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Slope stability analysis of a dam. Case study: Hălceni Reservoir, Iasi county, Romania

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Abstract: Considering the overall behavior monitoring of an earth dam, the infiltration regime and the stability of slopes are the most important aspects to be considered, in order to permanently assess the technical status of the dam and its risk of collapse or breach. This paper presents the stability analysis for the upstream slope of Hălceni Dam, performed by the finite element stability method, using SLOPE-GeoStudio program, under the condition of the drawdown water level. Firstly, the infiltration curve in the dam was drawn with SEEP/W-GeoStudio program, according to the maximum level measured during the flood in June 2019. The effects of slow drawdown and rapid drawdown from the maximum water level in the reservoir were analyzed. Built-in finite element algorithms used in the SEEP/W and SLOPE/W solved the analysis and the results were obtained as a range of Factor of Safety (FS) values, that were later compared to the admissible Factor of Safety established in the legislation and the technical regulations in force in Romania. Both the measured parameters and the visual observations showed that the dam performed exceptionally well, in accordance with design specifications and predicted behavior for the evolution of the response parameters to external stresses.

1. Introduction

Dams are barriers to flow which are either constructed or natural (Osuagwu et al., 2017). In the designing of an earth dam, it is important to verify that the slope of the embankment is adequate by considering the factor of safety of the required slope (Faris and Aqeel, 2013). The monitoring of the deformations of embankment dams has an important role in assessing long-term behavior and in evaluating safety (Tedd et al., 1997).

The primary purpose and overall safety of the dam play a vital role in the design criteria (Athani, 2015). Moreover, every design criteria must fulfil the following fundamental design aspects:

- Stability of embankment and foundation under critical conditions such as earthquake and flood
- Control of seepage and pressure in both the embankment and foundation (Balan, 2021c)
- Safety measures to control overtopping situation
- Erosion control methods (Li and Desai, 1983).

An important aspect of dam design and behavior monitoring is sliding stability. For the slope of a dam to be stable, the forces that tend to produce the slide must be taken over by the shear resistance of the material, on the considered sliding surface.

The statistical methods for modeling the susceptibility to landslide occurrence for a certain area, independent of their high degree of accuracy, cannot be infallible, requiring the in-field validation (Codru, 2022).

The primary objectives of the instrumentation and monitoring systems can be summarized as follows: to confirm the design assumptions and predictions of performance at the construction phase, to monitor performance of the embankment during the impounding of the reservoir, to confirm safe operation through the life of the dam including the provision of early warning of the development of unsafe trends in behavior, to verify the safe aging of the structure (William, 2004).

If the shearing resistance of the soil, at any time after the construction of the slope becomes less than the induced shearing stress, the portion of soil mass between the slope and the critical internal surface will slide down along this surface, until, the new slope formed by the sliding mass makes the shearing stress less than the shearing strength of the soil (Faris and Aqeel, 2013).

Many soil slope stability problems involve complexities relating to geometry, material anisotropy, non-linear behaviour, in-site stress and the presence of several coupled processes (e.g. pore pressure, seismic loading, etc.) (Salahudeen et al., 2022).

For earth dam slopes, sliding stability is checked by circular cylindrical surfaces. The data required to start the calculation are dependent on the geometric characteristics of the slopes, the geotechnical properties of the dam (bulk weight, cohesion, internal friction angle, etc.), the hydrostatic level in the dam body, and the water level in the reservoir. The analysis of slope stability is carried out for 2 purposes:

- for the dimensioning of the slopes of some earth embankments, when the physical-mechanical parameters of the earth and the main geometric characteristics imposed by functional criteria (height, depth, width at the crown) are known and it is required to indicate the angle of inclination of solid slopes;
- to estimate the stability reserve for the existing slopes, with well-specified geometry.

In both situations (design and verification), the behavior of the embankment is estimated by means of a comparison between the calculated Factor of Safety, respectively the restricted Factor of Safety.

Sudden drawdown stability computations are performed for conditions occurring when the water level adjacent to the slope is lowered rapidly. To take account of this fact in stability computations, the resisting forces are calculated for submerged weight of the material below water surface, and the actuating forces are calculated for the saturated weight of the material below water surface. All materials below drawdown level are submerged, and therefore, resisting and actuating forces below the drawdown level are calculated on basis of the submerged weight of the materials slope (Faris and Aqeel, 2013).

One of the most used methods in the analysis of the stability conditions for a stratified or homogeneous slope is the strip method developed by the Swedish researcher Fellenius. Each possible sliding surface is characterized by a degree of insurance, expressed by a Factor of Safety. The stability analysis consists of determining the most dangerous sliding surface, which corresponds to the minimum value of the Factor of Safety. It is reported in the specialized research that the values of SF (Factor of Safety) may range between 1,1-1,5 for the flood regime, for the rapid and slow drawdown (Michael, 2003).

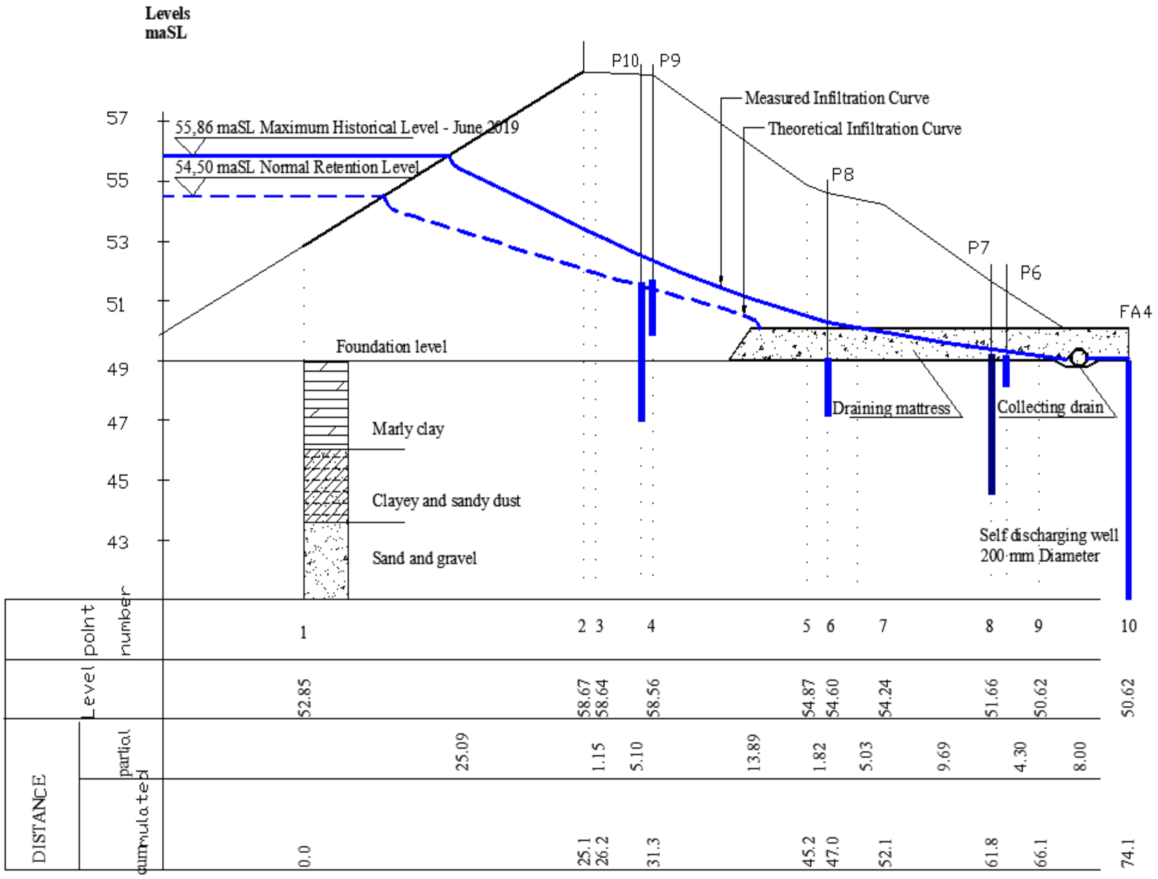
2. Materials and Methods

2.1. Materials

Hălceni Reservoir is located on the Miletin River (cadastral code XIII.1.15.25), the left tributary of the Jijia River, at hectometre 830 from the springs and about 16 km from the confluence with the Jijia River, as it was inventoried in the Romanian water cadastre (Crenganiș, 2023). The retention dam is located in the northern part of the Iasi County and the reservoir is operated by Water Basinal Administration Prut-Barlad. The Hălceni reservoir is located in the special avifaunistic protection area called *Eleșteele Jijiei și Miletinului*, located in the northeast of Moldova, on the territory of Iași County, an integral part of the European ecological network Natura 2000 in Romania. "*Eleșteele Jijiei și Miletinului*" represents the last RAMSAR site designated in Romania, in June 2020 and the first Ramsar site in the region of Moldova. This protected area represents a wetland (rivers, lakes, marshes, peatlands, cultivated arable land and pastures) that provide feeding, nesting and living conditions for several species of migratory, migratory or sedentary birds. Therefore, the Hălceni reservoir is of particular importance from an ecological point of view, and the failure of this dam would have a significant impact on the environment.

The retention in the Hălceni Reservoir is made with a frontal, homogeneous earth dam, with a double trapezoidal cross-section. The dam body has a 10.5 m height, a canopy length of 1013 m, and a canopy width of 5.0 m (Water Basinal Administration Prut-Barlad, 2011). The dam is provided with a drainage mattress of 30.0 m width and 0.90 m thickness, located in the downstream third of the footprint base.

Figure 1 shows the theoretical infiltration curve calculated for this type of dam (Balan, 2021a) and the infiltration curve measured in the piezometers, soon after the maximum historical flood. Installed piezometers upstream of the core show a higher pressure than the downstream, due to the high saturation state of the phreatic line (Beiranvand and Komasi, 2019)(Figure 1).



Level point number	1		2	3		4		5	6		7		8		9		10
Level	52.85		58.67	58.64		58.56		54.87	54.60		54.24		51.66		50.62		50.62
DISTANCE partial		25.09		1.15	5.10		13.89		1.82	5.03		9.69		4.30		8.00	
DISTANCE cummulated	0.0		25.1	26.2		31.3		45.2	47.0		52.1		61.8		66.1		74.1

Figure 1. Cross section of the Hălceni dam body

A catalogue of flood events that occurred in the Miletin catchment between 1979 and 2019 was studied in order to identify the historic flood that was transited through the Hălceni Reservoir and its outlets. In June 2019, important quantities of rainfall were registered in the Miletin River catchment, upstream of the Hălceni Reservoir. Figure 2 presents the recorded inflows, and flow discharges through the outlets, and the variation of the water level in the reservoir during this historic flood.

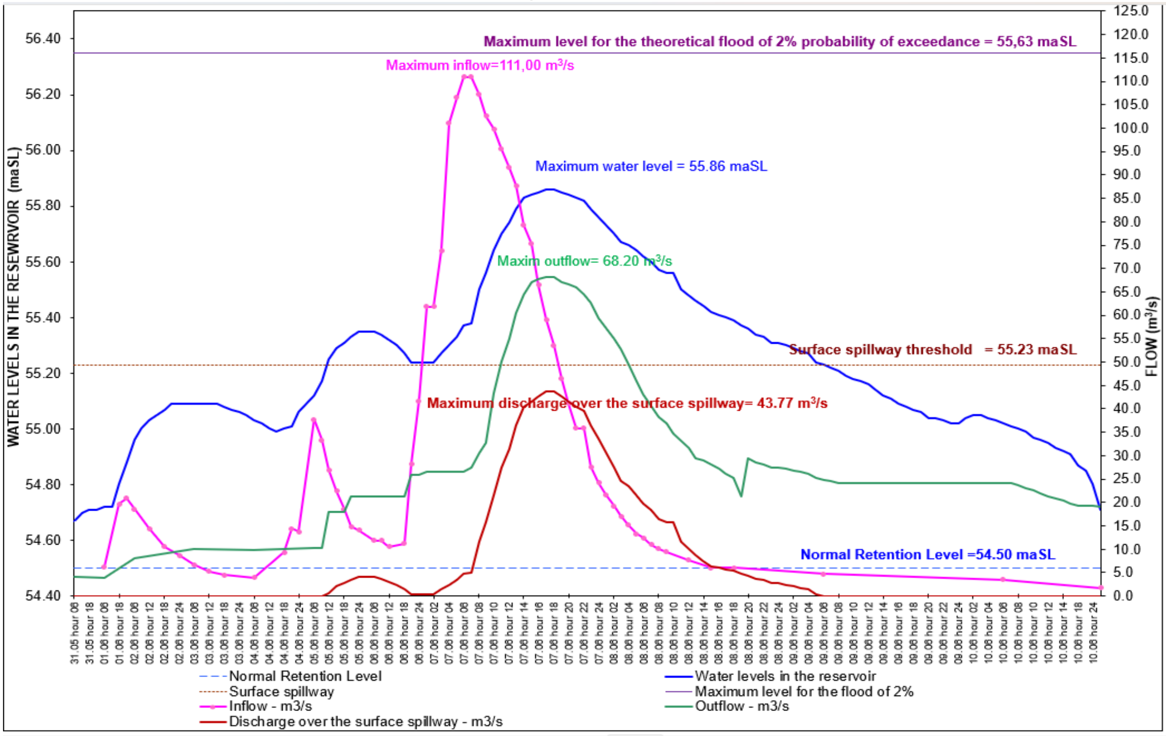


Figure 2. Water levels, inflow and outflow discharges – historic flood year 2019

The cumulated precipitation over the previous five days in the Miletin catchment according to the SCS methodology were larger than > 53.4 mm in the growing season, do the antecedent moisture condition was AMC III (Balan, 2016). The rainfall led to significant increases in the water level in the Halceni Reservoir, starting with the date of 31.05.2019. The upward trend in the water level in the reservoir was kept during the following days, by successively exceeding the threshold of the surface spillway, then reaching the maximum flow level of 55.86 maSL (meters above Sea Level) in 07.06.2019-17^{00} hours, and maintaining it for 2 hours (Balan, 2021b). Several maneuvers were carried out in the following period to the gates of the bottom outlet to evacuate outflows of 10,0 m^3/s, 18,0 m^3/s, and 29,0 m^3/s respectively. The maximum inflow of 111.0 m^3/s was registered on 07.06.2019 - 06^{00} hours at the hydrometric station Sipote (Water Basinal Administration Prut-Barlad, 2023).

2.2. Method

GEOSTUDIO software is a geotechnical program that is based on finite elements and can do analysis such as stress-strain, seepage, slope stability, and dynamic analyses. SEEP/W and SLOPE/W are sub-programs of GEOSTUDIO which can simulate the movement and pore-water pressure distribution within permeable materials like soil and rock (Mohammed and Ibtisam, 2020).

SEEP/W (SEEPage for Windows) is a finite element software product that is coming under GEOSTUDIO, used to model the movement and pore-water pressure distribution within porous materials like soil and rock (Abhilasha et al., 2014). There are three main parts of a finite element analysis. The first part is creating the numerical domain, including selecting an appropriate geometry and creating the discretized mesh. The second part requires the specification of material properties for the different subregions of the domain. The third part is to specify the appropriate boundary conditions (Seepage Modeling with SEEP/W, 2012).

The process of subdividing the continuous element into smaller pieces is known as discretization or meshing. Parts are known as finite elements. In GeoStudio - SEEP/W, the geometry of a problem is defined with Points, Lines and Regions. Boundary conditions and material properties can only be applied to geometric objects. The upstream face is divided into two segments, with a Point added to the set water level in the reservoir, so that the boundary condition representing the water level in the reservoir only applies to the submerged portion of the upstream face. The base is divided into two segments, if the dam is equipped with a drainage mat at the bottom. The SEEP/W program includes a set of VWC functions for soils of various textures. From the Define Materials tab, the type of soil can be set for the region under analysis and the functions Volumetric water content and Hydraulic Conductivity can be chosen. The VWC function is chosen from the program according to the soil in the region under analysis (available types are: clay, dusty clay, dust, sandy dust, sand, gravel) and the saturated water content imposed by the user. For saturated-unsaturated media conditions, the hydraulic conductivity (K) is not constant. As the soil becomes unsaturated, the hydraulic conductivity decreases, it consequently becomes a function. The K function is usually estimated from a Volumetric Water Content (VWC) function, using one of the two available methods: the Fredlund-Xing Huang method and the Van Genuchten method. Values for saturated hydraulic conductivity (Ksat) and residual water content are set by the user (SEEP/W Tutorial – Getting Started, 2017).

SLOPE/W can effectively analyze both simple and complex problems for a variety of slip surface shapes, pore-water pressure conditions, soil properties, analysis methods, and loading conditions (Hasani et al., 2013).

SLOPE/W and SEEP/W have been used with the "Morgenstern method" to perform the stability analysis. It is designed and developed to be a general software tool for the stability analysis of earth structures for the project of a water reservoir (Durga et al., 2017)

Geotechnical properties of an embankment material as the type of soil, density, cohesion, angle of internal friction, hydraulic conductivity, etc. affect the stability of slopes and therefore, these data can be utilized to determine the susceptibility of a slope to sliding. The conventional limit equilibrium methods of slope stability analysis used in geotechnical practice investigate the equilibrium of a soil mass tending to move down slope under the influence of gravity (Faris and Aqeel, 2013).

The slope stability analysis can be executed using GeoStudio® (SLOPE) Software, which is a modern limit equilibrium software useful for handling complexity within an analysis. Determining the position of the critical slip surface with the smallest factor of safety is one of the most important aspects of stability analysis. During the solution process, a potential slip surface is generated and the associated factor of safety is calculated.

In Slope – GeoStudio software, internal water pressures in a stability analysis can be defined using a steady state analysis or a transient groundwater infiltration analysis. The effect of seepage through the embankment is to reduce embankment stability by increasing the actuating forces and decreasing the resisting forces. Analysis of this condition, reservoir is assumed to be at the normal storage level in which case the phreatic line is assumed to have fully developed (Faris and Aqeel, 2013).

In accordance with piezometric surfaces, an automatic surface load is applied along the soil surface, if the internal water pressures are positive. To model the rapid drawdown, it is useful to first evaluate the pore water pressure conditions by doing a finite element transient seepage analysis with SEEP/W. The advantage of this approach is that the hydraulic properties of the materials are appropriately considered and a time component can be included in the analysis. With this approach, rapid drawdown is not just instantaneous but can be modelled as a process. GeoStudio allows easy integration between SLOPE/W and SEEP/W making the rigorous effective strength method an attractive alternative for conducting a rapid drawdown analysis (GEO-SLOPE International Ltd, 2017).

The change in water level in a reservoir directly influences the dam's stability state. Stability analysis during rapid drawdown is an important consideration in the design of embankment dams, as the stabilizing effect of the water on the upstream face is lost, but the pore water pressures within the embankment may remain high. As a result, the stability of the upstream face of the dam can be much reduced (Moharrami et al., 2013). The earth dam may be exposed to the collapse in the case of the rapid drawdown of water level (Jasim, 2017).

Determining the position of the critical slip surface with the smallest factor of safety is one of the most important aspects in a stability analysis. During the solution process, a potential slip surface is generated and the associated factor of safety is calculated. This is repeated for many possible slip surfaces and the slip surface with the smallest factor of safety is taken to be the critical slip surface. The Entry and Exit technique for establishing the slip surface can be used in both 2D and 3D stability analyses. The main advantage of this approach is the ability to visualize the extents and/or range of the sample slip surfaces before solving. Thus, the analyst can easily isolate various failure modes by repositioning the input and output areas. An input-output zone for a 2D analysis requires each zone to be drawn along the ground surface and then subdivided into specified increments. Each point in the input area is connected to a point along the output area to form a line, which is divided by an orthogonal line. Radius points are created to form the required third point of a circle. This radius point is used together with the entry-exit points to form the equation of a circle. (GEO-SLOPE International Ltd, 2017).

3. Results

The GeoStudio - SEEP/W program was used for the numerical modelling of infiltration through the Hălceni Dam. The two-dimensional model for the Hălceni Dam was initiated by reproducing the cross-section of the dam. Points, Lines, and Regions were defined for the contour of the dam.

The dam model was simulated using the actual reservoir levels as the forcing function (Jung et al., 2015). Maximum water level of steady seepage case was considered to evaluate seepage (Malik and Karim, 2020). The seepage flow through the core zones of the dam was found to be correlated with the reservoir water levels (Lee et al., 2018).

Knowing that the Hălceni Dam was made of dusty clay with a water content of 0.4, as written in the design specifications (Water Basinal Administration, 2011), the material type for the region under analysis was defined in the program, the water content of the fill was imposed and the functions Volumetric water content was chosen, respectively Hydraulic Conductivity by the Van Genuchten method.

The boundary conditions for the model built for the Hălceni Dam were established:

- The water level in the reservoir was specified as a boundary condition in the upstream area of the dam - the water column in the lake corresponding to the maximum level (58.66 maSL recorded during the flood produced on the Miletin River in June 2019;
- The boundary condition for the drainage in the downstream area was established as a flow type with a constant value of 0.0 m^3/s and was associated with the line segment that traces the draining mattress of the dam.
- A zero pressure boundary condition (hp = 0 m) was applied at the point at the downstream slope foot of the dam.

The analysis of the infiltration through the body of the Hălceni Dam, assuming the existence of a water level in the reservoir of 55.86 maSL, led to the results presented graphically by the curve of the free surface of the infiltration water (saturation limit) (Figure 3):

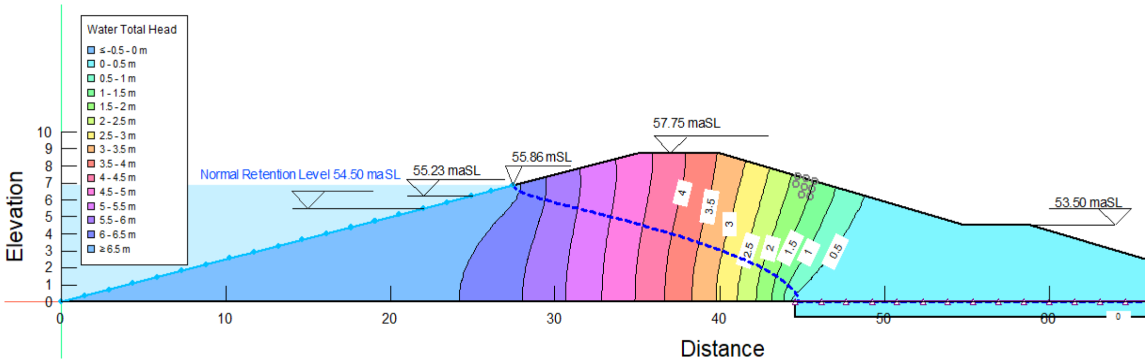


Figure 3. Hydrodynamic pressure spectrum and infiltration curve

The two-dimensional model for the Hălceni Dam, which was built and run in the infiltration analysis with the SEEP/W program, was used as a source for the model built in SLOPE, for the numerical modelling of the stability of the upstream slope of the dam. The infiltration curve in the dam was drawn according to the maximum level of 55.86 maSL, measured during the historic flood of June 2019.

Applying the ENTRY-EXIT method of drawing the sliding surface, 4 points (2 straight line segments) were defined on the upstream slope and on the canopy, for the orientation of the circular sliding surface (Figure 4).

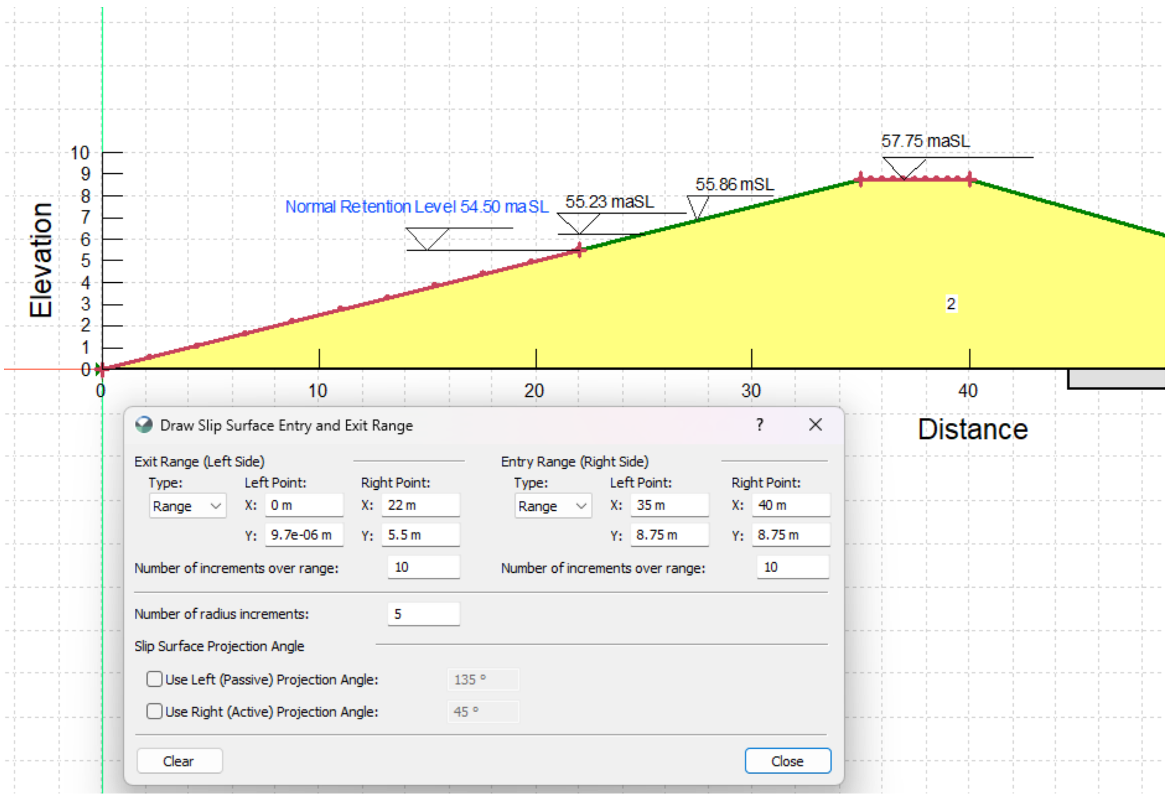


Figure 4. Defining the sliding surface for the upstream slope of the dam

The effects of slow drawdown and rapid drawdown were analyzed in differentiated ways. For the critical slip surface, a critical Factor of Safety was calculated and compared to the admissible safety factor established in the legislation and the technical regulations in force in Romania. The transient analysis was established for a 30-day interval with 3-day calculation steps.

3.1. The Slow Drawdown of the Reservoir from the Historical Maximum Level

For the stability analysis in the hypothesis of slow drawdown of the reservoir from the historic level, the SLOPE program traced 99 circular sliding surfaces and for each of them, values of the Factor of Safety were calculated (Figure 5).

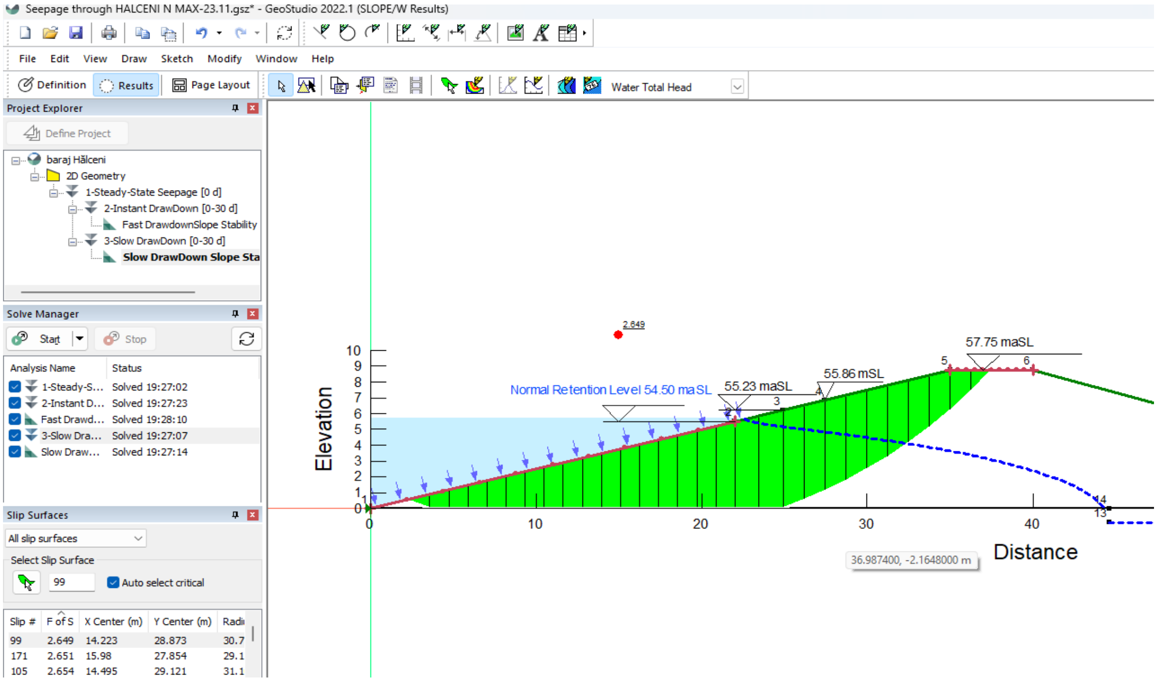


Figure 5. Calculation of the Factor of Safetys in the hypothesis of slow drawdown of the level

The minimum value of the Factor of Safety is 2.649, which meets the permissible condition for the slow drawdown of the reservoir SF>1.5.

3.2. The Rapid Drawdown of the Reservoir from the Historical Maximum Level

For the stability analysis in the hypothesis of the rapid drawdown of the reservoir from the historical maximum level, the SLOPE program traced 81 circular sliding surfaces and for each of them, the value of the Factor of Safety was calculated (Figure 6).

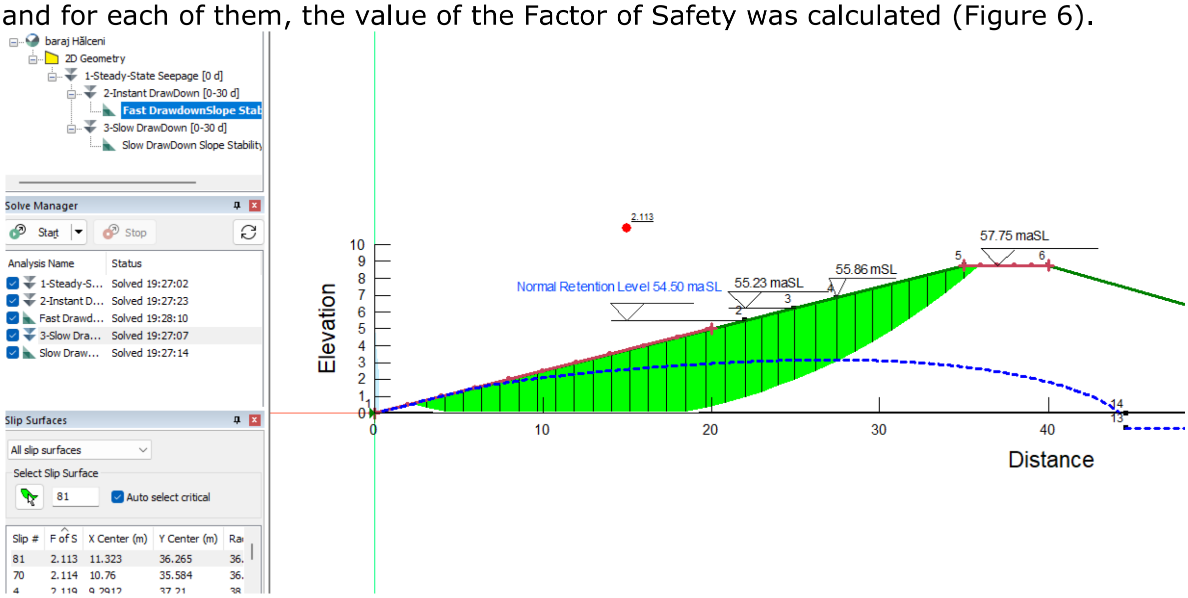


Figure 6. Calculation of the Factor of Safetys in the hypothesis of rapid drawdown of the level

The minimum value of the Factor of Safety is 2.113, which meets the permissible condition for the rapid drawdown of the reservoir SF>1.2. Figure 7 shows the shape of the infiltration curves through the dam, corresponding to each previously defined time step. The curve corresponding to the minimum Factor of Safety intersects the upstream slope at a height of 1.46 m, afterwards, it follows the slope line.

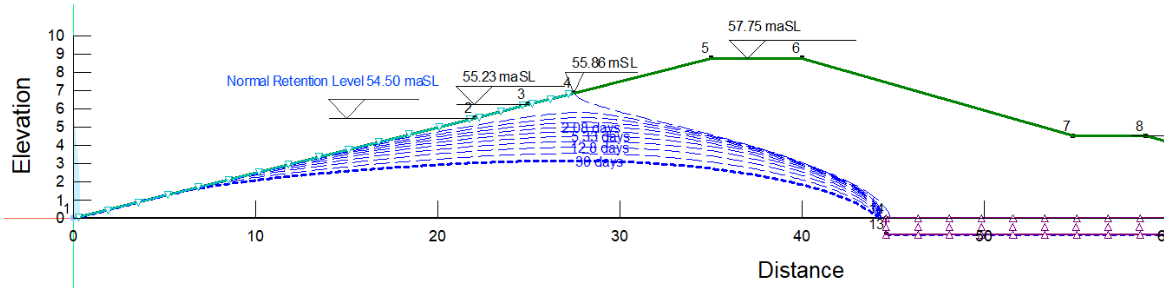


Figure 7. Infiltration curves at the rapid drawdown of the water level of the reservoir

From the *Draw Graph* tab of *SLOPE* program, the diagram of the values for the Factor of Safety as a function of time was drawn, for a set interval of 30 days.

It can be seen that from the value of 3.04 for the initial time step, the Factor of Safety suddenly drops to the value of 1.67, with the instantaneous decrease of the water level in the reservoir (Figure 8).

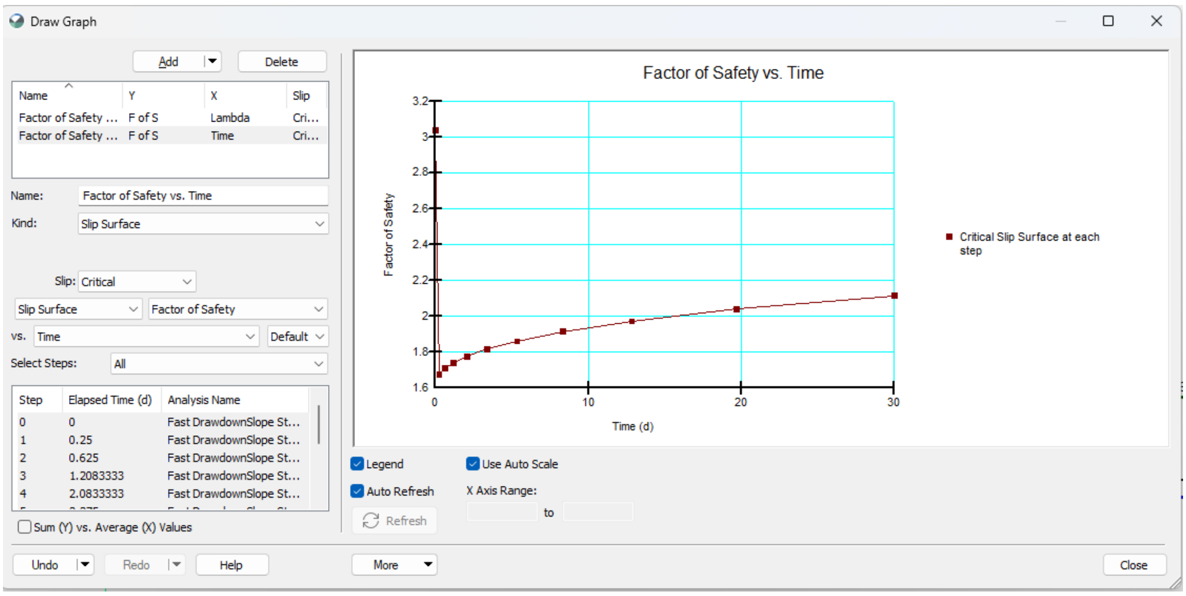


Figure 8. Diagram of Factors of Safety as a function of time

4. Discussion

During the flood produced on the Miletin River and transited by the Hălceni Reservoir, no dangerous infiltrations were reported, indicated by inexplicable or dangerous increases of the hydrostatic levels measured in the piezometers, located in the body of the dam, or by other visual observations of the behaviour of the downstream slope of the dam. The embankment behaved exceptionally well, under the action of significant external factors (precipitation and high water levels in the reservoir), and the structural stability was not endangered. The dam has a considerable reserve of stability.

This hypothesis of rapid drawdown has never been tested, as the situation never occurred during the exploitation of the Hălceni Dam. The reservoir has never been subjected to a rapid drawdown of the water level.

In order to allow an earth dam to tolerate easily and without problems any significant changes in water level on the upstream slope, the rate of dewatering of Hălceni Reservoir should never exceed the hydraulic gradient of 0.5 m in 24 hours. This mandatory condition is an official rule for the exploitation of the Hălceni Reservoir, which was established within the *Rules of Exploitation*.

The verification of the results of stability analyses is essential. Analyses should be performed using more than one method, or more than one computer program, in a manner that involves independent processing of the required information and data. Selection and verification of a suitable software for slope stability analysis is of prime importance. It is essential that the software used for analysis be tested and verified, and the verification process should be described in the applicable design and analysis studies for further use in the Hălceni Dam behaviour monitoring analysis or even analog applications of the method to other earth dams.

5. Conclusions

Considering the overall behaviour monitoring of an earth dam, the infiltration regime and the stability of slopes are the most important aspects to be considered, in order to permanently assess the technical status of the dam and its risk of collapse or breach.

The benefit of using computer programs developed by GEOSTUDIO is to ensure the correctness and reliability before embarking on further study, as it is known the long-term hand calculations are time consuming and expensive. It is easily anticipated that these emerging method and technology may become standard design tools for the analysis of slope stability, in future studies.

Built-in finite element algorithms used in the SEEP/W and SLOPE/W solved the analysis and the results were obtained in the form of slip surfaces and a range of Factor of Safety (FS) values. For the critical slip surface, critical Factors of Safety were calculated and compared to the admissible Factors of Safety established in the legislation and the technical regulations in force in Romania (1.2-1.5 for the flood regime, for the rapid and the slow drawdown).

During the historic June 2019 flood, the dam performed exceptionally well, in accordance with design specifications and predicted behaviour for the evolution of the response parameters to external stresses.

Both the visual observations made by the hydrotechnical agents and the measured parameters that were rapidly interpreted and validated led to the conclusion that the dam is currently in a very good technical state. Also, it was seen that the system of behaviour monitoring is properly established and the necessary measurements are done with the periodicity established by official documents and the legislation in force.

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Author contributions: All authors contributed equally.

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