Stability of the Right-Bank Slope of the Oka River

Igor Gandelsman and Artem Gandelsman

Abstract The article analyzes the engineering and geological conditions of the right bank, which is in a state of dynamic equilibrium, of the Oka River in the city of Pavlovo. Calculation schemes have been compiled to perform calculations of the total static stability of the slope for two calculated cases in the existing natural state and taking into account the water saturation of the water-bearing rocks, the boundaries of the landslide zone for various cases have been determined. The article identifies possible risks, analyzes the main models of the behavior of the soil base taking into account negative factors, calculates the stability of soil massifs using various known methods. The geometric scheme of the computational model was built on transverse profiles. The width of the calculated area was chosen in such a way that there were no changes in the stress–strain state of the array due to the introduction of artificial boundary conditions along the edges of the finite element grid. The method of calculating stability based on numerical modeling programs by reducing strength characteristics has a number of advantages over the traditionally used methods of calculating stability based on the equations of limiting equilibrium. Based on the results of calculations, the boundaries of the landslide zone for various cases were determined by the method of circular cylindrical sliding surfaces (SAM). A potential landslide zone has been identified, including residential development. Based on the calculations performed, it is proposed to provide alternative measures to ensure the safety of buildings falling into a landslide zone to ensure reliable fastening and minimal impact on the existing slope.

Keywords Landslide slope · Static stability · Landslide pressure · Geological structure

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1 Introduction

During the construction of buildings, land plots located on the banks of rivers and ravines are sometimes used. During the operation of these buildings, atmospheric influences are inevitable, man-made, as well as changes in hydrogeological conditions are possible. Anti-landslide measures for these objects are not always carried out in the proper volume, the volume and structure of green spaces are insufficient.

All this can lead to the loss of stability of slopes, the formation of landslides that threaten existing buildings and people living in them [1–13]. When operating such facilities, it is advisable to monitor the condition of the slope, make dynamic forecasts of its reliable operation when the initial conditions of their operation change.

The theoretical foundations and methods for calculating slopes are described in the works of domestic researchers S.S. Vyalov, Yu.K. Zaretsky, Z.G. Ter Martirosyan [1–3], A.A. Bartolomey, G.V. Postoev [4], A.B. Ponomarev [5], A. Torgoev [6] and foreign scientists A. Bishop [7], N. Morgenstern [8], E. Bromhead [9, 10], G. Gitirana [10], A. Federico [11], A. Malkavi [12], S. Gshvind [13], K. Komamura, D.N. Loops, A.P. Hwang AP [14], A.W Skempton [19], H. Herrmann [22], K.Cha [24], etc. el.

Despite numerous studies, it is still important to ensure the stability of specific slopes in various localities [14–18, 19–21].

The criterion for ensuring the stability of the slope is the condition that the calculated values of the generalized shear forces on the collapse prism do not exceed the forces of the ultimate resistance of the soil mass or the moments of forces tending to turn (overturn) and hold the soil mass. This calculation is allowed to be performed only for the simplest forms of the sliding surface separating the collapse prism from the stationary soil mass (in the form of a straight line segment or a circle). In general, stability calculations are performed for arbitrary shapes of the sliding surface. The slope stability coefficient (slope) is found as the minimum value of k_{st} for all possible test sliding surfaces. The slope stability coefficient (slope) can be found both using traditional methods of the theory of marginal equilibrium (with or without splitting the slide prism into compartments) and elastic–plastic calculations by the finite element method using the method of reducing strength characteristics.

The article considers the issues of the current state of the landslide slope, presents the results of the calculation taking into account various models of the soil base. Based on the results, work is proposed to prevent landslides on this section of the Oka River bank.

2 Methods

The climate of the design area is moderately continental with moderately harsh and snowy winters and moderately warm summers. The wind regime is formed under the influence of physical and geographical features. Cyclonic activity is predominant here for most of the year. The area belongs to the zone of sufficient moisture. The annual precipitation is 527 mm. The height of snow by the end of winter (the second decade of March) reaches 50 cm.

The geological structure of the site up to the studied depth of 70.0 m involves deposits of quaternary age (Q_{IV}) (soil-vegetation layer (pdQ_{IV}), alluvial sands pulverized (aQ_{IV}), loess loams deluvial-solifluction loams ($prQ_{II\text{-}III}$) and medium-sized sands ($dsQ_{II\text{-}III}$), sediments of the upper Permian system (P_3).

The absolute level of the roof of deposits varies from 70.7 to 124.8 m of the Baltic system. The absolute mark of the sole of the deposits varies from 70.6 to 124.5 m.

The hydrogeological conditions of the site up to a depth of 20.0–70.0 m (January- February 2022) are characterized by the presence of Quaternary and Upper Permian aquifers. The groundwater level is recorded at depths of 0.9–13.7 m, which corresponds to the absolute marks of 69.8–111.1 m of the Baltic system (Table 1).

The aquifer is unpressurized, the water-bearing soils are quaternary sediments. The Upper Permian clays (P_3) serve as a water barrier. The aquifer is fed by infiltration of atmospheric precipitation. The Oka River is an area of both supply and discharge of groundwater. The aquifer has a hydraulic connection with the Oka River.

One of the most important tasks in the practice of construction is to assess the stability of soil slopes. The criterion for ensuring slope stability the dependence for the stability coefficient k_{st} is the condition: $k_{st} = R/F \geq (\gamma_n \cdot \psi)/\gamma_d$. The slope stability coefficient is found as the minimum value of k_{st} for all possible test sliding surfaces. The slope stability coefficient can be found using traditional methods of the theory of ultimate equilibrium, or by elastic–plastic calculations using the finite element method using the method of reducing strength characteristics. In construction practice, to determine the stability of a ground structure or slope, the methods of marginal equilibrium of the following authors are used - Shakhunyants, Maslov, Tertsagi, Bishop, Morgenstern, Spencer and others. Calculation methods are divided

Table 1 Physical and mechanical characteristics of soils

No	Name of the engineering-geological element	standard values				calculated values (α = 0.85)			Calculated values (α = 0.95)		
		ρ, g/sm³	c. кPa	φ, deg	E, MPa	ρ, g/sm³	C, кPa	φ, гdeg	ρ, g/sm³	c. кPa	φ, deg
1	sand dusty, medium density, saturated with water (aQ_{IV})	1.95	2	26	11	1.95 ± 0.00	2	26	1.95 ± 0.01	1,3	24
2	clay semi solid, loess, subsidence ($prQ_{II\text{-}III}$)	1.97	25/15	20/18	11/10	1.97 ± 0.01	22/14	18/7	1.97 ± 0.02	20/12	17/7
3	Clay semi solid ($dsQ_{II\text{-}III}$)	2.10	41/34(19)	14/11(14)	15	2.10 ± 0.01	37/30(17)	13/10(7)	2.10 ± 0.02	34/27(15)	12/9(5)
4	Sand medium size, medium density ($dsQ_{II\text{-}III}$)	2.00	1	35	30	2.00 ± 0.00	1	35	2.00 ± 0.01	0,7	32
5	Clay solid (P_3)	2.01	87/64(45)	30/21(17)	21	2.01 ± 0.02	81/58(41)	28/19(14)	2.01 ± 0.03	77/55(39)	26/18(15)
6	Clay of medium strength (P_3)	R_c = 26.9/31.3 MPa									

by mechanisms: satisfying the general equilibrium of moments (Fellenius, Bishop), methods of equilibrium of forces (Shaunyants, Kray, Maslov-Berer) and methods of equilibrium of moments and forces (Yanbu, Morgenstein and Price, Spencer). A number of assumptions are made in the computational model [7–9, 15]: the solidified body hypothesis is used; a certain shape of the sliding surface is allowed; stresses are replaced by forces; assumptions about groundwater pressure and seismicity are made. The general sequence of application of limit equilibrium methods is such that they are first set by the sliding surface, after which the position of the critical sliding surface with the minimum value of the stability coefficient is determined by iterations. As follows from the above sequence, the disadvantage of this approach is that the sliding surface is set before the calculation begins. As a rule, the decision on the possible shape of the sliding surface is made on the basis of calculations on circular cylindrical or polygonal (pre-defined) sliding surfaces [19].

The slope stability coefficient (slope) can be found both using traditional methods of the theory of marginal equilibrium (with or without splitting the slide prism into compartments) and elastic–plastic calculations by the finite element method using the method of reducing strength characteristics.

Thus, based on the need to cover as many cases encountered in practice as possible (heterogeneous geological structure, presence of groundwater, seismic impacts, etc.), the methods of marginal equilibrium have many assumptions and simplifications, but at the same time they allow obtaining sufficient results for practice in the case of engineering-geological conditions of moderate complexity.

The method of determining stability, devoid of the described disadvantages, is the method of reducing strength. According to the underlying principle, the sliding surface is determined automatically by the calculation input. From the provisions of soil mechanics, it is known that the stress state at any point of the soil is considered as the limit in the case when a slight additional effect disturbs the equilibrium and leads the soil into an unstable state. The destruction of the soil occurs as a result of overcoming the internal forces of friction and adhesion between the particles on certain sliding surfaces.

In general, the stability of the structure is determined by the safety coefficient, which is the ratio of the maximum possible strength of the soil to the minimum value necessary to ensure the equilibrium of the actions.

The SRM – shear reduction method is implemented in programs based on the finite element and finite difference method (Midas GTS NX, Plaxis, GEO5, Phase2, FLAC). The fracture prediction is carried out by simultaneously lowering both shear strength indicators: $c_r = c/k_{st}$, $\varphi_r = \varphi/k_{st}$.

A significant advantage of the strength reduction method in comparison with the methods of limiting equilibrium is that the sliding surface and the stability coefficient are determined simultaneously during the calculation process.

The analysis of the comparison of stability calculations based on the methods of limiting equilibrium and strength reduction for a large number of parameters of embankments with different configurations showed that such methods as Taylor (calculated by untrained strength cu), Bishop, Morgenstein (strength was given by effective characteristics c' and φ'), which can be considered proven However, they do not have much difference with calculations using the strength reduction method. Discrepancies of several percent are due to the fact that MPR uses exclusively circular cylindrical sliding surfaces, and the method of reducing strength has no restrictions on the geometry of the fracture mechanism [13, 14, 16, 20, 21].

The method of calculating stability based on numerical modeling programs by reducing strength characteristics has a number of advantages over the traditionally used methods of calculating stability based on the equations of limiting equilibrium. For simple cases, all methods give the same result, in other cases, the discrepancies reach up to 20%.

3 Results and Discussion

Calculations of the overall stability of the slope are carried out in a flat formulation. The position of the design section is timed to the most characteristic section of the slope. Stability calculation is performed for the existing terrain of the territory. The calculation scheme (see Fig. 1). The topography and geological structure of the site is taken from the materials of engineering surveys.

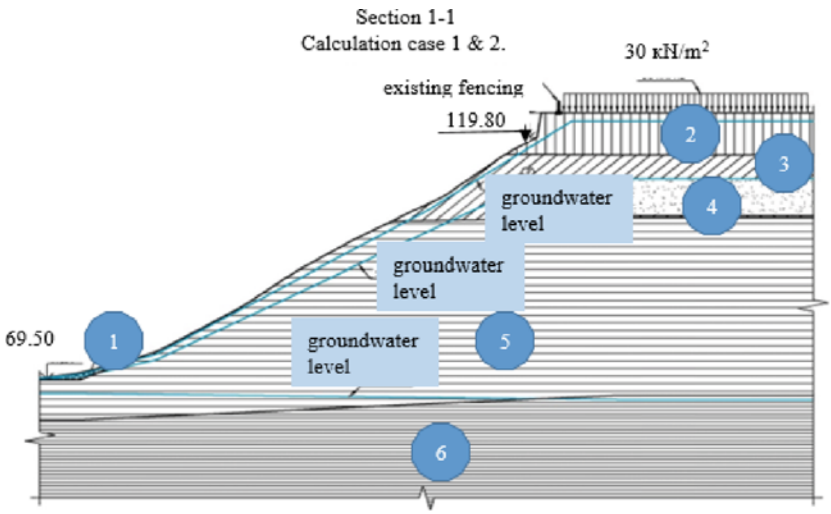

Fig. 1 Calculation scheme of the ground slope

Table 2 Results of slope stability calculations

Section	Calculation result	$\gamma_c \cdot \gamma_n$	Condition
	Bush		
1–1	1.01	1.15	Not being executed
2–2	0.73	1.04	Not being executed

Calculations of the general static stability of the slope in a flat formulation were performed for two design cases: design case No. 1 (main) – the slope is considered in the existing state, the physical and mechanical characteristics of soils in the natural state; design case No. 2 (special) - the slope is considered in the existing state, taking into account the water saturation of the water-bearing rocks.

The load from transport and buildings is 30 kN/m^2. Seismic loads are not taken into account, since the estimated seismicity is less than 7 points.

The calculation results are shown in Table 2 (see Figs. 2, 3). The boundaries of the landslide zone for potential landslide phenomena for a slope in a natural and water-saturated state are determined by the method of circular cylindrical sliding surfaces. The boundary corresponding to the value of the bush stability coefficient $k_{st} = 1.15$ is determined, beyond which the slope stability is ensured in accordance with regulatory requirements. For a slope in a water-saturated state, a boundary corresponding to the value of the stability coefficient $k_{st} = 1.04$ is determined, beyond which the slope stability is ensured in accordance with regulatory requirements.

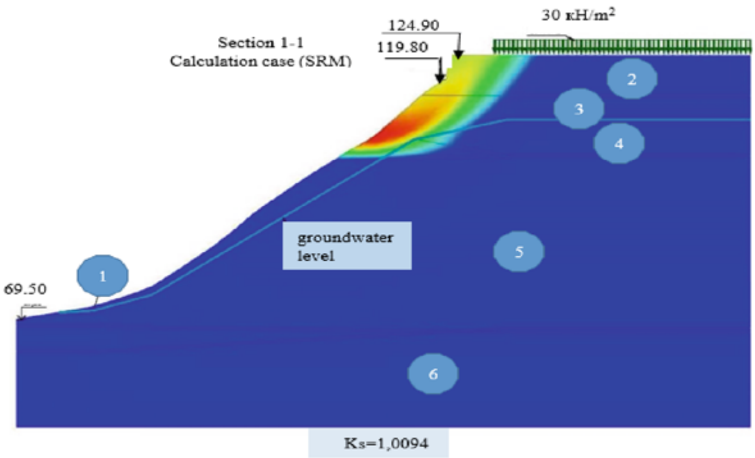

Fig. 2 Calculation results of slope stability in Sect. 1–1

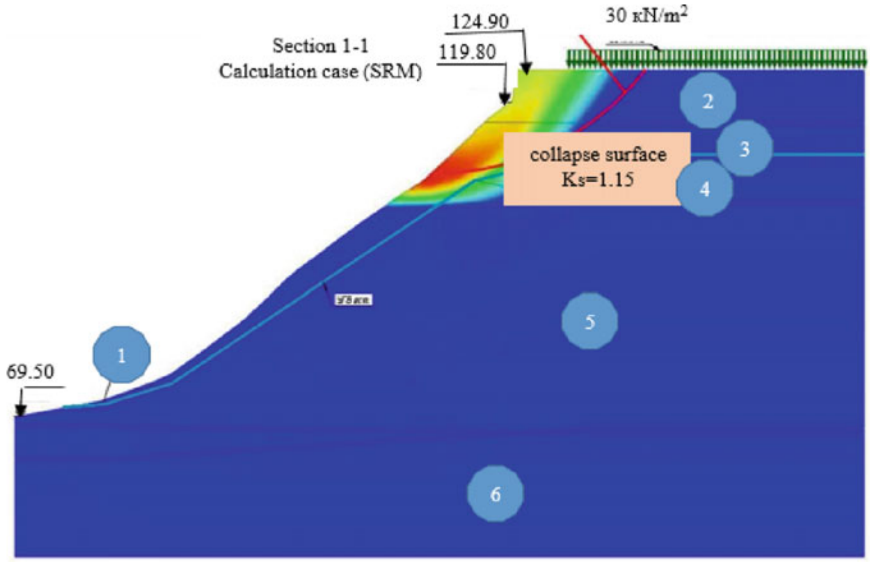

Fig. 3 Results of stability calculation by the method of circular cylindrical sliding surfaces of the slope in Sect. 1–1

Fig. 4 The area of potential landslide phenomena

4 Conclusions

Based on the results of the slope stability studies, taking into account the existing relief, the following conclusions can be drawn:

1. the slope is in the existing state, the physical and mechanical characteristics of the soils are determined in the natural state, the stability coefficient was kst = 1.01;
2. the slope in the existing state, taking into account the water saturation of aquifers, the stability coefficient was kst = 0.73.

The slope is not stable. The stability coefficients obtained as a result of calculations do not meet regulatory requirements.

2. According to the results of calculations by the method of circular cylindrical sliding surfaces, it is clear that existing buildings fall into a potential landslide zone. The boundaries of landslide zones for different cases are shown in Fig. 4.

3. Based on the results of calculations, it was determined the need to take measures to ensure the safety of buildings and structures falling into the landslide zone (removal of buildings from the landslide zone, implementation of anti-landslide measures, etc.). As an alternative, it is possible to use the Titan anchor system designed to solve a wide range of engineering tasks. One of the main areas of its application is anti-landslide fastening and stabilization of slopes, fixing unstable steep sections of the coastal strip. The use of this technology, especially in combination with Geobrugg slope reinforcement systems, avoids the use of bulky support and enclosing structures, allows you to quickly and efficiently carry out work in a confined space without negative destructive effects on nearby objects and ensure reliable operation of the slope for decades.

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