Assessment of landslide stability of ground cuts in Permic sediments of the Urzhum stage in the territory of the Volga uplands (Russia)

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Abstract The article discusses the problem of landslide processes activation during the construction of highways on the Volga upland territory in the central part of the East European platform. Currently, this territory is actively developing and requires the construction of a significant number of highways, including high-speed ones. At the same time, the roads geometry requires excavating deep roadway recesses in the existing terrain. This has provoked landslides activation in some areas, the scale of some of them can be classified as catastrophic.

Keywords: Landslide hazard assessment, East European platform, Permian deposits, Numerical stability calculation

The territory description

In recent decades, beginning in the 1990s, the Central Russian region has experienced remarkable development. Urban agglomerations have expanded, agro-industrial complexes have been established, and new cities have emerged as vital industrial and economic hubs. Such growth necessitates the establishment of more efficient logistics systems to manage transportation networks. Among these corridors are the M-7 and M-12 federal highways, currently under construction, which will connect to Moscow. These highways encompass extensive engineering structures within the road infrastructure, traversing diverse geomorphological landscapes often characterized by significant differences in elevation. The need to level the Earth's surface often requires extensive excavation work, particularly in areas with steep terrain. In such cases, disregarding the long-standing engineering-geological conditions of the terrain can lead to the activation of adverse geodynamic processes, such as landslides, rockfalls and erosion. This article explores the characteristics of landslide development within the sedimentary complex of the Middle Permian system along the embankments of the high-speed road excavation on the highway M-12, traversing the northeastern part of the Volga Upland.

Considering that the formation of engineering-geological conditions is influenced by both internal and external factors, the stages of Volga Upland geological evolution should be briefly examined. The starting point will be the period of formation Urzhum stage deposits, which compose the upper part of the geological section and serve as the foundation for road construction. In the area under consideration during the Urzhum Age, sediments of a continental variegated carbonate-terrigenous formation were deposited. Within the formation sections, there are cyclic alternations of light gray dolomites, greenish-gray and red dolomite marls, red-brown clays, greenish-gray sandstones, and dark gray limestones. The accumulation of the variegated formation occurred in a single, very large basin (lake), which in terms of its size could be referred to as a sea. Hydrochemically the sedimentation basin exhibited an unstable regime; periods of salinization were interspersed with periods of desalination. This resulted in repeated alternations of carbonate and carbonate-clayey rock layers with clays and layers of clayey-sandy sediments.

A vast shallow reservoir with a leveled, gently sloping bottom contributed to the formation of layers with horizontally occurring deposits, which can be traced for hundreds of kilometers. Towards the end of the Urzhum age, significant quantities of coarse clastic material began to enter the territory from the Middle Urals. This influx of terrigenous components led to the gradual shallowing of Lake Urzhum and the formation of an accumulative alluvial plain in its place. Meandering rivers carved water-erosive paleovalleys filled with sandy material, around which swampy lowlands developed. The transition from an arid climate to a colder and more humid one at the end of the Urzhumian era facilitated the growth of shrub vegetation and the colonization of the territory by terrestrial vertebrates.

In the Mesozoic era, a restructuring of the structural plan of the territory commenced due to the emergence of ramparts within the Vyatka ridges system. During the Jurassic period, uneven amplitude uplift of the crystalline basement blocks resulted in uplift and folding deformations of sedimentary cover rocks, including those from the Urzhum age, forming the foundation of the Volga Upland. Presently, the Volga Upland comprises several gentle anticlinal folds alternating with gentle synclinal troughs. Alongside wide arched uplifts, various local tectonic disturbances in the form of intersecting regional faults further complicate the tectonic landscape.

As per the layout, the M-12 highway's bridge section across the Volga River must traverse the domed part of the Oktyabrsky uplift.

The height difference from the highest hypsometric point on the hill (175 m) to the Volga River's waterline (53 m) totals approximately 122 m. Following excavation work during site preparation for construction, an extensive road excavation with a depth of about 80 m and a width of up to 20 m was constructed. To facilitate excavation, the road excavation slopes were terraced, with terrace ledge heights around 6.0 m and platform widths about 3.5 m. Given that the excavation slopes primarily consist of rocky soils, the slope angles of the ledges ranged between 80-90 degrees.

Exposed soil massif sections reveal a layered occurrence of rocks. In the lower part, interlayers of light gray dolomites alternate with greenish-gray and red-pink dolomite marls, red-brown mudstone-like clays, and occasional greenish-gray sandstones. Layer thicknesses range from 0.5-2.5 m. Notably, dolomite marls in some areas feature thin (up to 5.0 cm) layers of greenish-gray and black wet clay due to organic matter enrichment. These clay layers often act as waterproof barriers against infiltration water from atmospheric precipitation. Moistened clay exhibits a viscous-plastic state, allowing deformation without loss of layer continuity. Higher up the section, greenish-gray sandstone interlayers appear among dolomite marls and mudstone-like clays. Generally, dolomite layer proportions decrease from bottom to top along the section, while clayey-sandy rock proportions increase. Sedimentary rocks from the Urzhum stage feature horizontal, inclined, and vertical cracks, with block structures predominant in dolomites and dolomite marls, and fragmented structures in mudstone-like clays

Sharp-edged fragments of dense clayey rocks and blocks of carbonate and carbonate-clayey rocks are separated by extended shiny cracks. Consequently, the soil massif is classified as medium-fractured in areas with dolomites and dolomite marls and as collapsible in areas with dense mudstone-like clays. Large-scale technogenic exposures enable the observation of Urzhum carbonate-clayey sedimentary complex rock occurrence features not only vertically but also laterally. A folded depression of Urzhum stage rock layers from east to west is observed between the villages of Grebeni and Sviyag, following the Volga River's right bank.

The most elevated anticlinal structure corresponds to the dome part of the Oktyabrsky uplift, featuring a gentle fold about 1.5 km wide and an amplitude of around 8.0 m. This fold abruptly terminates on the eastern side with the Volga River valley, while smoothly transitioning into a synclinal fold on the western side. The synclinal fold is approximately 1.0 km wide with an amplitude of about 6.0 m, gradually transforming into another gentle anticlinal fold about 1.0 km wide, with an amplitude of 5.0-6.0 m on the western side. All folds exhibit straight vertical axial planes, symmetrical, lock-shaped configurations, with wing incidence angles not exceeding 15 degrees. Along the folds complicating the western slope of the Oktyabrsky uplift, a gradual decrease in plicative disturbances in the western direction is observed. This nature of folded deformations of sedimentary rocks arises from the vertical movement vector of crystalline foundation blocks along moving faults.

Sedimentary rocks above the basement blocks with the greatest uplift intensity form gentle anticlinal folds, while those with the least intensity form synclinal folds. By the time of tectonic activation, sedimentary rocks from the Urzhum stage had already acquired rigid structural connections of the crystallization type. Consequently, layer bending was accompanied by disjunctive disturbances. Sections distinctly reveal wing bends complicated by parallel cracks, along which sedimentary layers experienced stepwise displacement from east to west, with displacement amplitudes reaching up to 0.5 m. Some areas of the folds exhibit graben-like structures.

In hydrogeological terms, the soil massif traversed by the M-12 highway excavation locally contains aquifers. The primary aquifers are confined to layers of sandstones, fractured dolomite marls, and argillite-like clays, beneath which lie layers of viscous-plastic greenish-gray clays enriched in organic matter. These aquifers contain free-flowing, infiltration-origin, fresh waters with a hydrocarbonate-calcium-magnesium composition. Their levels in aquifers are influenced by seasonal fluctuations. Hydrodynamic connection between the underlying and overlying aquifers is evident in sections. Groundwater flows downward can be traced to the river level of the Volga, indicating that the entire fractured soil mass functions as a single transit zone for the infiltration of atmospheric precipitation.

Construction of a geomechanical model and calculation methods

One of the primary stages in conducting slope stability quantitative assessment involves schematization during the construction of mathematical models. This schematization can be broadly categorized as either generalized or specialized. Generalized schematization simplifies a complex real-world object into a conceptual model, bounded by the constraints of scientific knowledge and information security achieved during geotechnical work. In contrast, specialized schematization simplifies the conceptual model into a specialized (geomechanical) scheme tailored to the specific task at hand, aiming to maintain adequacy while providing detailed descriptions of the real-world object. The objective of specialized schematization is to achieve maximum simplification with minimal loss of adequacy.

The implementation of specialized schematization involves several interrelated stages, including schematization of the slope massif structure and soil properties and their distribution within the studied massif. During engineering surveys in the study area, more than 20 engineering-geological elements were identified. Twelve engineering geological sections were constructed within the excavation area, forming the basis for 12 geomechanical models. Stability calculations for the excavation sides indicated stability coefficient values of at least 1.41, suggesting a significant stability margin for the design.

However, during the road construction stage from April to October 2022, five landslides of various sizes occurred for unknown reasons. The largest of these had lengths of up to 100 m and heights of up to 30.0 m (see fig.1). To assess the situation after excavation opening, K(P)FU employees conducted fieldwork on its sides, including layer-by-layer examination and description of rocks, recording of identified cracks' characteristics, and selection of monoliths. Based on these results, large-scale (1:500) zoning maps were compiled to depict the degree of danger of geological and engineering-geological processes, along with a special map of engineering-geological conditions.

Figure 1 Sliding landslide at the construction site of the M-12 highway.

Based on the analysis of the work results, the primary conclusion drawn was that the initiation of landslide processes stemmed from the removal of weathered sandstone materials through suffusion during groundwater unloading into the excavation. The exposure of sandstones to the surface, resulting from excavation, intensified weathering processes.

Concurrently with the increase in soil removal due to suffusion, extensive separation cracks began forming on the upper terraces of the southern slope of the road excavation. These cracks gradually widened, separating large rock blocks from the main soil mass. The development of radial sidewall crack systems is attributed to the absence of supporting forces from the open space of the mine workings, capable of counterbalancing surrounding pressure.

Avulsion cracks, intersecting all horizontal sedimentary rock layers in the massif, determined the subsequent mechanism of landslide displacement. Vertical fissure channels, intersecting aquiferous sandstones and fractured dolomite marls, act as pathways for downward groundwater migration, leading to increased rock moisture and reduced stability within the soil massif.

The separated soil mass, which retains some cohesion in the form of fallout blocks, exerts pressure on the underlying rocks of the slope. This additional load triggers detachment cracks further down the slope, affecting rocks on the lower terraces.

Upon surpassing a certain rock strength limit in the probabilistic slope collapse prism, an avalanche-like destruction of the undermined soil mass occurs in a localized area.

Landslide bodies exhibit a complex structure, consisting of multiple terraced steps formed by stacked large block heaps. Aquiferous sandstone layers at the base of the slopes serve as the foundation for landslide displacement.

Utilizing Rocscience software products, stability calculations of the excavation sides were conducted using updated data.

The simulation results, without considering the suffusion process development resulted in the safety factor values exceeding 1.3. However, accounting for the formation of suffusion cavities within water-saturated sandstone interlayers at sites of groundwater discharge resulted in safety factor values lower than 1 (refer to Fig. 2).

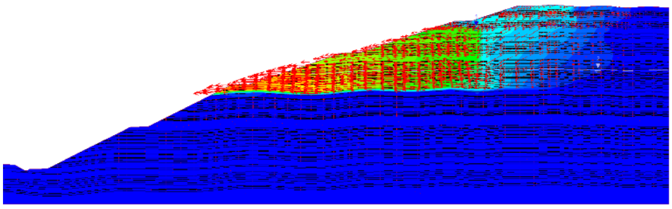

Figure 2 Slope stability modeling results.

Conclusion

Hence, in challenging natural environments, particularly when designing critical engineering structures, it is crucial to accurately evaluate changes in natural conditions during construction and operation. This includes recognizing potential and not always apparent interactions of engineering-geological processes, which could result in significant social and economic consequences.

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