sum of holding forces, kN	Stability factor F_s
O ₁	354	414		183961		433849	1.50
O ₂	363	422		131132		331869	1.52
O ₃	375	431		120486		264119	1.34
O ₄	390	402		76595		186814	1.53
O ₅	402	379		52885		127480	1.59

Table 3: Results of slope stability calculations (condition 2).

Sliding center	Radius, m	Sliding length, m	surface	Sum of forces, kN	shear	Sum of holding forces, kN	Stability factor F_s
O ₁	354	414		184088		472253	1.46
O ₂	363	422		131289		332265	1.48
O ₃	375	431		120646		264397	1.31
O ₄	390	402		76746		187186	1.50
O ₅	402	379		52991		127755	1.54

Table 4: Results of slope stability calculations (condition 3).

Sliding center	Radius, m	Sliding length, m	surface	Sum of forces, kN	shear	Sum of holding forces, kN	Stability factor F_s
O ₆	345	409		170510		419374	1.31
O ₇	342	406		278562		714519	1.41
O ₈	339	402		218642		543127	1.36
O ₉	339	390		384350		1040653	1.47

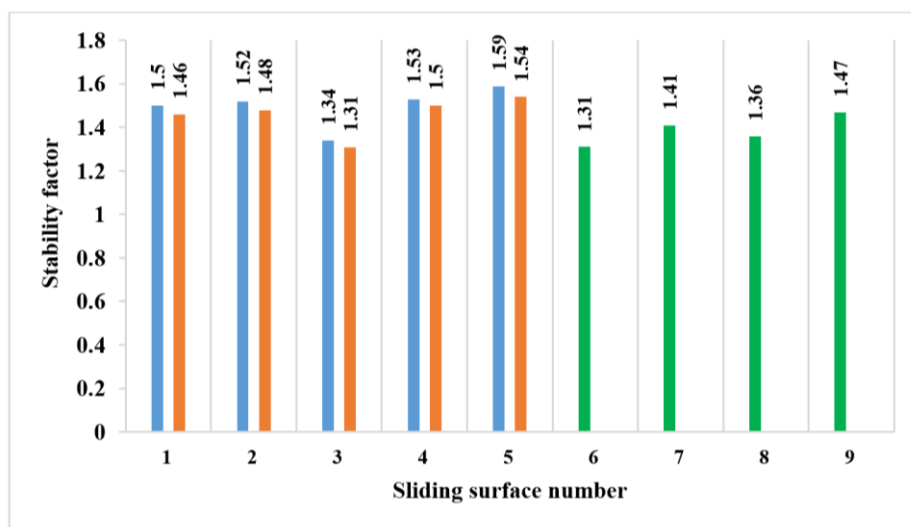


Fig. 12: Slope stability factors.

As can be seen from these tables and the figure, the results of slope stability calculations in the first two conditions are almost identical: the sums of shear and holding forces on the sliding surfaces, as well as the values of the stability factor corresponding to these sliding surfaces, are very close. The stability factor values range from 1.31 to 1.59. Of the five sliding surfaces considered, the third (with a sliding center O_3 and a radius of 375 m) in the calculations of slope stability in conditions 1 and 2 has stability factors equal to 1.34 and 1.31, respectively.

Based on the results obtained, we can say that the slope is practically in a non-equilibrium (dangerous) state. In other words, a small negative impact (excessive moisture from rain and melt water, construction of objects, cutting off parts of the slope, seismic and other mechanical impacts) can easily provoke a loss of slope stability, landslides.

Moistening the soil of the surface layer of a slope 70 cm thick with rainwater, as one would expect, has virtually no effect on the stability factors when the sliding surfaces are below the base of the slope, but can cause loss of slope stability by sliding the soil mass along a sliding surface located close to the moistened surface layer (for example, along the O_6 sliding surface with a radius of 345 m, $F_S = 1.31$).

To prevent landslides, it is recommended to use the following methods separately or in combination: 1) the installation of drainage systems to drain melt and rainwater; 2) the installation of retaining walls to contain the sliding soil mass; 3) the use of geosynthetic materials (geocells, geogrids, geotextiles) to reinforce the soil; 4) slope profiling and terracing to reduce the slope angle; 5) biostabilization of the slope using vegetation to strengthen the soil. These measures, combined with slope condition monitoring, will help reduce the risk of landslides.

7. Conclusions

In the vicinity of Mount Kok Tobe, the total annual precipitation ranges from 489 mm to 660 mm, with an average of 575 mm per year. Moreover, the greatest amounts of precipitation (up to 165 mm per month) fall in the spring months (March, April, and May). The daily maximum precipitation in these months reaches 50 mm. This amount of precipitation per day can moisten the surface soil layer of the slope, presumably up to 60-70 cm.

A modified CCSS method has been developed and used in the calculations, which, together with the Terzaghi-Fellenius method, makes it possible to speed up and increase the accuracy of determining the position and characteristics of sliding surfaces.

Calculations have shown that the slope is practically ($F_S = 1.31$; $F_S = 1.34$) in a nonequilibrium (dangerous) state. A slight negative impact (excessive moisture from rain and melt water, construction of objects, cutting off parts of a slope, seismic

and other mechanical impacts) can easily provoke a loss of slope stability, landslides. Moistening the surface layer of a 70 cm thick slope with rainwater can lead to the loss of slope stability by causing the soil mass to slide along the sliding surface near the moistened layer.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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