Sustainable use of natural resources in a hazardous landslide slopes of Cheboksary reservoir (river Volga)

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Abstract. Often uncontrolled construction with insufficient consideration of the geotechnical and hydrogeological conditions of the territory, the increased man-made impact on the slope in the conditions of growing urbanization are leads to serious problems: landslide deformations and emergencies on the coast of the Cheboksary Reservoir, on the territory of the Cheboksary urban district and in the adjacent territories of Chuvash Republic. The increase in recreational load on coastal geomorphic systems also contributed to the activation of landslide, erosion, deflation and other dangerous relief-forming processes, and also affected the quality of water resources. The problem of assessing the stability of hazardous landslide slopes and slopes for civil, transport construction and recreational development of the coast of the Cheboksary reservoir is analyzed in this article. Minimizing the risk and damage from hazardous slope processes, including landslide, depends on the knowledge of the structure of the landslide geomorphic system and the slope array, harmonization of the interaction of the components of the designed object with the components of the geological environment (GE). On the basis of a professional analysis of engineering and geological factors, correct design models are proposed, with exact values of the slope stability coefficient (Cs) and rational design solutions leading to a reduction in natural and man-made risks.

1. Introduction
The problems of construction and territorial development of the coast of the Cheboksary reservoir are quite complex and require the solution of many issues on environmental management, on the safe functioning of such natural-technical systems.

Within the limits of Chuvashia on the Volga coast there are areas of two reservoirs of the Volga cascade: Cheboksary reservoir and Kuibyshevsky. The Cheboksary reservoir section is represented by both upstream and downstream. The lower backed bay is at the same time a zone of pinch-out of the backwater and the upper section of the Kuibyshevsky. The operation of the Cheboksary Reservoir began in 1981 at an intermediate mark of normal reservoir level NRL – 63 m (instead of 68 m). Since then, the banks are in the stage of adaptation to new conditions, the development of new equilibrium profiles, accompanied by the massive development of abrasion-landslide processes on the right bank and abrasion-scree on the left bank, and with a small share of abrasion-accumulative due to the relative youth of the reservoir. With the creation of the reservoir, its coastal areas began to be actively involved in the economic turnover and built up [1]. В качестве разделителя дробной и целой частей используется «точка» (в том числе на рисунках и в таблицах).
The high Volga right bank from Nizhny Novgorod to Volgograd has long been known as an area of intensive development of landslide processes, and is described in detail in numerous literature from the end of the 19th century on. (P.I. Krotov, A.P. Pavlov, I.S. Ragozin, G.S. Zolotarev, G.A. Golodkovskaya, A.P. Dedkov, etc.). Today, it is in this region with millionaire cities, with a high concentration of population and production potential of the country, the problem of the stability of the slopes is particularly acute due to fundamental changes in natural and man-made conditions, especially in connection with the creation and operation of a cascade of reservoirs. As a result, new known factors such as lithologic, stratigraphic, geomorphological, and erosional factors were added – increased bases of erosion, transformation of the hydrological and hydrogeological regimes of coastal areas, rising groundwater levels and changes in the weight of coastal massifs, including from building hazardous landslide slopes. The shortage of land resources and suitable areas, as well as architectural considerations, is forcing the builders of Cheboksary to actively engage in landslide slope surfaces with significant steepness, often affected by ravine erosion. There is an alignment, territory planning, backfilling of ancient and modern ravines and beams with technogenic soil (Fig. 1, 2).

Figure 1. The reconstructed Moscow Embankment (Volga River Embankment) in the city of Cheboksary

Figure 2. Embankment before reconstruction. One can see the cut-off tongue of the landslide-flow, which was put forward on the asphalt path

The rationale for the optimal economic development of the hazardous landslide slopes of the Cheboksary reservoir in order to provide the population of the Chuvash Republic with high-quality capital construction, social and industrial infrastructure will be devoted to this report. The obtained results are applicable for urban planning, recreational and transport development of the territory not only of the Chuvash Republic, but also of other territories under the conditions of intensive technogenic impact and influence of the functioning of reservoirs.
2. Materials and methods
The problem of assessing the stability of the slopes (Cs) remains in engineering geology (EG) and related sciences very relevant. This is evidenced by numerous publications and our own practice (since 1970) [2–14]. But the same information shows that against the background of the emergence of many certified design schemes and programs, the prevalence of the geotechnical approach in such surveys is preserved. This approach does not perceive the irreplaceable role of the geological component in solving the problem of determining the stability of landslide slopes. Unreasonably widespread method of circular-cylindrical sliding surfaces (CCSS), a complete replacement of domestic methods of calculation for foreign (Morgenstern-Price (1965–1971), Bishop (1955), Yanbu (1954), etc. [14]) without significantly improving the reliability of results, as well as reducing the demands on the quality of survey materials, the clogging of landslide studies by primitive algorithms, which underestimate the role of a specialist in the calculation process, have caused many emergencies. As a result, the problem of sustainability, instead of solving, is pushed into a dead end: most of the methods used for assessing Cs have retained the shortcomings of the geotechnical approach, on which K. Terzaghi, M.N. Goldstein, N.N. Maslov et al. paid attention [3, 5].

In addition to simplified design schemes that are far from the mechanisms of real landslides, the inability of many designers and even state expertise in the process of accepting objects can be attributed to the shortcomings of the geotechnical approach: a) to detect gross errors in exploration materials, especially geomorphological ones, which inevitably provoke erroneous design solutions and multimillion-dollar damages during the construction and operation of the object, b) their blind faith in the possibility of obtaining real design parameters of the shear strength of soils of the displacement zone by statistical processing of the results of laboratory tests according to the method of State Standard (GOST) 20522-96. The disadvantages include the drop in demand in the community of designers in qualified geological conclusions, and the growth in consumption of “machine” variants of geotechnical sections instead of sections built by an EG specialist. Below are considered the features of geotechnical and geological approaches to the problem of assessing the stability of slopes for construction purposes.

Much contribution to solving the problem of estimating Koo was made by M.N. Goldstein [3]: developing K. Terzaghi’s thoughts on the relationship between soil mechanics and engineering geology, he was the first to point out the reason for such a state: “… it seemed to many that only purely mathematical difficulties restrain the progress of soil mechanics …. However, the practice soon showed all the groundlessness of such hopes, forcing us to pay special attention to the development of engineering geology (our emphasis)”. The role of engineering geology is particularly increasing, according to M.N. Goldstein, in cases where “the complexity of the geological structure of the site and the heterogeneity of soil properties exclude the possibility of any kind of accurate calculation ... using methods of modern soil mechanics”. In such cases, engineering geology should help “assess the degree of approximation of the performed calculations and indicate the order of possible deviations of the results of calculations from reality ...”. From the foregoing it is clear that M. Goldstein among specialists in landslides, including geologists, came closest to understanding the source of unreliable Cs. But another conclusion follows from his position – the time of hopes for solving stability problems only on the basis of a mechanical-mathematical approach has obviously passed. Geotechnics is likely to have exhausted its capabilities in this area, and further progress should be expected from the geological component of the Cs problem. But the trouble is that this truth is far from being realized by many geologists and prospectors.

With existing regulatory documents, the results of the thoughtless execution of the designer’s will (how many wells and where to drill, how deep, how many monoliths to take, what tests to perform) are quite satisfactory for the examination, without bearing any serious responsibility for the quality of the computational models and calculations. Unfortunately, mainly geotechnics, not sufficiently sophisticated in geology and exogenous geodynamics are make models and calculations, As a result, the problem Cs remains, as it were, in a state of suspense between geotechnics and geology. There are sufficient up-to-date data (materials from surveys of design institutes, laboratory studies of soils at Moscow State University, etc.), indicating that errors in Cs estimates are made due to the inexperience
of specialists. The amateurishness of surveyors and designers has now become the scourge of modern landslide, the main cause of the most expensive emergencies.

The choice of a rational method of calculation for mass use in design and survey organizations we have decided in favor of the method of “leaning slope” as the most correct, simple, convenient and quite reliable for determining Cs slopes and Pl (landslide pressure) for designing anti-landslide measures (ALM). The method is considered in detail by I.O. Tikhvinsky (1981). As part of our algorithm, it allows to get Cs and Pl on the borders of all structural elements and blocks of landslide geomorphic systems, fairly reliable data on the role of various factors in the slope stability, at different positions of the surface water level (SWL), under loadings and unloading compartments taking into account the soil resistance to compression in front of the frontal edge of the flat displacement unit (IIC) of the entire landslide system. In relation to the design formula of a leaning slope, we have chosen an algorithm and a table of source data that requires constant work of the prospector himself at all stages of the sustainability assessment procedure – from drawing up a structural calculation model using his own data from a field landslide mapping and filling the table of source data to communicating with a computer during the calculation, consciously changing the strength characteristics for obtaining the peak and residual parameters of soils of the displacement zone. By this, our algorithm is significantly different from most algorithms that operate according to the principle of the so-called “black box” almost without the participation of a surveyor. Geotechnics are usually engaged in calculations, and as a result, it often turns out that the calculation model is poorly connected with the geological structure and the structure of the forecast or real landslide.

It is important to note that the quality of the assessment of the Cs slope is determined not so much by the number of applied methods, but by the quality of the computational model and the accuracy of the shear strength parameters of soils of the displacement zone, discussed below.

3. Results and discussion
Drawing up correct design models, i.e. such models, which reflect the structure of real landslides, their mechanisms, are compiled according to certain principles. The main condition for the compilation of such models is the availability of own field detailed mapping materials of the landslide area with the definition of the genetic type of slopes, their condition and boundaries, types of landslides on the mechanism and structure in accordance with modern concepts of the structure and component-element composition of landslides. Below in Figure 3 shows the structural model of a multi-block landslide, with the main components of landslide systems that are part of the correct design models.

![Figure 3](image)

**Figure 3.** A single-level slip landslide, consisting of 5 blocks: a – functional kinematic scheme; b – structural-functional graphic model. Bp – head rotation unit, IIC – flat displacement block, Cж – internal plastic compression block, Bn – lingual tongue block, E – compression resistance at the front edge of the tongue

The correctness of the computational model is a direct consequence of the competence of the researcher of slope processes and phenomena, including landslides, in matters of their genetic diversity, their structure and composition, their mechanisms of nucleation and separation from the array, the characteristics of their movement and stop, their natural classification.
The choice of design parameters of the averaged shear strength of soils of the displacement zone according to the results of reverse calculations is carried out differentially depending on the genetic type of the slope, the absence or presence of landslides of various types within it, their sizes, age and preservation, on survey tasks. Success is determined by the degree of geometric conformity of the calculated model to the original: the former for old landslides, the modern one for current landslides, and the future for forecast ones. The need for such indicators of strength arises after a direct calculation of the stability according to laboratory tests of soils and obtaining a result that diverges from the optimum (for example, Cs > 1.0 for a landslide slope, or Cs < 1.0 for a clearly stable slope). To design an ALM on a landslide slope, it is necessary to have indicators of both peak strength, at which the landslide body is separated from the massif, and residual strength, at which the landslide body movement stops. In multilevel landslides each tier can have its own strength parameters. Reverse calculations should be performed on the same models on which the software is designed. Peak parameters are obtained on retrospective models, reflecting the pre-creep condition of the slope, and residual ones – on models that depict the post-creep state of the slope, taking into account its modern profile and changes in its denudation processes after the landslide body disappears. These secondary changes can be quite significant, especially on the banks of reservoirs, rivers, lakes and seas.

Other recommendations in the problem of assessing sustainability will also be relevant. The landslide capture depth of an array is determined by drilling and sounding data, and additionally by geometric constructions of the kinematics of the system blocks (especially rotation blocks (Bp) and reset (Cб)). The latter method is especially effective for slip landslides with head blocks Bp, which are less than 25–30 m. According to our data [15], blocks in a tier play different functional roles, and the magnitudes of the shear and holding forces of the tiers depend on the type of their active head units – rotation (Bp), plane displacement (IIC) or reset (Cб). In fig. 3 it can be seen that between the Bp and IIC blocks, in the process of movement, compressive stresses arise at the bottom of the displacement surface, and tensile stresses occur in the upper part. As a result, when plastic soils between them can be formed shaft extrusion due to squeezing plastic clay from the bottom up to the surface, and for solid, semi-solid soils – crack fracture and graben-like structures by lowering the wedges of the soil separated from the edges of the crack. In the frontal part of a landslide, the block Bп is often formed not by pushing or pushing the ground to the surface, as is usually shown in the design diagrams, but by compressing the soils of the frontal part of the tier according to the “barrel” principle (remember the cooper who made wooden barrels) and abrupt progressive movement of similar compression zones in the direction of displacement of the system by progressive involvement in the movement of new portions of the slope. The shear forces of the head block are maximum for block Bp, minimum for IIC. In almost all cases, when the mechanism of separation of a landslide from the massif, especially at its beginning, is almost close to the mechanism of slip landslides, it is advisable to determine Cs using the methods of limiting equilibrium, developed, like the method of "leaning slope", in relation to landslides with a "fixed" sliding surface.

If it is necessary to assess the stability of non-slide slopes (talus, erosion, scree, etc.), with a natural Cs more than 1.0 (1.1–1.15), such predicted landslides are preferable by the mechanism, dimensions and shapes of the displacement surface, which are set landslides in the area surveyed in similar landscape conditions. The mechanism of forecast landslides is established according to survey data. The mechanism of forecast landslides is established according to survey data. In this case, the question of the possibility of the formation of particular landslides due to technogenic changes in the hydrogeological and soil conditions of the massif is being resolved. Technological factors of sustainability are also considered – the limits of possible undercuts and powders in the vertical planning of the construction site, the stability of the projected vertical benches and slopes, recommendations for improving their sustainability.

4. Conclusion
Minimizing the risk from hazardous processes depends on the accuracy of forecasting the conditions for reliable operation of the natural-man-made system. To obtain the optimal result, it is enough to have one
method for solving the problem on the correct model with the calculated characteristics of the soils of the displacement zone, refined by inverse calculations.

There are numerous new data on the landslide phenomena of recent years, which have arisen as influenced by the regime of the Cheboksary hydroelectric station, and the urban economy. They were studied for the purpose of building up landslide slopes. In their study, typifications and classifications, their own methodological developments were applied, starting with clarifying the concepts of “landslide”, “landslide process” and “landslide mechanism” and ending with the principles of systematics and nomenclature of simple and complex landslide systems, their typification and classification. We recommend to increase the stability of the slopes of the Cheboksary reservoir with a number of ALM: 1) vertical leveling of the slope (cutting off the head active blocks of landslides, which will lead to unloading of the head parts of the landslide tiers), 2) regulation of runoff, 3) adjusting the frontal part of the landslide systems with counter banks.

Among a number of principles of applied landslide, developed in the course of the research, we substantiate the principles of structural mapping of landslide systems and their elements, recognition of landslide taxons according to their diagnostic features in nature, making kinematic computational models for designing rational composition of anti-landslide activities. The classification of landslide systems should be based on: signs of separation of the landslide body from the massif; signs of movement of the landslide body; signs of the structure of the landslide body. They express the essence of landslide bodies, the type of displacement mechanism, without the determination of which sustainable environmental management in the hazardous landslide slopes of the Cheboksary reservoir is impossible.

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