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Code 1583 - preliminary steps for studies to assess the safety of an earth dam in terms of use and lowering the reservoir level for public supply during the water crisis

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Abstract: The spring 2021 climate forecast report from the National Institute of Meteorology (INMET) and the National Institute for Space Research (INPE) indicated an increased possibility of below-average rainfall in almost the entire region of the state of Paraná, which is consistent with the historical trend of decreasing rainfall in the Paraná River basin since the 1990s, with an intensification in the 2000s. This led to a water emergency situation in Paraná, which was decreed by the state government in 2020 and 2021. The Curitiba region depends on the Curitiba and Metropolitan Region Integrated Supply System (SAIC). Due to the intense drought in 2020 and 2021, SAIC's reservoirs suffered a significant reduction in stored water levels and volumes, reaching 28% of their total capacity in August 2020. This was the biggest water crisis in the last 90 years in the history of the state of Paraná, with several reservoirs reaching levels close to historic lows, but maintaining constant discharges in order to maintain power generation or public supply. In these cases, with the reservoirs at lower levels and with a smaller volume, the variation in the water level on the upstream slope of the earth dam varies differently from the levels when the dam and reservoir are in normal operation or outside of a water crisis. In view of the atypical behavior of reservoir levels, and based on good dam engineering practice, when the operating regime changes or the reservoir water level drops, the safety aspects of these structures should be reassessed through geotechnical analyses for conditions of rapid lowering, in order to learn how these structures behave under these conditions. This article sheds light on the important stages of this thorough technical investigation of the extensive documentation of a project like this, data on instrumentation and performance, how they were built and behaved during the construction and filling of the reservoir, knowledge of geotechnical parameters of the materials of the dam massif and foundation, recorded field observations made at the time of preliminary investigation during the design, project and construction phase; obtaining hydro-meteorological data from the region, in order to obtain the "as-built" geometry of the structure, with the aim of modeling the typical section reliably to the structure in the field in order to infer this numerical model and vice versa, and obtain results on its performance during this atypical period.

Key words: dams; public supply; water crisis; reservoirs and slopes

1 Introduction

In order to carry out any geological, geotechnical, hydrological, hydro-geological or hydro-technical study focused on dam safety, it is essential to have all the known information on the characteristics of each part of the dam, so that the unknown parts can be inferred, whether they are sections, materials, instrumentation or construction methods, in order to be able to model the behavior of the structure using numerical methods or models. Sanepar has large dams in operation, which supply Curitiba and the metropolitan region and an urban population of more than 3.5 million people. In 2020, the state of Paraná faced one of the biggest water crises in its 90-year history. The reservoirs of these dams reached levels close to historic lows and maintained constant discharges in order to maintain public supply to the greater Curitiba and metropolitan region. In these cases, with the reservoirs at lower levels and with a smaller volume, the variation in the water level on the upstream slope of the dam varies differently from the levels when the dam is in normal operation. In view of the atypical behavior of dam reservoir levels, a detailed geotechnical study was carried out in order to improve knowledge of the behavior of these structures with a view to safety and prevention of more critical situations that could occur, in parallel with the development of an integrated monitoring system. Eletrobrás' 2003 document *Civil Design Criteria for Hydroelectric Power Plants* states that in order to guarantee slope stability, four loading cases must be checked: end of construction, stable percolation, rapid lowering and seismic. The work was carried out in conjunction with the technical team from Sanepar and the Itaipu Technological Park Foundation - Brazil, which was involved in carrying out geotechnical analyses for the rapid lowering condition and in developing monitoring systems. Given that the dams were built in different periods, even in different decades and, consequently, designed by different companies, it was necessary to carry out a thorough analysis based on an extensive set of documentation on the dams in the Curitiba metropolitan region, including basic and executive design information, as-built and monitoring information, detailed documentation on the structures, as well as an analysis of the performance and instrumentation reports, in order to obtain a general overview of the health of the structures during the period of atypical behavior.

2 Objectives

To demonstrate the stages that precede the numerical modeling, the historical series of reservoir levels and instrumentation has been analyzed, to define the periods that will be simulated later. In order to verify the behavior of the safety factor under these conditions, demonstrate these important stages of this thorough technical investigation of the extensive documentation framework of a project like this, it can start from data on instrumentation and performance, how they were built and behaved during the construction and filling of the reservoir, knowledge of the geotechnical parameters of the materials of the dam massif and foundation, the recorded field observations made at the time of preliminary investigation during the design, project and construction phase; hydro-meteorological data from the region, in order to obtain the "as-built" geometry of the structure, with the aim of modeling the typical section reliably to the structure in the field in order to infer this numerical model and vice versa, with the aim of numerical modeling with results on the structure's performance during this atypical period.

3 Methodology used

The critical conditions for stability during rapid lowering are associated with various factors such as the amplitude of the variation in the reservoir's water level during lowering, lowering speed, structure geometry and soil permeability, among others. For this reason, it is important to carry out case studies with real reservoir operating conditions, with proper validation and calibration of the model, in order to verify the stability of the structure for specific behavioral conditions. It should be emphasized that the analyses carried out were aimed, based on the documentation and information provided by the developer, at developing a representative geotechnical model for flow and stability simulations aimed at observing variations in the safety factor of the upstream slope through rapid lowering.

To prepare the studies, dam designs with instrumented sections should be made available, containing, for the most part, information on the compacted mass, drainage system and dam instrumentation, as well as "as-built" documents and designs that reflect the reality of the dam in the field, as well as associated structures such as spillways, engine rooms, water intakes and instrumentation. The section drawings drawn up during the dam safety diagnosis can provide important information that can be used to complement the information taken from documents and/or old projects and reports, mainly because they may contain changes to the typical sections due to the conditions inherent in the construction, maintenance or operation phase of the dam, and which, depending on the magnitude, may change the entire typical design section, affecting the outcome of the study, boundary conditions and modeling input parameters.

On this occasion, extensive documentation on the dams was revisited in order to:

· Check field observations made at the time of research and construction;

· Obtain as-built information on the geometry of the structures;

· Verify the flow and stability analyses carried out at the time of design and during the period of operation of the structures;

· Check the geotechnical parameters of the dam body and foundation materials;

· Verify information from topographic surveys;

· Obtain historical instrumentation data;

· Obtain historical hydro-meteorological data for the region.

After analyzing the documentation, it was possible to draw up a geotechnical model of the main sections of the dams using the most up-to-date information available (geometry, instrumentation, surveys, materials, etc.). This model was used for geotechnical analysis of flow and stability in order to verify the conditions of flow and stability of the upstream slope for rapid lowering during the water crisis that occurred, as well as to predict situations of rapid lowering that might occur. The geotechnical analyses were based, in addition to the reference documents for the projects, on rainfall data available on the HidroWeb portal of the National Water Agency (ANA) and on the website of the National Meteorological Institute (INMET). According to the Inventory of Stations available on HidroWeb, the area where the dams and reservoirs supplying Curitiba and the Metropolitan Region are located has several active rainfall stations. The Curitiba station (code 83842) has records of 29 complete years of data available on the INMET website, and is therefore adopted as representative of local rainfall. The Curitiba station is located at 49º 13' 48" South latitude and 25º 27' 00" West longitude and is 923.5 meters above sea level, approximately 11.5 km from the Iraí Dam, 18.7 km from the Passaúna Dam, 14.5 km from the Piraquara II Dam and 21.5 km from the Piraquara I Dam. The study region has a well-defined rainfall seasonality, with a wet period in summer and a dry period in winter. The average annual total, determined from the records of 29 complete years from 1981 to 2010, is 1,575.8 mm, with the minimum average monthly total in August (74.0 mm) and the maximum in January (218.3 mm). The state of Paraná has gone through one of the biggest water crises in its history, recording below-average rainfall since 2018, which was exacerbated in March 2020. From August to October 2020, rainfall was between 50% and 70% below average throughout Paraná, with an even more worrying situation in the Curitiba Metropolitan Region. The water deficit in the region, where the impact on public supply is most serious, was 346 millimeters during 2020. As of 29/10/2020, the level of the dams that make up the Curitiba and Metropolitan Region Integrated Supply System was at 27.5%, one of the lowest in its history.

4 Geometry (dam and foundation) materials with defined parameters

In order to define the study sections, it is essential to know all the technical documentation or databook for the dam and associated structures, reference documents such as: basic design, executive design, "as-built", "as-is", instrumentation, material test bulletins, technological control of materials, construction history, records and operational technical reports for maintenance and operation of the dam. As the human eye is irreplaceable, information must also be collected during on-site visits in order to compare existing documents and evaluate the various criteria. In order to carry out dam safety studies, be they stability, flow and percolation or rapid lowering studies, there is one basic condition: it is necessary to use known geotechnical parameters, either from tests or from bibliographies, relating to the characteristics of the soil in the region where the dam was built (type of material, specific weight, etc.), such as permeability and shear strength, because for stability, percolation and rapid lowering studies, the permeability of the materials is a very important parameter. The ideal scenario for rapid subsidence analysis is to use effective parameters obtained from consolidated undrained (CU) triaxial tests. In the case of these studies, reports with the results of these tests for some dam materials were found in the geotechnical investigation report carried out at the time of the project.

5 Sufficient instrumentation to validate the flow analysis

The ideal scenario for rapid lowering studies is to use the water levels upstream (reservoir level) and downstream (water level indicators) as boundary conditions and to use the instruments in the massif and foundation to validate/calibrate and eventually adjust the model. Thus, the greater the number of instruments in the section distributed along the massif and foundation, the greater the likelihood of a numerical model that is representative of the structure's behavior.

6 Upstream slope in contact with reservoir

The operation of dams requires constant changes in the reservoir's water level, which can change the safety factor against sliding of the upstream slope of earth dams over time. The safety factors of upstream slopes tend to vary over a wider range and with greater speed, as the slope is directly in contact with the reservoir pressure. This applied stress is dissipated in the massif and has less influence on the safety factor of the downstream slope.

7 Geometry of the analysis sections

In the case of several sections meeting the above conditions, the one with the most significant geometric and/or geotechnical differences, indicating the lowest safety factor in terms of stability, is selected. This choice always aims to analyze the critical conditions, making the rapid lowering study in favor of safety. Some of the selection criteria are based on geometric characteristics.

8 Choice of section(s) to be studied

The most instrumented sections of the dam can be chosen, with instruments in the filter, gallery, massif and foundation. The next criterion for defining the section to be studied could be height and the non-existence of equilibrium berms, which contribute to the stability of the slope. When analyzing the report on the Geological-Geotechnical Assessment of the RPSB, it was noted that the section chosen for the stability analyses was considered the critical section, as it is close to the original riverbed, but this may vary from site to site, or from structure to structure, or from engineer to engineer. For the percolation analyses, the data from the instruments in the known section was used.

9 Section as executed

During construction, some adjustments are usually made to the original design, with the aim of adapting it to the foundation conditions found in the field and optimizing the use of construction materials. The main adjustments found in the studies and documents consulted had a direct impact on the modeling of the dam section under study:

· Elimination of the outer zone of the upstream massif and the lower zone of the downstream massif, resulting in the use of the same material throughout the dam massif;

· Alteration to the geometry of the horizontal mat in the downstream portion of the dam, since the drainage mat was built at a lower elevation than that defined in the project, so that the structure was in direct contact with the foundation;

· Alteration to the geometry of the footing drain to match the excavation carried out, since with the placement of the drainage mat in contact with the foundation as mentioned in the previous paragraph, it was necessary to make adjustments to the meeting between the footing drain and the drainage mat;

· Alterations to the dam's crest as a result of the implementation of a variable uplift counter-slope, from zero to a maximum of 0.90 m in the highest part of the dam, causing the dam's crest elevation, in some sections, to be at EL. 892,20 m. During the modeling, it was assumed that the material present in the overtopping (between EL. 891.30 and 891.20) is the same material used in the embankment body (compact clay);

· Changes to the geometry of the drainage shafts downstream and upstream of the core and replacement of the continuous layer of sand with discontinuous drains consisting of gravel wrapped in geotextile. In addition, the upper downstream drainage shaft was only built between stakes 30+7.5 m and 47+7.5 m. Thus, downstream of section P6', located at pile 16+9 m, only one drainage shaft was executed in the lower portion of the massif (EL. 882.75 m). Since there is no information on the technical specifications of the geotextile used, as a simplification of the numerical model, the drainage shafts were modeled as a layer of granular soil equivalent to the material used in the vertical filter;

· Detailing of the rip-rap, since a layer was made that allowed the rockfill to be interconnected with the drainage shafts on the upstream slope;

· Reduction of the vertical filter in the last 2 meters from the top to 0.60 m;

· Displacement of the dam's axis, about 50 m upstream from the location foreseen in the basic project, prompting reinforcement of the program of complementary investigations by carrying out surveys to reconnoiter the dam's foundation.

· It should be noted that foundation treatments were carried out by means of injections between piles 29+3.6 m and 51+15.4, which had no impact on study section P6', since it is located at pile 16+9.0 m.

10 Sections as instrumentation is updated

From the installation reports of the new instruments, during maintenance and operation of the dam, it was possible to validate the characteristics of the soil layers present in the sections by identifying the materials found during the drilling required for installation. The installation reports for the instruments in the downstream portion of the P6' section (PC-66A, PC-65A and PC64A) show the presence of material compatible with the core, with water loss at the height of the filter and intercepting the foundation at a height compatible with the interface between the ZG3 and ZG1B materials. The installation report of the piezometer located in the downstream portion of the massif (PC-62A) indicates the interception of clay material representative of the dam's core, compatible with its installation level.

11 Topographic survey

With the installation of new geodetic landmarks, the topography and georeferencing of the tops of the Dam's instruments was carried out, as shown in Table 1.

Table 1. New instrument mouthpieces

Instrument	Old pipe mouth dimension	New tube mouth dimension	Difference
PC-61	891,68	892,11	0,43
PC-62A	891,69	892,66	0,97
PC-63	891,725	892,12	0,39
PC-64A	891,81	892,74	0,93
PC-65A	891,84	892,67	0,83
PC-66A	891,87	892,60	0,73
PC-67	880,414	Not located	-

On the basis of the drawings produced as a result of this survey, there is a difference of 0.28 m between the dam's topping elevation as verified in the design documents as executed (EL. 892.20 m) and the topping elevation identified in the field (at EL. 892.48 m). The slope of the downstream wall remained the same as the design: 1V:2H. On this occasion, the water level at the foot of the dam was also determined at EL. 879.50, which is representative of the water mirror in the area and can be seen in the figure. The existence of this pool of water is attributed to the drainage ditches suggested in the project for the river floodplain region, which were intended to drain the areas at lower levels, as well as to lower the water table in the region. At the time of construction, EL. 887.50 was determined for the downstream water level in normal operation.

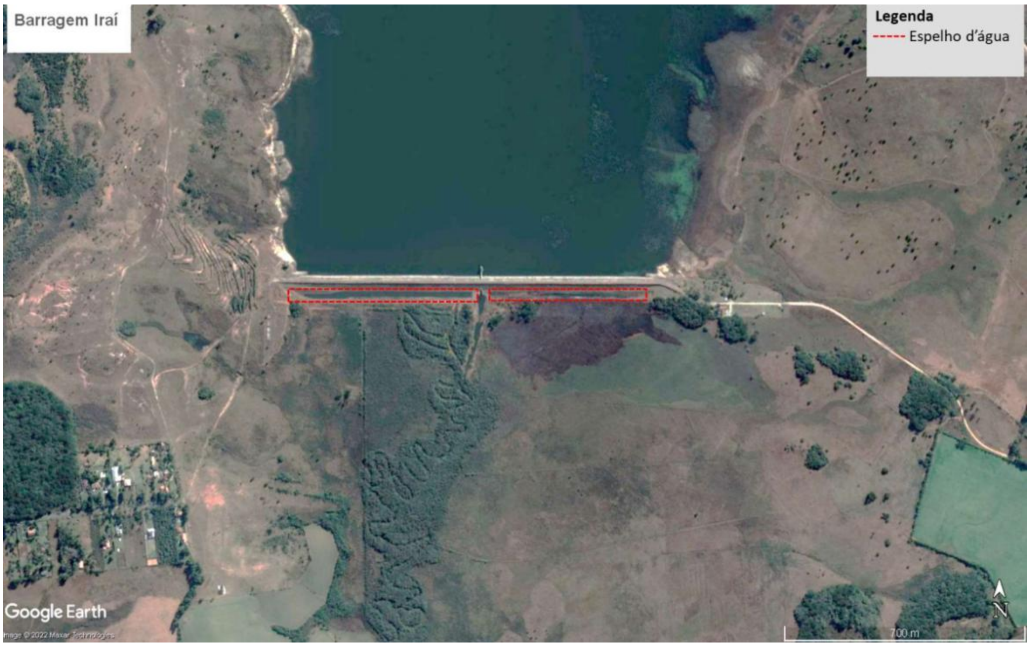

Figure 1. Image of the Dam area with emphasis on the downstream water mirror / Source: Google Earth, 2022

The existence of this water mirror was also confirmed in the field during the team's visit to the dam. There is uncertainty about the elevation of the land below the water mirror, in the place where the downstream filling trench would be. Therefore, this study assumed that the downstream ditch of profile P6' has not been filled in and is flooded. Based on this information, the geometry of the P6' section was recomposed with the surface surveyed in 2016, and the installation height of the instruments was updated in the drawing.

12 Prior existence of stability analyses for rapid lowering

The main objective of carrying out the study on previously studied sections is to provide a comparison between the predicted and observed behavior of the dam. Of the documents made available, the most likely was to find rapid lowering studies in the Geological-Geotechnical Assessment reports that make up the Periodic Dam Safety Review, however, this document mentions that the study was not carried out since rapid lowering was considered unlikely, i.e. the possibility of it happening was not considered, a premise that should be considered in the next periodic dam safety reviews. In the absence of these studies for the dam, the stability analyses for the permanent flow condition were considered as a criterion when defining the sections, since they are generally carried out on the highest sections considered critical for the stability conditions of the downstream slope.

The dam's design memory can present rapid lowering simulations for the profiles considered most representative at the time (P3, P18, P20 and a typical profile corresponding to the dam's central zone). The research carried out as part of the dam studies can be divided into three phases:

· Studies and Projects relating to the Construction of the Dam: the report includes information on the investigations carried out in the Basic Project as well as the complementary investigations carried out at the time the document was drawn up. These investigations, in particular the percussion and rotary borings, will be mentioned below in order to define the permeability of the different foundation layers. This document presents a very detailed description and characterization of the materials available for construction, based on interpretations of laboratory tests and field investigations.

· Technical Report comprising the Revision of the Base Project and the Project for Tendering, Technical Assistance and Construction Management: this report brings together the previous studies, presenting the modifications made to the project due to construction characteristics, as well as complementing the geotechnical investigations by carrying out new soundings to get to know the foundation, as well as the materials used during construction. Special mention should be made of the rotary borings carried out on the foundation, in which infiltration tests were carried out to find out the hydraulic characteristics of the materials. The document also contains the results of tests carried out during construction to ensure quality control.

· Diagnosis of the Behavior and Safety of the Dam: This study was carried out with the aim of diagnosing the behavior and safety of the dam and its attached structures based on visual inspection of the structures and adjacent areas, monitoring resulting from the reading of the equipment installed in the dam and geotechnical investigation work using percussion borings to characterize the situation of the embankments. Laboratory tests were also carried out at this stage on field samples representative of the dam massif.

13 Parameters adopted

The permeability coefficients of the materials that make up the dam's foundation were defined based on an analysis of the results of infiltration tests (soils) and water loss under pressure tests (carried out on rock). With regard to the materials that make up the body of the dam, the designer mentions that permeability coefficients were adopted based on the results obtained through variable load permeameter tests carried out in the laboratory, with regard to the materials of the Guabirotuba-tinguis Formation and colluvium. For the filter and drain materials, the coefficient values were estimated according to their granulometric characteristics. Table 2 below summarizes the coefficients used for the different materials described in the previous sections.

Table 2. Permeability coefficients

Material		Permeability Coefficient (k) [cm/s]	
		Kv	Kh
	Upstream slope protection (rip-rap)	1×10^{1}	1×10^{1}
	Massifs and central area of the dam (core)	2×10^{-6}	1×10^{-5}
	Filters and drainage veins	1×10^{-2}	1×10^{-2}
	Downstream foot drain	1×10^{0}	1×10^{0}
	Filling the upstream trench	1×10^{-5}	1×10^{-5}
	Upper foundation layer (ZG4)	1×10^{-3}	1×10^{-3}
	Middle layer of the Foundation (ZG3)	1×10^{-4}	1×10^{-4}
	Lower foundation layer (ZG1B)	5×10^{-5}	5×10^{-5}
	Rock top (ZG1A)	5×10^{-5}	5×10^{-5}

The mechanical characteristics of the materials used in the drainage system and rip-rap were determined by the designer based on their particle size distribution. The properties of the other materials were determined according to the analysis and weighting of the geotechnical prospecting results. A summary of these parameters is shown in Table 3.

Table 3. Resistance parameters

Material		Specific Weight (γ) [KN/m³]	Cohesion(c ') [KPa]	Angle of Friction (φ ') [°]
	Upstream slope protection (rip-rap)	20	0	40
	Massifs and central area of the dam (core)	19	10	30
	Filters and drainage shafts	19	0	35
	Foot drain	20	0	36
	Backfilling upstream ditch	16	0	20
	Foundation top layer (ZG4)	16	0	20
	Middle layer of the foundation (ZG3)	16	0	25
	Bottom layer of the foundation (ZG1B)	19	0	29
	Rock top (ZG1A)	Impenetrable		

It should be noted that, initially, the cohesion of the materials (with the exception of the core) was set to zero, as was done by the designer during the design simulations. As well as representing a conservative situation, this decision was taken with the aim of making the simulations in this study as close as possible to the design simulations so that the predicted results can be compared with the expected results in this study.

14 Acceptance criteria for safety factors

In stability analyses, it is common to use safety factors as a criterion for accepting the results. The minimum acceptable safety values vary according to the type of application considered and the stage of the dam's useful life (construction, operation and rapid lowering, earthquakes), as well as according to the publication used as a reference. In Brazil, the values indicated by Eletrobrás published in the manual *Criteria for Civil Design of Hydroelectric Power Plants* in 2003 are usually considered. In addition, there are publications by the National Water Agency (ANA, 2016b) and the bibliographic reference of the book published by engineer Paulo Cruz (Cruz, 2005), a renowned international consultant on dam safety in Brazil. Among international publications, the criteria published by the United States Bureau of Reclamation (USBR, 2011) is commonly used.

15 Final standard section

Based on the above, the final section of the P6' profile used in the study is presented.

16 Validation of the numerical model

The SLOPE/W module, which was used for the numerical analyses, provides various methods for calculating limit equilibrium for stability analyses, including: Morgenstern-Price, Spencer, Fellenius, Bishop. The first stage of the stability simulation was therefore carried out to analyze sensitivity and choose the calculation method to be used in subsequent simulations. The flow conditions analyzed in this study are as follows.

- Case 01: permanent regime - stable period of the reservoir used for calibration and validation of the numerical study model;
- Case 02: transient regime - lowering during a period representative of the water crisis observed in recent years;
- Case 03: transient regime - hypothetical scenarios;

- Case 3.1: Complete lowering from the maximum normal reservoir level to the toe of the dam in 24 hours;
- Case 3.2: Complete lowering from the reservoir's normal maximum level at a rate of 108.47 cm/day for several days until reaching the toe of the dam.

The modeling of the section under study, as well as its calibration with a view to a greater degree of representativeness of the field structure, was only possible once up-to-date information was available regarding geometry, instrumentation and its records, reservoir level history, updated topographic survey and records of geotechnical parameters obtained through triaxial and permeability tests. At this stage, the simulation results were observed and the information was compared with the instrumentation and field findings in order to calibrate the model with any changes in boundary conditions, permeability, anisotropy, geometry, reservoir level, among others. In view of the importance of this instrumentation data during this study, as well as its relevance for monitoring the dam and associated structures, it is recommended to keep a record of these instruments, as well as the reservoir level. The results obtained from the simulations using the calibration criteria for material permeability, geometries and boundary conditions were considered representative since, even when classified as homogeneous, there is heterogeneity in the soil due to its formation, transport and/or compaction conditions, as well as the length of the sections (which only have boundary conditions at the ends), the simplifications adopted in the model and the uncertainties inherent in numerical modeling.

It should be noted that the water level on the downstream slope of the dam was kept constant in all the analyses carried out, at EL. 879.50 identified by the 2016 topographic survey, in order to represent the existing water mirror in the area.

In future analyses, it is recommended that a transient flow boundary condition be applied to this region, using the daily water level (or any other periodicity for which a record is available) from instrumentation. In this regard, it is recommended that instruments be installed that make it possible to measure the level in the water mirror downstream of the dam.

With the numerical model calibrated and validated, the reservoir's operating conditions were simulated between 01/04/2018 and 17/08/2021 in the dam by applying transient flow considering the daily variation in the reservoir's water level for this period. In general, the simulations showed that the instruments installed in the sections of interest showed little variation over the period, but accompanied the variations in the reservoir level. When compared with field records, these readings show convergent behavior. During these analyses it was possible to observe the change in phreatic level during the calculation stages caused by the actual lowering of the reservoir. The results of these analyses were used as input data in the next stage of the study to verify the possible effect of these drawdowns on the stability of the soil massif.

Next, hypothetical flow scenarios were simulated in order to assess the behavior of the massif when subjected to complete depletion of the reservoir, considering the highest lowering speed ever observed in the dam's history (108.47 cm/day recorded on 30/04/2020). In these scenarios it is possible to observe the dissipation of pore pressures inside the massif when it is subjected to rapid lowering, and it shows that after 50 days of hypothetical depletion the phreatic is horizontalized. The critical conditions for stability during a rapid drawdown are associated with various factors such as the amplitude of the variation in the reservoir's water level during the drawdown, the speed of the drawdown, the geometry of the structure and the permeability of the soil, among others. For this reason, it is important to carry out case studies with real reservoir operating conditions, with proper validation and calibration of the model, in order to verify the stability of the structure for specific behavioral conditions. It should be emphasized that the analyses carried out were aimed, based on the documentation and information provided by the developer, at developing a representative geotechnical model for flow and stability simulations aimed at observing variations in the safety factor of the upstream slope by rapidly lowering a representative section of the massif.

17 Results obtained

The results obtained from the project were the geotechnical models of the main sections of each of the structures, associated with the knowledge accumulated during their development, the flow and stability analyses of these sections with a view to analyzing their behavior during a water crisis and a hypothetical operating scenario. In addition, the development of the integrated monitoring system will be a legacy for Sanepar as a tool for optimizing the analysis of instrumentation and visual inspections.

The dam safety management actions during the water crisis provided the Sanepar team with a significant advance in understanding the behavior of the structures as well as optimization in the analysis of instrumentation data, hydro meteorological variables, technical drawings and visual inspections through the integrated monitoring system.

18 Analysis and discussion of results

The information on the geotechnical model can be used in future studies by updating the information and helping the engineering team to quickly and efficiently analyze the behavior of the structures. The information on the flow and stability analyses can guide future dam safety actions in conjunction with the operation of the reservoir. In addition, the knowledge acquired in the process has been consolidated in recorded videos for knowledge management with future employees working in dam safety. The systems optimize information analysis time, reduce the likelihood of errors and provide data reliability due to standardization on Sanepar's own database servers. In addition to the direct results of the model, the processed data and information from drawings, instrumentation, hydro-meteorological data and others were organized into a single database and inserted into an integrated monitoring system that provides Sanepar staff with efficient data analysis, reducing the time needed for interpretation and decision-making.

19 Conclusions/Recommendations

It is recommended that any replications of the simulations using the model provided be carried out with due caution, observing the purpose for which the model was developed and making the relevant updates and adjustments, whether by updating the boundary conditions (e.g. reservoir level, efficiency of drainage systems, downstream water level, etc.), instrumentation data (such as changes in reading patterns, installation of new instruments, etc.), new information on the characteristics of the materials and geometry (from new laboratory or field tests, for example), among others. Interpretation of the results must be carried out by a specialist dam engineer with the technical capacity to assess the general context from the geological-geotechnical, instrumentation and other dam-related knowledge points of view.

As mentioned, the activities in this study were carried out to obtain the safety factors of the upstream slope under real and hypothetical operating conditions, with a view to analyzing rapid lowering, which is related to one of the failure modes associated with embankment dams. In the context of stability analysis, it is recommended that the studies be continued in more detail using, for example, a probabilistic approach.

In general, it is recommended to carry out ongoing studies covering the general behavior of the structure and analyzing other failure modes, such as internal erosion, settlement, efficiency of drainage systems, among others. The integrated monitoring system includes modules for collecting data in the field (mobile applications) from both instruments and visual inspections, transforming raw data into engineering variables, data management and drawings. To enable all the data to be stored in a single database, specific coding was developed to identify the instruments per dam, always linking to the original code in order to perpetuate historical analyses.

The development of geotechnical models provides dam safety teams with continuous learning during the development period and, in order to promote the transfer and management of knowledge, videos were recorded on an e-learning platform with a view to passing on the information to future collaborators who may work on the subject.

In future analyses, it is recommended that a transient flow boundary condition be applied to this region, using the daily water level (or any other periodicity for which a record is available) from instrumentation. To this end, it is recommended that instruments be installed to measure the level of the water mirror downstream of the dam. The activities were carried out by Sanepar's dam safety team together with the technical team from the Dam Structures Competence Center of the Itaipu Technological Park Foundation - Brazil (FPTI-BR), which carried out the geotechnical analyses aimed at rapid lowering and the development of monitoring systems.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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