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ARTICLE

Monitoring the Stability of a Hydraulic Structure in Central Kazakhstan during a Period of Intense Precipitation in the Warm Season

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ABSTRACT

The warm season, characterized by heavy rainfall, is critical for the stability of ash dump embankments, including the embankment at the Topar Main Distribution Power Station (MDPS). During this period, the groundwater level rises and the dam foundation becomes more water-saturated, which increases pore pressure and filtration flows in the dam body. Geotechnical monitoring during such periods allows for the timely detection of changes in stress-strain conditions, local deformations, and potential water seepage zones. The calculation of the stability reserve coefficient showed a value of 1.708, which is significantly higher than the standard value of 1.20 for Class II structures. The decrease in stability is mainly due to pore pressure rather than the formation of critical slip surfaces. Modeling of the stress-strain state, taking into account the weight of the dam, pore pressure, and boundary conditions, showed a uniform distribution of shear stresses without the formation of cylindrical or elliptical slip surfaces. This indicates that even under the worst conditions, with maximum rock moisture and minimum strength characteristics, the dam slopes remain close to the limit state. Both traditional methods and modern remote technologies are used to monitor the condition of hydraulic structures. Comparing monitoring

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data with climatic information on precipitation during the warm season allows us to assess the dam's response to hydrological loads and identify areas with an increased risk of filtration flows.
Keywords: Hydraulic Engineering; Dam; Heavy Precipitation; Warm Season; Finite Element Modeling

1. Introduction

The deterioration of hydraulic engineering infrastructure in Kazakhstan is one of the key engineering and environmental problems that has arisen as a result of the long-term operation of facilities without sufficient modernization. A significant portion of dams, reservoirs, and control units were built in the second half of the 20th century and have already reached or exceeded their design life. At the same time, the deterioration of structures is exacerbated by natural processes such as filtration, suffosion, corrosion of concrete and metal, and the accumulation of fatigue deformations in materials. The lack of systematic monitoring of the condition of structures in certain regions makes it difficult to identify critical damage in a timely manner and increases the risk of accidents.

Contemporary climate change is increasing the load on outdated hydraulic engineering infrastructure, especially in the country's sharply continental climate. Spring floods caused by intense snowmelt, as well as localized torrential rainfall in summer, create variable hydrostatic and filtration effects on structures, accelerating the processes of destruction. As a result, the reliability of many facilities is gradually declining, requiring the development of comprehensive programs for the diagnosis, reconstruction, and adaptation of hydraulic structures to new hydroclimatic operating conditions [1,2].

The increase in climate instability in the northern and central regions of Kazakhstan in recent decades is manifested in increased interannual variability in temperatures and precipitation, as well as in more frequent extreme weather events. There have been more abrupt seasonal transitions, instability in snowmelt timing, shifts in peak runoff periods, and an increase in the proportion of intense short-term downpours. These changes indicate a transformation of the regional climate regime characteristic of sharply continental steppe zones.

The increase in the amplitude of hydrometeorological fluctuations plays a special role: winters with little snowfall may be followed by years with abnormally high snow reserves, leading to sharp fluctuations in flood loads. The warm season is characterized by alternating dry periods and localized high-intensity storm precipitation. This uneven distribution of moisture creates additional risks for natural and engineered systems, as the traditional design parameters used in the design of structures are increasingly inconsistent with actual conditions [3,4].

Increased climate instability has a direct impact on the stability of hydraulic structures in the region. Variable hydrological loads contribute to accelerated wear and tear of structures, increase the likelihood of filtration processes, and reduce the reliability of facility operation. Under these conditions, there is a growing need for systematic monitoring of climate parameters, revision of regulatory design characteristics, and implementation of adaptive engineering solutions that take into account current climate change trends.

The increase in the frequency of extreme precipitation in the northern and central regions of Kazakhstan is considered in contemporary climate studies to be one of the key indicators of regional climate instability [5]. This part of the country has a sharply continental climate with annual precipitation of approximately 300 to 450 mm, but moisture distribution is highly uneven and varies significantly from year to year [6]. The intensification of contrasts between dry periods and episodes of heavy rainfall is leading to an increase in short-term storm events capable of causing localized flooding and accelerated soil erosion.

According to a study by Kusainova et al. [6,7], based on meteorological observations and hydroclimatic calculations, pronounced fluctuations in the water balance have been identified in the forest-steppe and steppe zones of Kazakhstan, reflecting the variability of moisture conditions. The results obtained showed that fluctuations in moisture supply significantly affect natural and economic processes, indicating the instability of the atmospheric precipitation regime.

Additional data on the mechanisms of intense rainfall formation are provided in studies on synoptic conditions for intense precipitation in Northern Kazakhstan. These studies note that extreme precipitation is most often associated with the passage of cyclones and cold fronts, as well as the intrusion of contrasting air masses, which increases the likelihood of short-term but very intense rainfall during the growing season [8]. Taken together, these factors confirm the trend towards increased climate variability and a rise in the frequency of extreme precipitation events in the region under study, which requires a review of hydrological calculation parameters and the adaptation of infrastructure to new climatic conditions.

Hydraulic structures are critical engineering structures, so accidents (dam or tailings pond breaches) can have catastrophic consequences, causing damage to businesses, agriculture, roads, housing and utilities, and the population. One such example is the largest accident involving the breach of a tailings dam at an iron ore mine in the Brazilian city of Brumadinho. Due to damage to the tailings dam, 12 million m^3 of mud flowed into the valley, sweeping away everything in its path. In addition to deaths and destruction, the tragedy significantly worsened the environmental situation in the region.

It should also be remembered that similar breaches have occurred in the post-Soviet space, with devastating consequences: residential and administrative buildings destroyed, roads washed away, communication and power lines damaged, and equipment and transport flooded. But the most terrible and irreparable consequence was the loss of human life. Examples of this include the breach of the dam on the Seiba River (Russia) on 19 October 2019, the breach of the tailings pond dam in the village of Kokpekt (Kazakhstan) on 31 March 2014, and the breach of the Sardobinsky reservoir dam (Uzbekistan) on 1 May 2017. In this regard, hydraulic structures, as objects of strategic importance, are subject to periodic (at least once every five years) comprehensive monitoring, including geodetic monitoring [9].

The insufficient study of the combined impact of spring snowmelt and uneven torrential rainfall on the stress-strain state of hydraulic structures remains one of the pressing scientific problems in hydraulic engineering and engineering hydrology. Research by Russian scientists shows that spring floods are the most dangerous phase of the water regime of many lowland rivers, forming the main hydrodynamic loads on structures and foundations. Additional studies of Siberian rivers show that the volume of floodwater is determined by a combination of soil moisture and freezing conditions, i.e., it depends on a complex of factors acting simultaneously [10–12].

Modeling of the stability of embankment dams shows that precipitation infiltration increases pore pressure and reduces slope stability, with rainfall intensity and duration having a decisive influence on the reduction in the stability reserve coefficient. Similar results have been obtained in numerical studies of various precipitation scenarios: moderate but prolonged rainfall can have a more destabilizing effect than short-term, high-intensity showers [13]. Despite this, the authors note that the impact of rain on the slopes of earth dams in Kazakhstan remains insufficiently studied due to the complexity of field observations and the variability of hydrogeological conditions [14,15].

The relevance of this study is due to the insufficient study of the effect of atmospheric precipitation on the stability of hydraulic structures in the Topar Main Power Distribution Station area, despite the increasing importance of climatic factors in ensuring their reliable operation. In the conditions of the observed variability of hydrometeorological parameters, including an increase in the intensity and unevenness of precipitation, there is a need for a detailed assessment of their impact on the strength and deformation characteristics of structures. The lack of previously conducted comprehensive research for this region limits the possibilities of timely risk forecasting and the development of effective engineering solutions, which emphasizes the scientific novelty and practical significance of the proposed work.

In the context of existing studies of the stability of bulk hydraulic structures, the issues of quantifying the effect of intense and prolonged precipitation on filtration processes, redistribution of pore pressure, and the development of local decompression zones in the body of the embankment remain insufficiently studied. In particular, there is limited data on the dynamics of changes in the strength characteristics of soils during their water saturation, as well as on the role of surface slope protection in reducing erosion and weathering processes under extreme weather conditions. The presented work fills in these gaps through a comprehensive analysis of the impact of precipitation on the stability of embankments in the area of the Topar Main Power Distribution Station, taking into account the protective shield (crushed stone or concrete coating) designed to prevent erosion and soil degradation. This makes it possible to clarify the mechanisms of interaction between hydrometeorological factors and structural elements of the structure, as well as to substantiate practical recommendations for improving their operational reliability.

The purpose of this study is to conduct comprehensive monitoring of a hydraulic structure to quantify its stability during heavy precipitation in the warm season using modern instrumental and computational methods. To achieve this goal, laser scanning and aerial photography technologies using unmanned aerial vehicles (UAVs) are used to obtain high-precision spatial information about the geometry and deformations of the structure. Based on the data obtained, numerical modeling using the finite element method is performed, which makes it possible to assess the stress-strain state of the structure during soil water saturation. The stability coefficient is calculated using the Mohr–Coulomb strength criterion, the advantage of which is a high degree of reliability due to the consideration of a wide range of physical and technical characteristics of soils. The integrated application of these methods provides a more accurate and reasonable assessment of the stability of the structure in conditions of increased hydrometeorological stress.

The works of Kusainova et al. [6,7] emphasize the importance of studying spatial and temporal changes in climatic characteristics in Northern Kazakhstan, where in recent decades there have been significant fluctuations not only in total precipitation but also in moisture distribution during the growing season. Despite the general trend towards weak moistening in precipitation analysis, studies show that the nature of these changes is not linear: there are different intervals of time series with opposite trend slopes, which indicates a high level of climatic instability and uncertainty in forecasts. This complicates the assessment of risks to the region's agroecosystems and engineering systems, as moisture resources have a direct impact on hydrological loads and soil stability.

An analysis of climatic trends in precipitation shows that in a number of regions of Kazakhstan, including the northern and central parts of the republic, there is a positive trend in extreme precipitation, i.e., the proportion of intense precipitation is increasing. This is reflected in an increase in maximum daily precipitation, which in the northern regions reached positive values of 2 to 7.8 mm per decade, which is interpreted as an intensification of severe thunderstorms in summer. Such trends are noted in climate series for the period 1971–2020, which analyze changes in extreme precipitation and its distribution across the country [3].

Data from the 'Review of Kazakhstan's Climatic Features' by the National Hydrometeorological Service of Kazakhstan confirm that in 2024, precipitation during the warm period exceeded the climatic norm, and the number of extreme meteorological phenomena (including torrential rains) in the republic increased significantly compared to previous periods. Among them are cases of heavy precipitation affecting flood and water loads on infrastructure. The results of Kazhydromet observations and analytical climate studies over the past decade show an increase in the number of natural climate extremes, including heavy rains, throughout Kazakhstan. Between 2007 and 2023, according to meteorological services, the number of heavy rainfall events increased by approximately 1.4 times compared to the earlier period, indicating an increase in extreme summer precipitation events characteristic of the country [16]. These empirical data reflect changes in the atmospheric precipitation regime in Northern Kazakhstan: the warm season is becoming increasingly prone to intense precipitation events, which, combined with climate variability, affects the water balance, flooding, erosion processes, and the load on engineering networks and structures.

The extent to which the topic has been studied is determined by research into scientific publications and works in the field of applied geodesy as applied to the tasks of geodetic monitoring and observation of displacements and deformations of embankment-type hydraulic structures. In the course of work on the dissertation, the works of well-known scientists in the field of applied geodesy were used: Besimbayeva O.G., Karpik A.P., Komissarov A.V., Melkyi V.A., Mogilny S.G., Mustafin M.G., Pimshin Yu.I., Ustavich G.A., Ustinov A.V., Khmurova E.N., Khoroshilov V.S., Chugaev R.R., Sholomitsky A.A., Shulz R.V., Yambaev H.K., Centolanza G., Di Martire D., Iglesias R., Monells D., Sica S., and many others [9].

2. Materials and Methods

Modern engineering studies of dam stability actively use numerical modeling methods that allow for the complex interaction of filtration processes and the stress-strain state of soils to be taken into account. One of the most common approaches is the finite element method (FEM), which is implemented in the GTS NX and Rocscience Slide software packages. FEM allows the construction of three-dimensional and two-dimensional models of dams, taking into account the geometry of the structure, the physical and mechanical properties of the soil, pore pressure, and water loads. Strength reduction methods (SRM) and stress analysis methods (SAM) make it possible to determine the stability coefficient, identify potential stress concentration zones, and assess the impact of filtration on dam safety. Special attention in modeling is paid to the effects of water saturation and pore pressure arising at maximum water levels and as a result of precipitation, which makes it possible to predict the behavior of the structure in extreme hydrogeological conditions [9,17].

Remote monitoring using unmanned aerial vehicles (UAVs) and aerial photography provides unique opportunities for rapid and highly accurate monitoring of the condition of dams and embankments. Aerial photography allows for the collection of volumetric geospatial data and the creation of three-dimensional models of objects, enabling the visualization of deviations and the detection of deformations in real time. Remote sensing technologies are also used to analyze slope displacement, identify areas of intense filtration, and assess the condition of drainage systems, which is particularly important for tailings ponds and embankment dams with heterogeneous foundations.

During the aerial survey, 790 images were taken. The length of the survey strip was about 820 m long and about 80 m wide. White plastic disposable plates with a diameter of 165 mm were used as reference points on the ground, fixed with dowels, which are confidently identified in the images and allow markers to be centered on their centers in the image processing program with an accuracy of one pixel, which corresponds to 2–3 cm.

As a result of processing the obtained photographs, dense point clouds, elevation maps, digital models, and orthophotoplanes were created. During the processing of the survey data, a dense point model was constructed with a preliminary orientation of the matrix based on the navigation coordinates of the photographing centers, where the accuracy is several meters. It is only after importing the calculated coordinates of the reference points into the program and precisely arranging them using special markers that we get an accurate spatial model of the area being photographed.

From the PhotoScan survey data processing report, the total error on the reference points was 3.4 cm (2.5 cm in plan and 2.3 cm in height), while the shooting resolution was 2.59 cm/pixels. These figures characterize the high accuracy of building a digital terrain model. After conducting field and camera work, aerial photography resulted in a three-dimensional surface of the embankment dam. The resulting surface is necessary for subsequent filtration calculations and calculations of the stability of the hydraulic structure. In addition, according to the photographs obtained, a visual inspection of the body of the dam was carried out for the presence of external violations of the integrity of the body of the dam and the accumulation of water at the base of the lower slope.

The combination of numerical modeling and remote monitoring provides a comprehensive approach to assessing dam stability. Modeling allows for the prediction of potential risks associated with filtration, pore pressure, and changes in soil moisture, while remote monitoring ensures the timely detection of actual changes in the condition of the structure under the influence of precipitation and snowmelt. This integrated approach allows for a more accurate assessment of the stability coefficient and informed engineering decisions to improve the reliability of dam operation in real hydrogeological conditions.

Modeling of filtration processes in soils is based primarily on classical hydrodynamic approaches, the central one being Darcy's law, which describes the movement of fluid through a porous medium. For steady-state conditions, steady-state filtration models are used, assuming constant hydraulic head over time, while for variable hydrological loads, unsteady-state models are used, taking into account changes in pore pressure and moisture over time. Modern calculations widely use numerical solutions of differential filtration equations, which allow for soil heterogeneity, permeability anisotropy, and complex geometry of structures.

Both classical analytical models and numerical methods are used to analyze the stress-strain state of soil structures. The most common model is the Mohr–Coulomb strength model, which takes into account the cohesion and angle of internal friction of the soil and is used to assess the limit state of slopes and foundations. More complex models include nonlinear elastic-plastic dependencies that allow for the gradual accumulation of deformations, consolidation, and soil loosening during water saturation. Such models are particularly important when analyzing dams and embankments, where deformation processes are closely related to filtration [17,18].

The most accurate results in engineering practice are provided by coupled hydromechanical models implemented using the finite element method. They allow simultaneous consideration of filtration flows, pore pressure and mechanical behaviour of soils, which is particularly important for assessing the stability of embankment dams under conditions of heavy rainfall or rising groundwater levels. Modern software packages allow for the modelling of various loading scenarios, construction stages, changes in humidity, and long-term behaviour of structures, providing a reliable assessment of their reliability and a forecast of possible deformations.

The sliding surface begins at a depth h, below which it is located at an angle to the maximum principal stress and is curved. The length of the straight section is the line of contact between the dam and the base and depends on the angle of its inclination.

The width of the prism of possible collapse is determined by the formula [9]:

$$Б = \frac{2\left[H(1 - ctg\alpha \times tg\frac{\alpha + \rho}{2}) - h\right]}{ctg\mu + tg\frac{\alpha + \rho}{2}} \quad (1)$$

where H is the height of the structure, m;

α is the angle of inclination of the dam slope, degrees;

h is the start of the sliding surface (depth), m;

μ is the angle of the sliding surface, degree;

p is the angle of internal friction of the soil, in degrees.

Among the recommended methods for calculating the stability of earth embankments and dams of hydraulic structures are the methods of G. Krey, K. Terzagi, and R.R. Chugaev (weight pressure, as well as inclined and horizontal forces), which operate with a prism of collapse divided into vertical elements and with an arbitrary or circular cylindrical sliding surface, satisfying the conditions of equilibrium in the limit state. Calculation methods based on the hypothesis of inclined and horizontal forces of interaction between the elements of the collapse prism, the weight pressure method, and others can be used.

Stability calculations for earth dams (embankments) of all classes should be performed for circular cylindrical slip surfaces. As part of the project, calculations were performed for circular cylindrical slip surfaces, which are sufficiently accurate and allow results to be obtained using all three conditions of body statics. The calculations were performed using the Rocscience Slide 6.0 software package, which allows calculations to be performed according to the above methodology.

Rocscience Slide is a universal program for 2D stress analysis using the finite element method, which can be used for the design of underground mine workings, quarries and their support systems, as well as embankment-type hydraulic structures. It can be used for both rock and loose soils, provides slope and embankment stability analysis and dynamic analysis, and includes an integrated groundwater filtration model. Rocscience Slide is a program for calculating the stability of soil structures using limit equilibrium methods with built-in finite element analysis of filtration in steady and unsteady states. The program has extensive probabilistic analysis capabilities, allowing you to assign a statistical distribution to almost any input parameter, including material properties, reinforcement properties, loads, and groundwater levels. Rocscience Slide 6.0 offers at least 17 different soil behavior models, including Mohr–Coulomb, anisotropic soil, Hoek-Brown, etc. [9,17,18].

3. Results and Discussion

Geodetic observations were carried out in the village of Topar, Abai District, Karaganda Region (Republic of Kazakhstan) (**Figure 1**). The object of the study is embankment dam No. 1 of the ash dump of Topar Main Distribution Power Station LLP (Limited Liability Partnership) (**Figure 2**), which is filled with heterogeneous soils. Depending on the height and type of foundation soils, embankment dam No. 1 belongs to class II, since according to Khannanov [9] and PRG [19], the natural soils forming the foundation belong to categories A, B, and C, and the maximum height of hydraulic structures is about 34 m. The embankment is 48 years old. The embankment soils on dam No. 1 have been exposed by boreholes at the edges to a depth of 3.0–3.9 m. In the middle part of the dam, the depth is 13.0–19.0 m. The fill soils contain thin layers of sand, inclusions of gravel and crushed stone up to 18%, and small gypsum crystals. According to laboratory data, the fill soils in the dam body are classified as clays, loams, and, less frequently, sandy loams.

The region where the ash dump of Topar Main Distribution Power Station LLP is located is characterized by a continental climate with pronounced seasonal fluctuations in temperature and precipitation. Of particular concern in a hydraulic engineering context are the intense precipitation events during the warm season, which can reach significant levels in short periods of time. This precipitation causes the surface of the dams and foundations to become saturated quickly, leading to an increase in the groundwater level and pore pressure within the embankment.

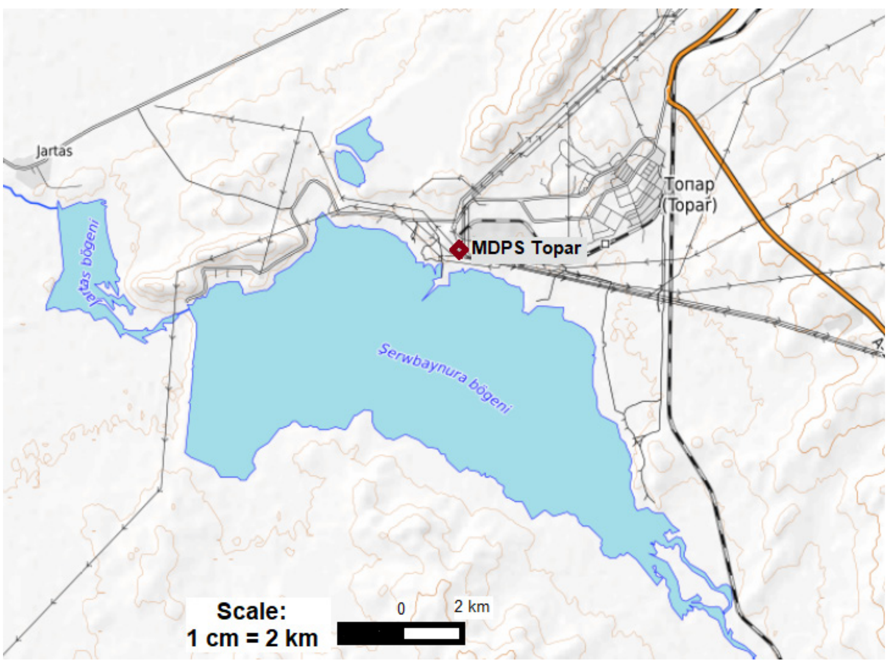


Figure 1. Topar Main Distribution Power Plant, located on the shore of the Sherubai-Nurinsky reservoir.

Figure 2. Bulk embankment No. 1 of the ash dump of Topar Main Distribution Power Station LLP.

Rainwater accumulation on the surface of slopes and infiltration into the soil cause uneven moistening of the dam body, forming local areas of weakening and reducing the strength characteristics of the soil. Areas with a clay core or low-permeability interlayers are particularly sensitive to such changes, where filtration flows under the influence of precipitation create additional pore pressure. The inflow of water into the soil layers leads to an increase in the water saturation of the dam foundation and exacerbates the stress-strain state. In such conditions, monitoring the condition of slopes and foundations, as well as implementing engineering measures to reduce filtration flows (drainage systems and slope loading), becomes critical for maintaining the stability of the hydraulic structure (**Figure 3**).

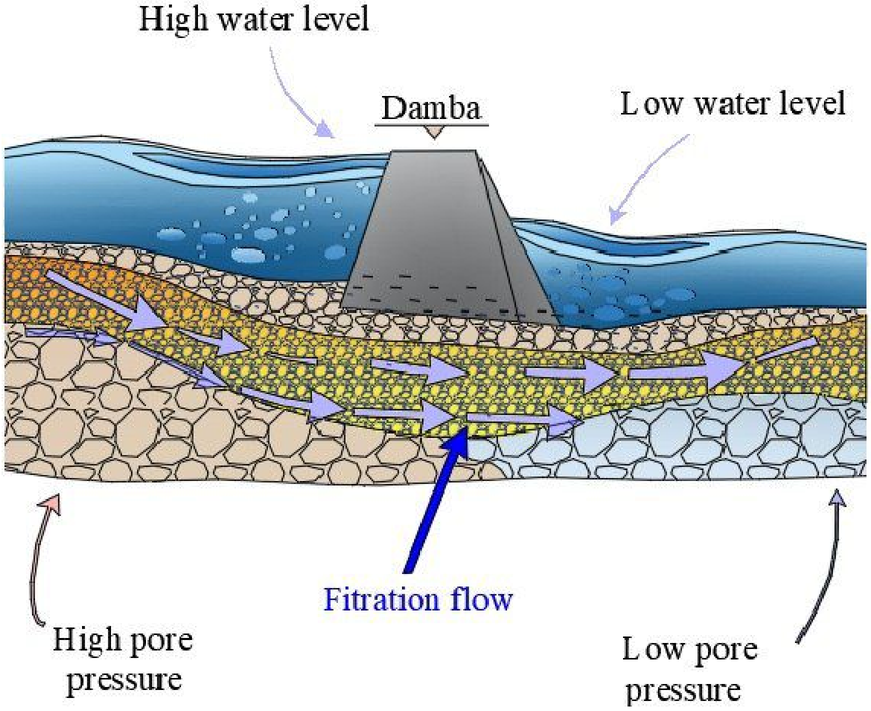


Figure 3. Filtration flow and pore pressure in soil.

Ensuring the specified capacity of the ash dump for a ten-year period of operation is accepted, taking into account the sectional operation of the ash dump, by increasing its height and partially expanding the area in the tail section of dam No. 1 [20]. The stability of the dividing dams depends on the level of ash in the lower reach of the dam. Therefore, based on the calculations performed, it is not permissible to allow the upper sections to be filled ahead of schedule and the lower sections to lag behind. The timing of the drainage of the section before extension, the filling of the extension dams, and the filling of the sections is provided for in the ash dump operation schedule. In general, embankment hydraulic structures—dams and dykes—are very economical, as they are constructed from soil materials extracted from shallow temporary quarries located as close as possible to the construction site. During the design and construction of embankments and dams from soil materials, engineering and geological surveys are carried out, as well as laboratory studies of the rocks that form the base of the dam and the soils used to form its body.

The stability of tailings pond containment and separation dams is determined by a combination of geological, hydrogeological, and man-made factors, of which the following have the greatest influence: the physical and mechanical characteristics of soils and tailings; the technology used to construct and operate the facility; the nature of the foundation; hydrodynamic, hydrostatic, seismic, and dynamic forces. When calculating the stability of the slopes of tailings pond containment dams, it is necessary to take into account that the physical and mechanical characteristics of the dam body undergo significant changes during the construction and operation of the structure due to uneven filling and filling of tailings pond sections, changes in the piezometric water level, filtration and removal of clay particles from the dam body, temperature conditions, dam height increase, the impact of vehicles, etc. From a geomechanical point of view, the protective embankment structure is a water-saturated mass that is in a dynamic state. As a result of waste accumulation, the protective structure grows in height, which leads to deformations of the embankment mass. With the appearance of a pond and as the height of the structure increases, the filtration regime changes.

Aerial photography allows you to obtain a large amount of geospatial data, represented by a set of points in three-dimensional space, which allows you to obtain a complete or partial three-dimensional model and visualization of the object under investigation (**Figure 4**).

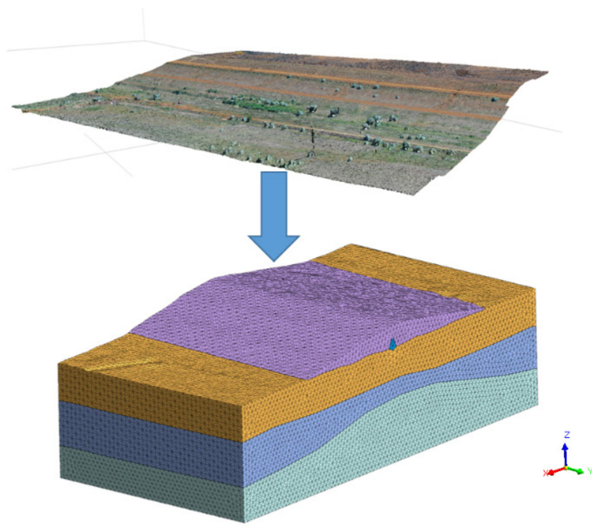


Figure 4. Three-dimensional model of dam No. 1 of the ash dump Topar Main Distribution Power Station LLP.

The three-dimensional data obtained allows stability calculations and filtration analysis to be performed. These calculations are performed in the Midas GTS NX software package, which is specifically designed for finite element modeling. GTS NX is designed to help engineers perform step-by-step calculations for excavations, embankments, construction, loading, and other impacts that directly affect design and construction. The program takes into account various parameters when modeling real objects. Linear and nonlinear calculation methods have been implemented in the program environment (linear/nonlinear static calculation, linear/nonlinear dynamic calculation, filtration and consolidation calculation, slope stability calculation) and various coupled calculation methods (filtration and stress-strain state, stress-strain state and slope stability, filtration and slope stability, and nonlinear coupled slope stability calculation).

In our case, the stability of the dam is checked at full water level using 3D filtration analysis. Seepage analysis can be divided into steady-state analysis and transient analysis. In our calculation case, a steady-state analysis is performed, which assumes that the soil is saturated with water. The model represents a dam section with a height of 30 m, a width of 150 m, and a length of 100 m. The analysis is performed to assess the stability of the dam at the maximum water level. To ensure the stability of the dam, a clay core is installed in the dam body. The model also recreates the dam foundation according to the results of engineering and geological surveys specified in the dam construction project.

Various finite element libraries can be used for geometric modeling in GTS NX. Different elements can be used for linear and nonlinear stress-strain state calculations, filtering, consolidation, and other types of coupled calculations. It is important to understand the elements used and their corresponding properties in order to perform calculations correctly. Since the model is three-dimensional, tetrahedron, pentahedron, or hexahedron elements are used, which can have 4/5/6/8/10/13/15/20 nodes. Pentahedra can be pyramid- or prism-shaped. Three-dimensional elements are solid elements. After the analytical model has been constructed, it is necessary to specify the loads that will act on it.

There are no strict regulatory requirements for the size of finite elements in the model. The mesh size is determined by the principle of convergence of results (mesh sensitivity study): when the mesh is crushed, the stability coefficient and the sliding surface are stabilized with an error of no more than 1–2%. The general principle is that there is a dense grid in the area of the slope and the prism of a possible collapse; away from the critical zone, it is rougher. Therefore, the characteristic size of the elements in the slope area and the surrounding area was 0.5 m. After the analytical model has been built, it is necessary to set the loads that will affect it.

The main loads and boundary conditions of the model are the dead weight and water load, which create a filtration flow and pore pressure in the body of the dam. Gravity is used to simulate the own weight or inertia of a structure and can be set for all elements having mass. The effect of gravity is set on all active elements. Gravity is also automatically set to the elements added during the construction phase. Similarly, gravity is automatically removed when the elements become inactive. In calculations based on pore pressure, its own weight is defined as an additional external force depending on the degree of water saturation. The GTS NX can take into account the water pressure corresponding to the water level position set for the model. Water pressure is taken into account in two-dimensional problems as pressure on the edge and in three-dimensional problems as pressure on the surface. The pressure value corresponding to the water pressure is determined as follows:

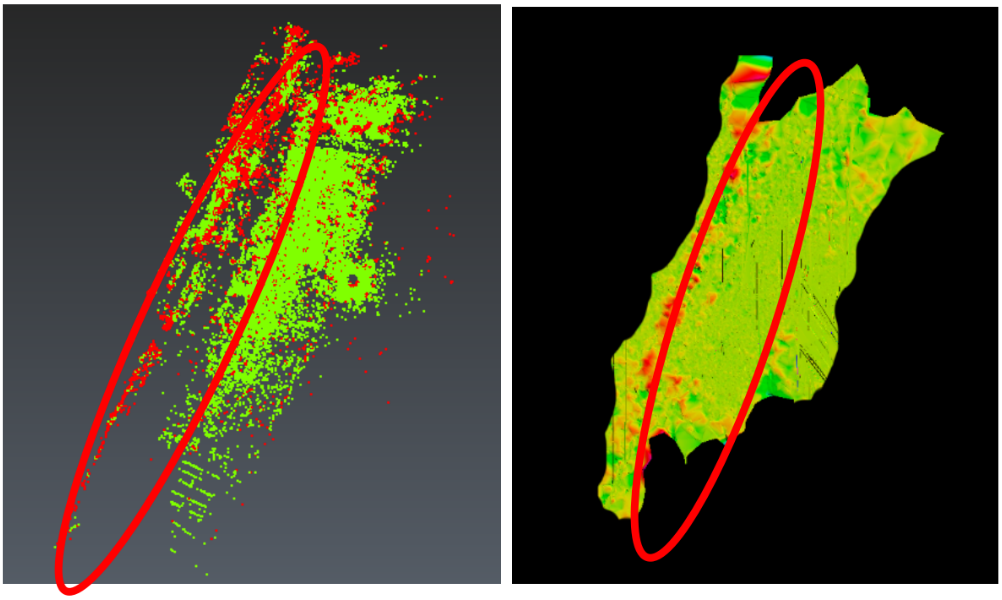
- The pressure is equal to the pore pressure determined on the target edge or surface;
- The pressure is equal to the hydrostatic pressure corresponding to the set position of the water level.

A method has been developed for geodetic monitoring of the condition of embankment dams using terrestrial laser scanning technology (TLS) [9], which allows both point methods and surfaces to be applied based on TLS data, significantly increasing the amount of information obtained and providing the most complete and clear picture of the distribution of displacements and deformations across the entire surface of the object under study or part thereof. This technique is particularly relevant when active deformations occur that restrict safe access to the area under investigation. The result of TLS is a three-dimensional image, or so-called laser reflection points (point cloud), of the embankment dam.

After registering the LRP, the next stage of the research work was to compare three point clouds of the same section of the dam in the same coordinate system but taken at different times.

This stage is carried out in two different software packages (3D Reshaper and TerraSolid), which process data using different principles and methods. Each software package for processing LRP data has its own advantages and disadvantages. In particular, when comparing LRP data obtained during different scanning cycles, the TerraSolid software package demonstrated the most efficient, accurate, and high-quality processing of LRP data.

One of the important advantages of the molding algorithm is that, while constructing the relief surface, it simultaneously selects laser points, i.e., highlights those that belong to this surface. Analysis of the digital surfaces obtained by comparing TLS data from different scanning cycles, which display deviations in the form of color coding, shows that there are no areas with red and green hues in the dam body and foundation. This indicates the absence of displacements and deformations. Significant deviations are present on the surface and are distributed along the drainage ditch section, the surface of which has been subject to constant changes due to the cleaning of the drainage ditch. Consequently, the greatest deviations were identified in the area where cleaning was carried out in the drainage ditch. This result was confirmed by a comparative analysis performed in PC 3DResheper (**Figure 5**).



(**a**) (**b**)

Note: Model sections without deviations. Areas with deviations.

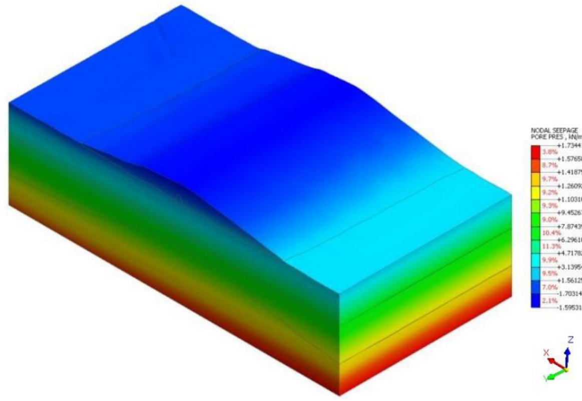
Figure 5. Displaying deviations in comparative analysis of LRP and digital surfaces: (**a**) Analysis results obtained in PC 3DReshaper; (**b**) Analysis results obtained in TerraSolid PC (Program Complex).

Data processing for calculating filtration and stress-strain state. Not all of the above tasks can be solved in a three-dimensional setting. The GTS (Geotechnical and Tunnel Analysis System) NX software package for three-dimensional modeling provides tools for simulating pore pressure, total stresses, and filtration flows. To do this, a three-dimensional model of the dam is created (**Figure 6a**), the properties of the dam materials and foundation layers are specified, and filtration calculations are performed (**Figure 6**).

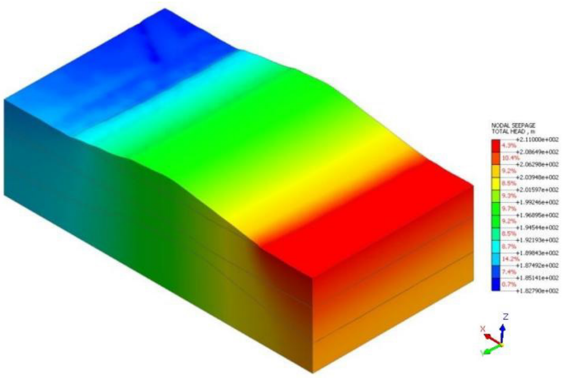
Calculation in Rocscience Slide 6.0 [21]: In the calculation scheme for the stability of the slope of an embankment dam, the slip surface is a combination of straight and curved sections. The shape of the slip surface in unloaded homogeneous slopes is ultimately determined by the direction of the principal stresses and the value of the angle of internal friction, ρ.

Stability calculations were performed taking into account the heterogeneity of the geological structure and engineering-geological conditions of the ash dump dam at Topar MDPS. The strength parameters for the selected engineering-geological elements are specified in the form of cohesion values c and internal friction angle φ (**Figure 7**).

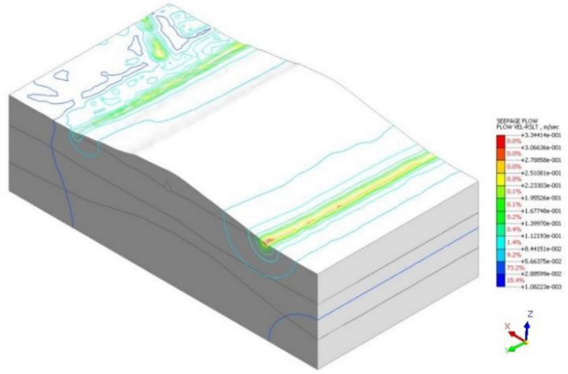
(**a**) Three-dimensional model of a dam.



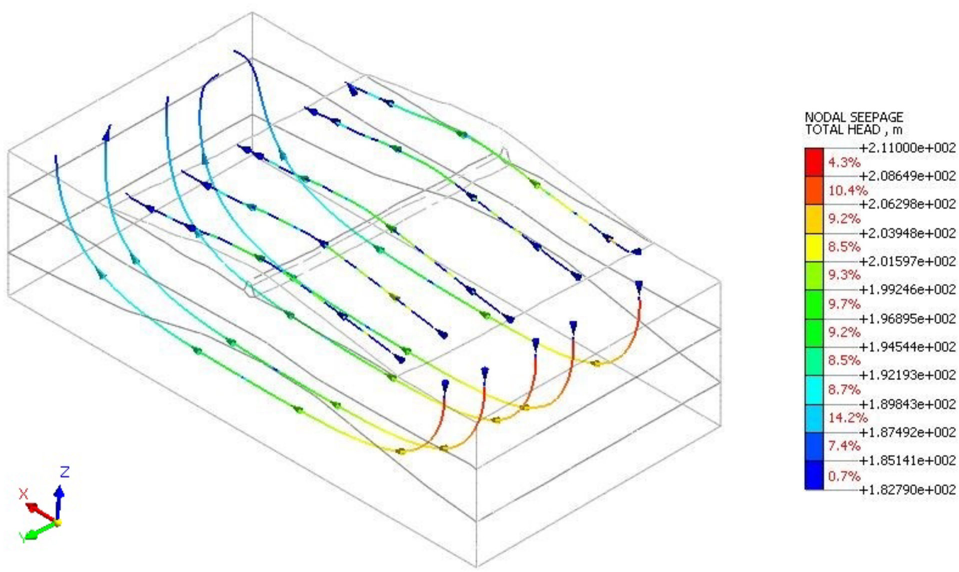
(**b**) Pore pressure.



(**c**) Overall tensions.



(**d**) Flow velocity (in isolines).



(**e**) Filtration flows.

Figure 6. Three-dimensional model of the dam and calculation results.

Note: Coloured scales indicate the total filtration pressure.

The area where the dam is located is considered seismically safe; therefore, seismic effects in the form of additional active shear forces were not taken into account in the stability calculations. Full finite element modeling of the steady state of groundwater (underground water) and the interpretation program are built directly into the program. The calculations were based on the physical and mechanical characteristics of the embankment and foundation soils obtained from engineering and geological surveys and ground-penetrating radar surveys. The calculation of the stability reserve coefficient showed a result of 1.708 (**Figure 8**), which is significantly higher than the design standard value of 1.20 for a Class II structure. According to the building codes [19,23,24], the coefficient of stability for the responsibility of the structure is taken into account in the calculations of the limiting conditions for various classes of structures: for class I—1.25; for class II—1.20; for class III—1.15; for class IV—1.10. In our case, the result of 1.708 is even higher than the norm of Class I structures.

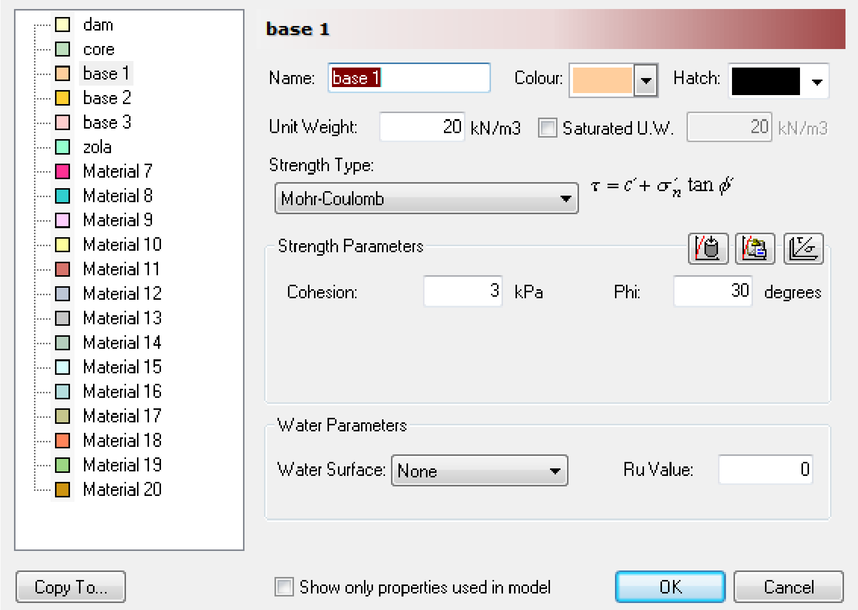


Figure 7. Window for entering the physical and mechanical parameters of the foundation soil and dam body [22].

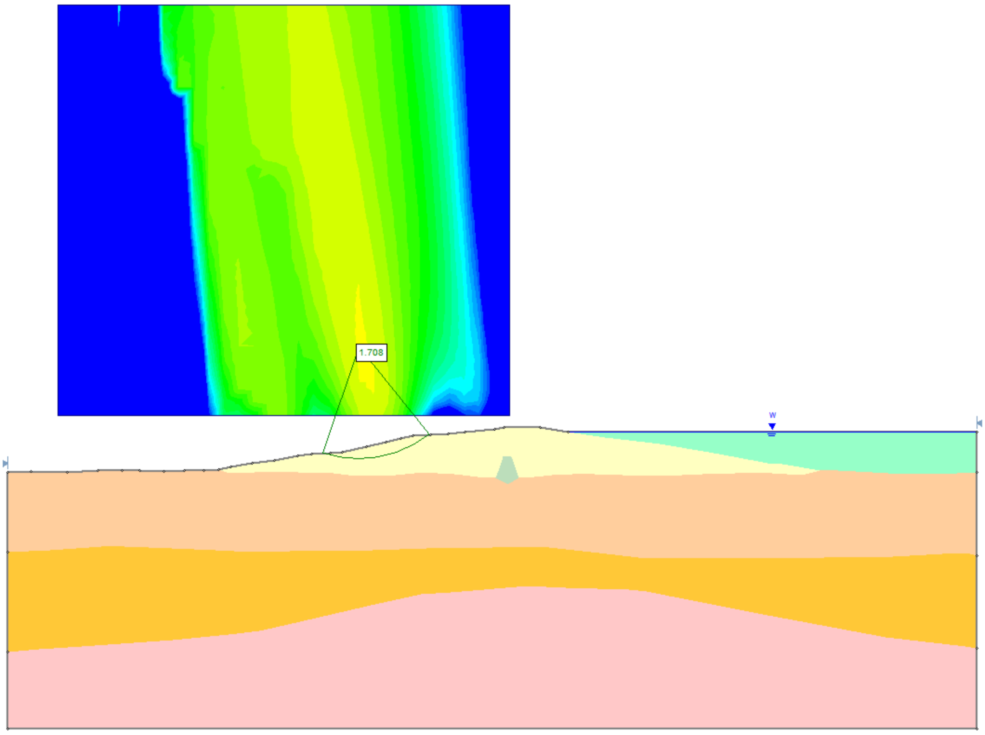


Figure 8. Calculation of the stability of the ash dump dam in PK Rocscience Slide.

Thus, under the worst conditions, with maximum rock moisture content and minimum strength characteristics, the condition of the dam slopes is close to critical. Due to the critical condition of the dam slopes, it is necessary to monitor the position of the depression curve in the dam body and take measures to increase their stability: drainage and loading of slopes with buttresses made of rock or semi-rock materials.

A study of the stability of the embankment dam of the ash dump at Topar Main Distribution Power Station LLP showed that stability calculations performed using the finite element method can vary significantly. Thus, when calculating using the strength reduction method (SRM), the stability reserve coefficient was calculated using the stress analysis method (SAM) in the GTS NX program [25], and in the Slide program [21], the program produced a circular cylindrical slip surface. Traditionally, when calculating the stability coefficient using different methods, the lowest one is selected for use. However, the most important element of the calculations in the program is the explanation of the results. Thus, in the GTS NX program, when calculating the finite element model using the strength reduction method, it is shown that with such dam geometry and the properties of its constituent materials and foundation rocks, there are no shear stresses or slip surfaces, and the low stability reserve coefficient is explained by pore pressure and filtration processes. Therefore, it is recommended to carry out geotechnical monitoring during periods of maximum liquid inflow into the ash dump and to pay special attention to water inflow into the drainage system.

In August and September 2023, abnormally high precipitation was observed in the Topar MDPS area. Approximately 90 and 92 mm of precipitation fell in August and September, respectively, which significantly exceeds the climatic norm: for August, it is 29 mm, and for September, 21 mm [16]. Such intense precipitation during the warm season created an increased load on the ash dump and its protective dam, as the heavy rainfall contributed to the rapid saturation of the soil base and an increase in pore pressure in the embankment. Increased moisture content in the foundation soil led to an increase in filtration flows and a local decrease in the slope stability coefficient. In some sections of the dam, uneven wetting was observed, which could cause local deformations and micro-shifts, especially in the contact zone with the clay core and less dense ash-slag layers. These processes highlight the high dependence of the dam's condition on hydrometeorological conditions and the need for operational control of the water level.

Taking into account abnormal precipitation, geotechnical monitoring and analysis using finite element numerical modeling showed that the main factors contributing to the reduction in the stability reserve coefficient during this period were filtration processes and pore pressure, rather than the formation of dangerous slip surfaces. This case confirmed the need for operational control of drainage systems and additional measures to strengthen slopes, especially during periods of heavy rainfall in the warm season.

To model filtration and pore pressure processes in conjunction with the assessment of the stress-strain state of the ash dump embankment, a two-dimensional problem solution is used. The first stage of the solution is to specify the geometry and properties of the embankment and foundation materials. The ash dump dam is an embankment dam, homogeneous with a denser core, without anti-filtration screens. Although the GTS NX software package allows calculations to be performed in stages of the process, in this case, we will perform calculations based on the maximum filling of the ash dump and the maximum water level [26].

The second stage involves calculations using strength reduction methods (SRM) and stress analysis methods (SAM). Let us consider only the results of the more accurate strength reduction method, comparing some of the results with the stress analysis method.

Figure 9 shows the calculated position of the seepage point on the left in the lower reach and the seepage surface specified for calculations on the right.

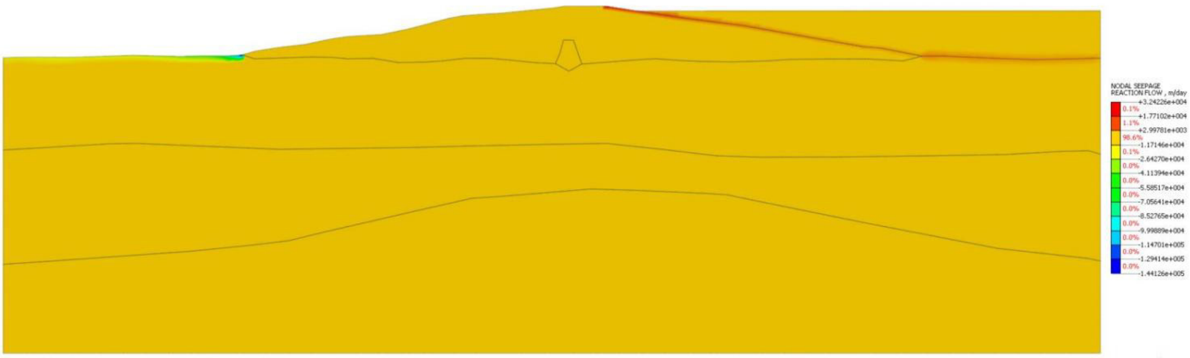


Figure 9. Position of the suction point.

Note: The colour scale indicates the rate of seepage (metres per day).

Seepage point and seepage surface—these indicators relate to filtration (seepage), the flow of water through the body of the structure and its base. They are calculated during the design and analysis of the stability of hydraulic structures. The seepage point (filtration outlet point) is a place on the lower slope of the dam or in the lower reaches, where the depression surface (seepage curve) opens into the open air or onto the slope surface. Below this point, the slope usually remains dry (or slightly moistened). Above it (along the slope), the soil is saturated with water, which can reduce the stability of the slope due to pore pressure. The better the drainage in the lower part (horizontal drainage, prism, tubular drainage), the lower the seepage point drops—this increases safety. Due to the fact that the dam structure has a clay tooth and a drainage ditch at the base of the dam, the seepage point is located at the very bottom of the hydraulic structure, which is shown and confirmed by the calculation results in **Figure 9**.

The seepage surface is an area on the lower slope from the seepage point up to the level where the water actually exits (seeps out) into the atmosphere. In this section, the streamlines intersect the slope surface at an angle (not perpendicular), and the pressure is equal to atmospheric pressure. There is a visible seepage of water (a "wet spot" on the slope). It is sometimes called the seepage face.

Calculations of vertical and horizontal shear stresses showed that they are fairly uniform and do not lead to the appearance of cylindrical or elliptical slip surfaces that could cause landslides in the body of the dam. The calculations obtained by the SRM and SAM methods were very close in terms of the calculated parameters, and none of these methods showed the presence of shear stresses and slip surfaces. Although the stability coefficients determined by the SRM method and the SAM method differ significantly and are equal to the limit for this category of structures [27]. However, the lowest calculated stability coefficient is always selected for use. It should be noted that the decrease in the stability coefficient is not related to the stress-strain state of the object but to filtration processes.

The stability of an embankment dam is significantly affected by the water saturation of the foundation associated with an increase in the groundwater level. This leads to a decrease in the strength characteristics of the foundation rock. To assess the stability of the slopes of embankment dams, a detailed study of all factors affecting the condition of the embankment structure is required, with the choice of a calculation method that would correspond to the specific hydrogeological conditions and physical and mechanical properties of the rocks forming the body of the dams and their foundations being of decisive importance.

Ash dumps occupy a significant area with varying topography, different conditions of sedimentation, and operating life, but with a common foundation for all retaining and dividing dams. Therefore, it is necessary to consider the impact on the condition of the enclosing dams of the water saturation of the dam body rock and foundation soil and additional loads from the slag heap. The area where the dam of the hydraulic structure is located is considered seismically safe; therefore, seismic effects in the form of additional active shear forces were not taken into account in the stability calculations. Full finite element modeling of the steady state of groundwater (subsurface water) and an interpretation program are built directly into the program. The calculations used the physical and mechanical characteristics of the embankment and foundation soils obtained from engineering geological surveys and ground-penetrating radar surveys. The calculated stability reserve coefficient was 1.708 (**Figure 8**), which is significantly higher than the design standard value of 1.20 for a Class II structure. According to the building codes and regulations [19,23,24], the coefficient of stability of the structure is taken into account in the calculations of the limiting conditions for structures:

- For Class I: 1.25;
- For Class II: 1.20.

In our case, the result of 1,708 is even higher than the norm of Class I structures. The decrease in stability coefficient is due to pore pressure rather than dangerous sliding surfaces.

In the third stage, the stress-strain state of the object is modeled, taking into account pore pressure, the weight of the object itself, and boundary conditions. Calculations of vertical and horizontal shear stresses showed that they are fairly uniform and do not lead to the appearance of cylindrical or elliptical slip surfaces that could cause landslides in the body of the retaining dam. Thus, under the worst conditions, with maximum rock moisture and minimum strength characteristics, the condition of the dam slopes is close to the limit. Due to the critical condition of the dam slopes, it is necessary to monitor the position of the depression curve in the dam body and take measures to increase their stability: drainage and loading of slopes with buttresses made of rock or semi-rock materials.

4. Conclusions

Precipitation during warm periods is one of the key factors affecting the water saturation of embankment foundations, including ash dumps. In regions with heavy rainfall, such as the Toparskaya MDPS area, a sharp increase in precipitation leads to rapid saturation of the upper soil layers and an increase in the groundwater level. Such saturation increases pore pressure in the dam body and its foundation, creating favorable conditions for the formation of filtration flows that can weaken the stability of slopes. Seepage flows induced by heavy rains during the warm season can carry fine particles from the foundation soil, changing its density and strength characteristics. As a result, local deformations, displacements, or subsidence may occur on the slopes and in the body of the dam, even in the absence of visible slip surfaces. Periods when the amount of precipitation significantly exceeds the climatic norm, as observed in August and September 2023 in Topar, are particularly critical.

The use of modern remote monitoring methods, in particular UAVs and 3D photogrammetry, allows the dynamics of filtration flows and local changes in the structure of the dam to be identified. Based on the data obtained, it is possible to predict possible areas of weakening and develop measures to manage water saturation, including drainage systems and slope reinforcement. Thus, warm season precipitation is an important factor in the formation of hydrogeological conditions that determine the stability of embankment dams and the need for regular geotechnical monitoring.

Seasonal hydrometeorological loads in the form of precipitation during warm periods have a significant impact on the long-term stability of embankment dams, such as the ash dump dam at the Toparskaya MDPS. Changes in the groundwater level and pore pressure in the dam body as a result of these loads can lead to temporary or local loss of foundation strength. The alternating periods of intense moisture and dry spells are particularly critical, as they contribute to uneven shrinkage and settlement of soil layers, creating a stress-strain state with an increased risk of filtration flows.

Modelling of the dam in GTS NX using the strength reduction method showed that, given the existing geometry and physical properties of the foundation and dam materials, shear stresses and slip surfaces do not form. The low stability factor is mainly due to pore pressure and filtration processes. In this regard, it is recommended to carry out geotechnical monitoring during periods of maximum water inflow into the ash dump, paying particular attention to controlling water inflow into the drainage system.

Taking into account abnormal precipitation, the results of geotechnical monitoring and numerical modeling using the finite element method showed that the decrease in the stability reserve coefficient during this period was mainly due to filtration processes and pore pressure, rather than the formation of dangerous sliding surfaces. This case highlighted the importance of operational management of drainage systems and additional measures to reinforce slopes, especially during periods of heavy rainfall in the warm season.

Intense precipitation during warm periods, especially when exceeding climatic norms, as observed in August and September 2023 (90 mm and 92 mm of precipitation compared to norms of 29 mm and 21 mm, respectively), intensifies the effects of filtration processes and pore pressure. As a result, the upper soil layers and the dam foundation are subjected to additional hydrostatic stress, which can cause local deformation of the slopes and dam body. Long-term repetition of such seasonal loads without appropriate measures to reduce water saturation can gradually reduce the stability reserve coefficient and lead to the limit state of individual sections of the structure.

The analysis of remote monitoring and aerial photography data carried out during the warm period makes it possible to identify the dynamics of changes in water availability and concentration of filtration flows in different zones of the dam. The combined use of numerical finite element modeling and monitoring makes it possible to predict the behavior of dams under the influence of seasonal hydrological loads and develop measures to increase stability: drainage, slope loading, and water inflow control.

The stability of the bulk dam is largely determined by the flooding of the base, associated with an increase in the groundwater level, which reduces the strength characteristics of the base rocks. In order to correctly assess the stability of the slopes, it is necessary to take into account in detail all the factors affecting the condition of the structure, while choosing a calculation method appropriate to the specific hydrogeological conditions and physico-mechanical properties of the dam materials, and its base is of key importance. The calculation of the coefficient of stability margin showed a value significantly higher than the standard indicator for this structure.

The decrease in stability is mainly due to pore pressure rather than the formation of dangerous sliding surfaces. Modeling of the stress-strain state, taking into account the weight of the dam, pore pressure, and boundary conditions, showed a uniform distribution of shear stresses, without the formation of cylindrical or elliptical sliding surfaces. This indicates that even in the worst conditions, with maximum rock moisture and minimum strength characteristics, the dam slopes remain close to their maximum condition. In this regard, it is recommended to monitor the position of the depression curve and take measures to increase the stability of the slopes, including drainage and buttressing of rock or semi-bedrock.

Thus, consideration of seasonal hydrological factors is necessary to ensure long-term safety and reliable operation of bulk dams. An increase in pore pressure in the bulk dam body is one of the main factors reducing its stability, especially during periods of maximum precipitation and rising groundwater levels. Preventive engineering measures aimed at reducing water saturation and regulating filtration flows are being taken to minimize the risk of critical conditions. Key measures include the installation of drainage systems that allow excess water to be drained from the base and body of the dam; the reinforcement of slopes with buttresses of rock or semi-bedrock, which reduces the load on water-saturated layers; the use of clay cores or anti-filtration screens that prevent water from entering the dam; as well as the regulation of the water level in the adjacent reservoir or slag dump, which reduces the hydrostatic pressure on the base and body of the dam. Additionally, monitoring and analysis methods are used: the installation of sensors for pore pressure, groundwater level, and precipitation allows you to quickly monitor the dynamics of water saturation and take timely measures to reduce pressure. A comprehensive combination of these measures ensures the long-term stability of the dam and reduces the risk of accidents, especially during the warm season with heavy rainfall.

Author Contributions

Conceptualization, A.K. and R.H.; methodology, O.M.; software, E.S.; validation, Y.K., A.M. and E.O.; formal analysis, A.M.; investigation, A.K.; resources, E.O.; data curation, O.M.; writing—original draft preparation, A.K. and R.H.; writing—review and editing, A.K.; visualization, R.H.; supervision, Y.K.; project administration, A.K.; funding acquisition, R.H. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

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The data used in this study is available at https://meteo.kazhydromet.kz.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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