



A DETAILED SAFETY AND RISK ASSESSMENT OF MASSINGIR DAM

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ABSTRACT

At the request of the Mozambican National Directorate of Water Program (DNGRH) and as part of the National Climate Resilience Program, a study aimed to evaluate the current safety of the Massingir dam and downstream valley was developed by the Consortium COBA/LNEC/SALOMON. The objectives encompassed a range of activities designed to ensure a thorough assessment and enhancement of dam safety, a critical issue to guaranty the integrity and reliability of this key water infrastructure in Mozambique. In this paper, structural and hydraulic-operational safety results are presented, as well as its adaptation to the new Mozambican dam regulations.

The Massingir Dam, the second largest in Mozambique, is situated on the Elephants River, a tributary of the Limpopo River. This 4,500-meter-long and 47-meter-high earthfill dam primarily supports irrigation in the Lower Limpopo Valley. Concluded in 1976, Massingir dam has a history of anomalous structural and hydraulic-operational behaviors and has already had several rehabilitation interventions.

The study involved a comprehensive evaluation of dam performance, including a review of operational procedures and detailed site inspections. It analyzed existing monitoring data and assessed current safety conditions. A thorough risk assessment identified both structural and non-structural mitigation measures.

The comprehensive assessment approach taken for the Massingir dam revealed strengths and weaknesses in current dam safety practices. By implementing the recommended measures, the safety and functionality of this dam will be significantly enhanced.

Key lessons underscored the critical need for regular monitoring and robust safety assessment procedures. This will contribute to the overall resilience and security of the region's water infrastructure and ensure the safety of populations living downstream.

Keywords: Earth dam, safety assessment, safety regulation.

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1. INTRODUCTORY CONSIDERATIONS

A comprehensive dam safety assessment for the Massingir Dam was conducted as part of a contract between the National Directorate of Water Resources Management (DNGRH) and the Joint Venture COBA-LNEC-SALOMON. This work was developed under the National Climate Resilience Program (RCRP) of the Government of the Republic of Mozambique, with funding from the International Development Association (IDA). The studies were based on a thorough analysis of all the foundational documentation, the original design, and the rehabilitation projects, the monitoring data, the results of inspection site visits to the dam and the downstream valley, as well as expedited support calculations.

The Massingir dam is a large dam, thus falling under the provisions of the Mozambique Dam Safety Regulation (MDSR) [1], classified as Risk Class I, with High Vulnerability and High Potential Damage. This classification, which should be reviewed every 5 years, establishes several responsibilities for the Project Owner, among which, the following will be prioritized in the short term [2]:

- Organization of the Technical Archive of the Project.
- Development of the Safety Plan (including the Observation Plan, the Operating Rules, the Internal Emergency Plan and the Environmental Safety Plan).
- Organization of the archive of data and results from the monitoring devices reading campaigns, which should be sent to Mozambique Engineering Laboratory (MEL) immediately upon their acquisition.
- Providing the necessary information to the Regional Authority on Dam Safety (RADS) for the preparation of the External Emergency Plan.
- Development and implementation of structural and non-structural measures and interventions for safety improvement and rehabilitation, defined within the scope of the safety assessment studies undertaken.

Massingir Dam is the second largest dam in Mozambique and is managed by Ara Sul. It is located on the Elephants River, a tributary of the Limpopo River, in Massingir District, approximately 12 km upstream from its confluence with the Chimwedzis River in Gaza Province. The dam serves multiple purposes, primarily for the irrigation of 90,000 hectares, flood control, hydroelectric power generation (not yet implemented), and water supply for the town of Massingir.

The Massingir catchment area covers 67504 km² with an average annual affluent volume of 1800 hm³. The maximum total capacity of the reservoir is 2844 hm³ (being the operational capacity of 2784 hm³) and the flooded area 150.78 km² (0,64 km² in South Africa) at level 125

m, the Normal Retention Level (NRL). The Maximum Flood Level (MFL) of the original design is at 126.45 m (subsequently revised to the elevation 128.5 m) and the Minimum Operating Level at 90 m.

Figure 1 shows a Google Earth view of the Massingir Dam.



Figure 1 – Massingir dam general view (google earth).

The dam is a zoned earth-fill dam, with a crest length of approximately 4,596 m and a maximum height of 47 m. Its construction began in 1971 under the Government of Portugal and was partially completed in 1977, after Mozambique gained independence. The Massingir Dam's hydraulic infrastructure includes a main spillway with six radial gates, designed to handle 10,500 m³/s at the Maximum Water Level (MWL) of 128.5 m. An auxiliary spillway equipped with Hydroplus fuse gates, commissioned in 2015, adds a discharge capacity of up to 10,000 m³/s for reservoir levels reaching 131.0 m. The bottom outlet system, located on the right bank, complements the dam's discharge capacity, ensuring operational and flood management flexibility. Due to issues stemming from armed conflict during this period and a lack of funding, the six spillway gates were not installed at the time of completion, nor was the powerhouse constructed.

The geological and geotechnical conditions of the foundation influenced the overall design of the dam and were the root cause of the problems that emerged after the initial filling began. The first filling of the reservoir began after the dam's partial completion in November 1977, the

same year when significant foundation issues were identified, the right bank being the most affected zone. These issues included piping and extensive water passes along large sections of the foundation.

In the early 1980s, rehabilitation studies were carried out, leading to the execution, on the right bank, along the downstream foot of the dam, of a drainage ditch measuring approximately 1.5 km and with several transversal ditches, crossing the foundation, aiming to improve local drainage and stability conditions.

Due to concerns about the dam's integrity, and because the gates of the spillway were not installed, the reservoir's maximum water level was restricted to elevation 110 for many years. During the year 2000, floods rose the reservoir level to elevation 124 for several hours what immediately worsened the percolation and internal erosion of the foundation. Following these exceptional floods, a review of the hydrological studies confirmed that the spillway was unable to pass the design flood.

Between 2004 and 2006, the following rehabilitation interventions were carried out.

- Foundation grouting along two sections of the right bank (between Pk 1800 and 2500, and between Pk 3000 and 3200) and of the left bank, at the lower elevations (between Pk 3500 and 3800), with three rows, each with primary holes spaced of 12 m, secondary holes and tertiary holes, execution control was made by GIN method, the grout take was generally low.
- Execution of a downstream berm at the dam toe at the right-bank, inverted filter, and stabilizing berms on the downstream natural ground for stability strengthening purposes.
- Execution of additional relief wells for seepage control, bringing the total to nearly 100 relief wells currently in operation. However, and despite this significant number of relief wells, seepage through the foundation remains uncontrolled.
- Rehabilitation of the riprap of the upstream slope of the dam.
- Raising of the crest of the embankment dam by 1 m, and installation of a concrete parapet wall on the upstream alignment of the crest (the crest over the spillway was not raised).
- Rehabilitation of the monitoring devices.
- Installation of the 6 radial gates on the main spillway (18 m wide x 10.5 m high).
- Repair of hydro-mechanical equipment of the bottom outlets.

After these rehabilitation works, in 2008, during the reservoir filling – specifically at the second filling stage, around elevation 122.5 meters (reached on April 7) – an accident occurred on May 22 at the bottom outlets, resulting in an uncontrolled release of water. Rehabilitation and reconstruction works of the bottom outlets were only completed in 2016. Meanwhile, an auxiliary spillway was added at higher elevations on the left bank in 2015.

Notwithstanding all the rehabilitation interventions, normal retention level (NRL) of 125 m has not yet been achieved. In fact, water levels above 121 m have been reached only sporadically,

and continue to cause uncontrolled water passages through the foundation of the dam on the right bank.

This paper focuses on structural safety, hydraulic-operational safety, and the safety of electrical equipment and installations, as well as on the structural and non-structural measures aimed at mitigating the risks of failure and various malfunctions, improving safety conditions, and adapting the dam to the current safety regulations. Downstream consequences of dam failure and operational flood releases are treated in the paper “Strengthening Key Water Infrastructure in Mozambique: A Risk Assessment of Downstream Valley of Massingir Dam”.

2. STRUCTURAL SAFETY ASSESSMENT OF THE DAM

2.1. Main characteristics of the dam

Massingir dam is composed of three typical cross-sections, primarily determined by the characteristics of the foundation soils (**Figure 2** and **Figure 3**).

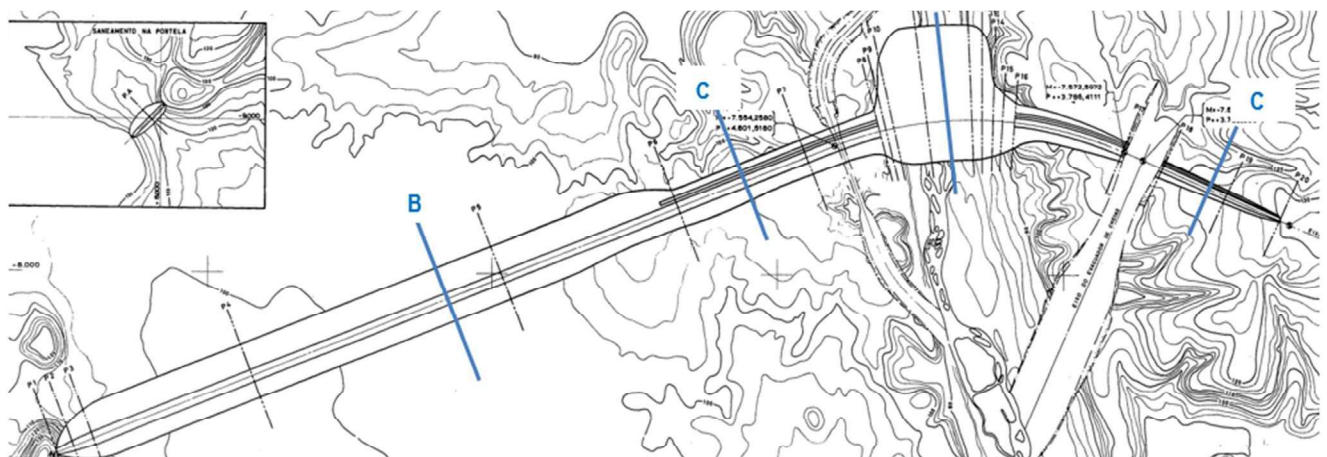


Figure 2 – Plan view of the original layout of the dam (adapted from [3])

The cross section of the dam on the central valley (cross-section A) is founded on a thick layer of low-strength, highly permeable alluvium, treated with vibroflotation to a depth of 15 m, in addition to the creation of relief wells downstream of the insertion of the dam into the foundation.

Cross-section A has a crest width of 12 m, initially located at elevation 130. The upstream slope has a variable steepness, between 1:2 (V:H) at higher elevations and 1:3.5 (V:H) at lower elevations. Below elevation 88, a clay blanket is in place, extending for approximately 350 m from the dam axis. The downstream slope also has a variable steepness (1:2 and 1:2.5) and includes four berms of different widths.

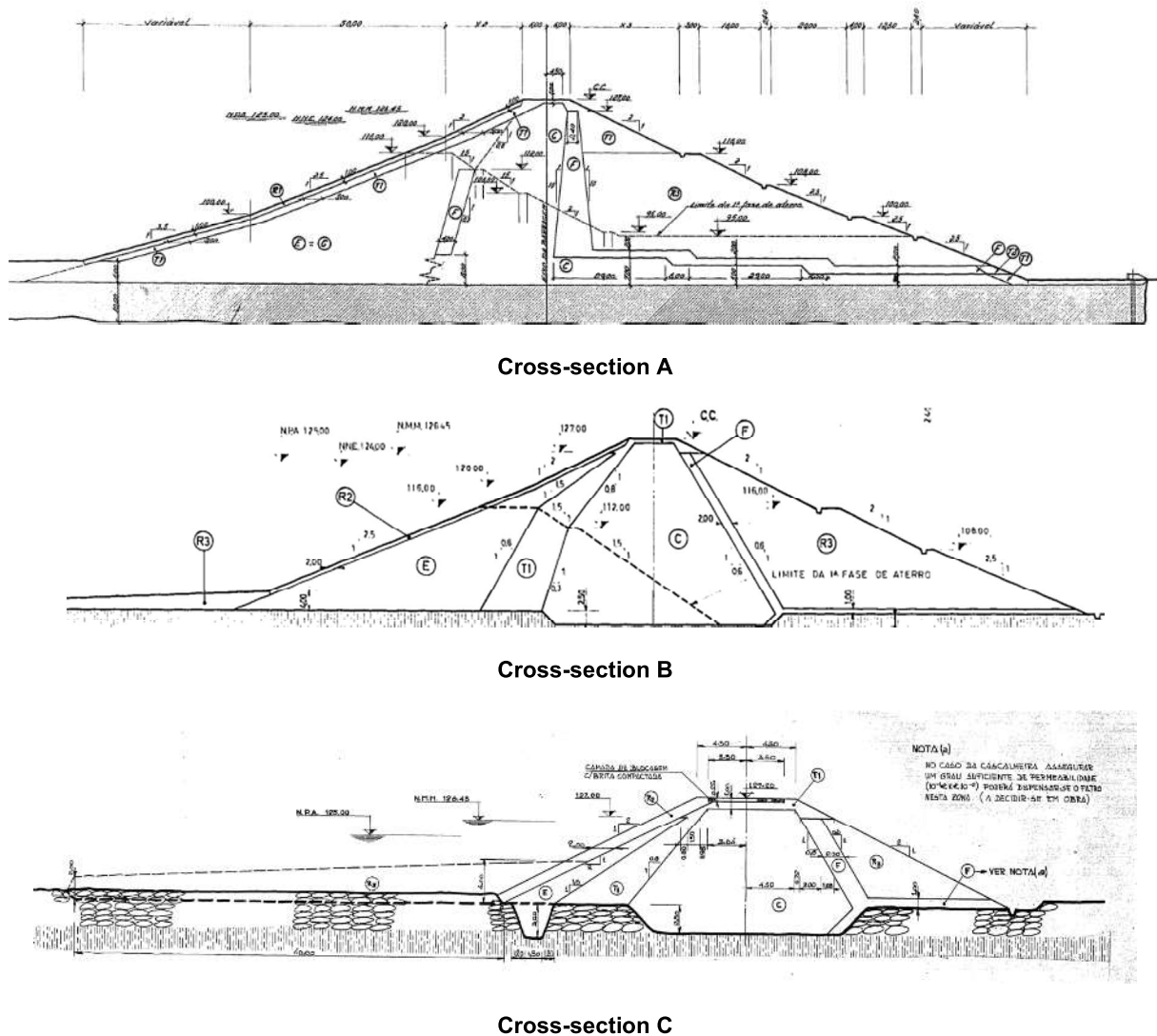


Figure 3 – Cross-sections of Massingir dam [3]

Cross-section A includes a central clay core slightly inclined towards the upstream side, which is separated from the downstream shoulder – primarily composed of rock materials from excavation – by a chimney filter. This filter extends sub horizontally beneath the downstream shoulder, with a thickness of 2 m, and rests on a clay layer, in a highly unusual layout. Upstream of the core, a subvertical filter below elevation 112 separates the core from the upstream shoulder, which consists of sandy-clay materials. The upstream shoulder is protected by a 1-meter-thick rip-rap layer, placed over a transition layer of clayey gravel.

Cross-section B has a crest width of 9 m, located originally at elevation 129.6. The upstream slope has a variable steepness of 1:2 (V:H) at higher elevations and 1:2.5 (V:H) at lower elevations. The downstream slope has a constant steepness of 1:2 and includes two berms of different widths.

Cross-section B features a large central clay core with slopes of 1:0.8 (V:H) upstream and 1:0.6 (V:H) downstream. The core is separated from the downstream shoulder – mainly

composed of rock materials from excavations – by a chimney filter with a thickness of 1 m, which extends sub horizontally beneath the downstream shoulder and contacts the foundation. A transition zone of gravelly clay materials separates the core from the upstream shoulder, which is made of sandy-clay materials and protected by a 2-meter-thick (measured horizontally) rip-rap layer. The clay core extends into the foundation, composed of silty-clay soils, through a cut-off trench approximately 3 m deep. At the upstream toe, a 40-meter-long layer of granular material was placed to prevent the alteration of the foundation soil and to minimize swelling effects of the clay.

Cross-section C is very similar to Section B in both its external geometry and internal zoning. The main differences are the absence of an upstream granular blanket in Section C and the presence of two cut-off trenches: one beneath the core, like that of Section B, and another upstream, beneath the cofferdam embankments. This section is found on gravelly materials.

2.2. Dam design

The dam design studies covered the necessary safety checks, having been developed based on the knowledge and calculation methods available at the time, which were naturally much more limited than those currently available to dam engineering.

In **Table 1**, the main conclusions regarding the design calculations carried out during the original design are presented.

Based on the freeboard design studies, the dam's crest elevation was determined using the maximum design flood level (126.45 m), with an additional wave run-up of 2.38 m calculated for a wind speed of 100 km/h, plus 1 m to account for potential seismic effects. This resulted in an elevation of 129.83 m, rounded-up to 130 m in the central valley where the dam has its greatest height. Furthermore, the crest elevation was increased by a maximum of 0.80 m to accommodate potential creep deformations of the dam-foundation system.

The freeboard calculation is constrained by the combination of actions related to the water level in the reservoir, equal to the Maximum Water Level (MWL), currently estimated at 128.5 m. The crest elevation defined in the rehabilitation project, 131 m, appears insufficient to accommodate the wave run-up caused by a typical wind speed of 60 km/h (a modest value) – ranging from 2.39 to 2.69 m, depending on the adopted methodology – a residual creep settlement, estimated between 0.12 and 0.15 m – and an allowance of 0.5 m for non-quantifiable factors, including seismic effects.

The re-evaluation of the freeboard should be carried out alongside an assessment of the hydraulic operation of the spillways – both primary and auxiliary – for the design flood (T=2000 years) and the verification flood (T=5000 years), in accordance with the MDSR. This process

must also include a reassessment of the freeboard, considering the potential existence of varying crest elevations along the length of the dam.

Table 1 – Design calculations. Summary

Calculations	Results	Observations
Global stability analysis under static conditions	Minimum global safety factor during rapid drawdown = 1.02. Minimum global safety factor during full storage = 1.82	Minimum global safety factor during rapid drawdown lower than the recommended. Minimum global safety factor during full storage higher than the recommended.
Global stability analysis under seismic conditions	Minimum global safety factor during full storage = 1.30	Conservative minimum global safety factor. However, since the seismic amplification appears to be lower than expected, the actual safety factor will be lower.
Amplification of seismic action	Horizontal peak acceleration on the dam base foundation: 0,14g. Horizontal peak acceleration on the crest: 0,18g	The peak acceleration value at the dam's foundation level appears to be close to the value that would be obtained for the SMP and type D ground (EC8). The amplification of the seismic action along the height of the dam is lower than expected, considering the characteristics of the embankments and foundation soils.
Hydraulic stability	Only the values of the hydraulic head were calculated.	It is expected that the water levels established in the foundation will differ from those in the body of the dam, due to the different permeability coefficients, which is not inferred from the calculation results.

2.3. Monitoring system and data

The monitoring systems at Massingir Dam currently faces significant deficiencies. The system lacks adequate organization and technological support for efficient data analysis and timely communication with relevant authorities, such as ARA-Sul and other safety monitoring entities. Although there is an ongoing civil works project aimed at rehabilitating piezometers and other monitoring devices, numerous critical issues remain unresolved.

The absence or malfunctioning of critical monitoring and measurement equipment, as highlighted by the MDSR, severely hampers the ability to assess the performance and safety of the Massingir Dam. The significant deficiencies in the quantity, functionality, and placement of these devices underscore the urgent need for corrective actions to be implemented in the short term. Also, there is no immediate transmission of monitoring data to either the Authority or the MEL, as specified by the MDSR.

The operators are knowledgeable and familiar with the procedures for data reading and analysis, but the technical means at their disposal, namely hardware and software, urgently require improvements.

Additionally, the process for measuring the relief wells must be changed to ensure the necessary health and safety conditions at work of the operators. For measuring the inflows to the relief wells, operators must enter these wells and descend ladders to the depth where the measurements are taken. During this process, operators face life-threatening dangers due to the presence of venomous snakes, scorpions and spiders that shelter inside (**Figure 4**). The high number of observation relief wells also makes this task physically exhausting, in addition to being hazardous.



Figure 4 – Relief wells in the right bank

Table 2 provides a summary of the devices installed at Massingir Dam and their current condition.

Since the surface displacements of the dam have not been recorded for a long time, and there is no reference reading of the marks installed in 2015, a topographic survey using drone technology should be conducted to obtain a quick assessment of the current elevations of the crest, necessary for a substantiated evaluation of the dam's freeboard. After this survey, it will be necessary to resume the readings of the superficial displacements of the dam.

The limited number of piezometers installed in the dam body and its foundation constrains the reliability of the seepage network analysis.

Table 2 - Monitoring devices installed and operational conditions

Device	Location	Total	Not operational	Observations
Surface marks	embankments and spillway	17	17	-Surface displacements of the embankment are not currently being monitored due to the lack of appropriate measurement equipment. -New markers were installed in 2015; however, they have not yet been used.
Open-tube Piezometers	Drainage channel	60	20	- Measurements are conducted weekly. -Some piezometers are obstructed by small debris due to the lack of proper protection for the housing boxes. -Ongoing works are in place to clear obstructions and rehabilitate the affected equipment.
	Dam body (Downstream Slope)	20	5	
	Left and right bank	12	0	
Electrical Piezometers	Dam body	21	0	- Measurements are conducted weekly. -Good condition.
Relief Wells	Drainage channel	77	19	-Measurements are taken every 15 days. -Some relief well chambers are damaged, submerged or compromised. -Relief wells on the left bank are not being measured due to overgrown vegetation and the presence of snakes. -Ongoing efforts are focused on rehabilitating the damaged equipment, clearing the overgrown vegetation, and installing a new Total flow meter.
	Drainage channel (new wells)	30	4	
Gallery Drains	Gallery	37	0	- Measurements are conducted weekly.
Level Scale	Water intake and spillway	2	-	-Daily readings are taken at 7:00, 9:00, 12:00, 15:00, and 17:00, with increased frequency and continuous monitoring during the rainy season. -Equipment is in good condition.
Level Gauge	Water intake and spillway	2	2	-

On the contrary, the measurement of piezometric levels and inflows downstream of the dam's toe provides a comprehensive view of the dam's performance in terms of foundation flow in the right bank.

As shown in **Figure 5**, the piezometric levels are read in 60 wells, between Stakes 0+212 and 2+112. The piezometric readings indicate a greater pressure near the higher levels of right abutment and in the vicinity of Stakes 2+000 where an upper limit is reached, at VD41. On 30/10/2023, the piezometric level at VD41 was 105.52 m, while the reservoir was at an elevation of 120.34 m.

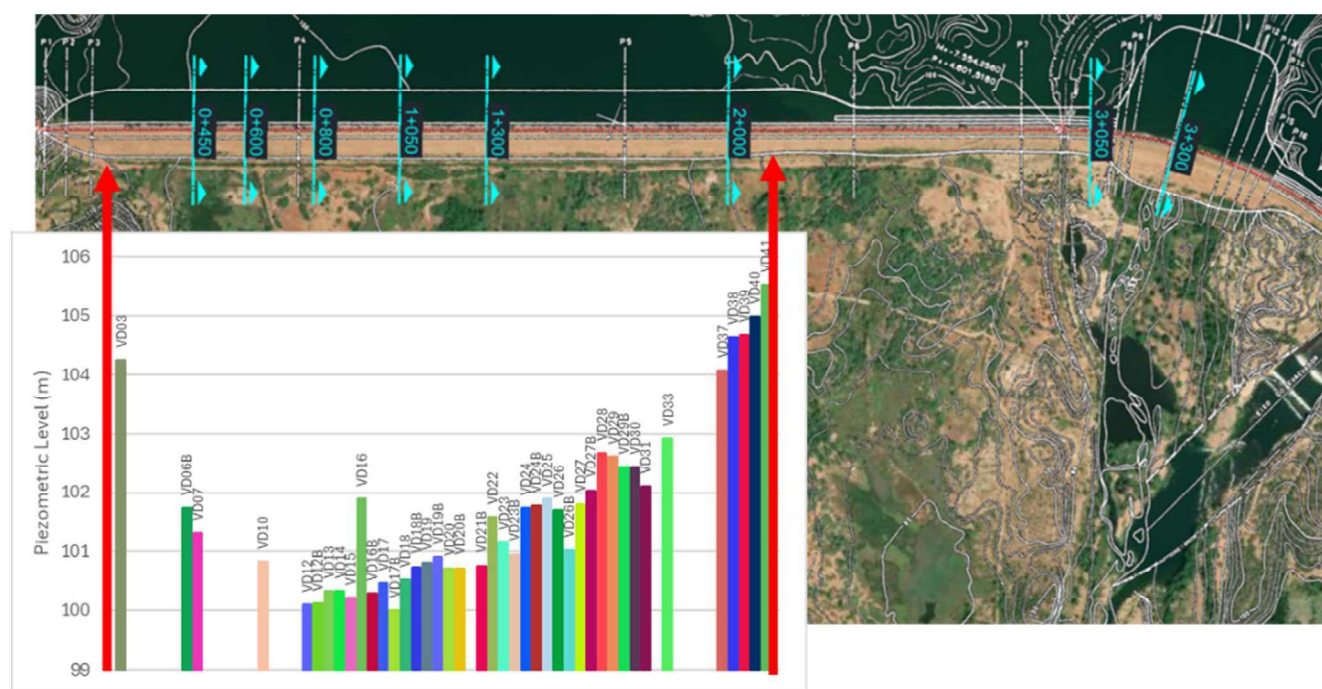


Figure 5 – Piezometric levels measured downstream of the dam on 2023-10-30

Figure 6 shows the history of the readings taken between January 2006 and October 2023. In the period between 2014 and 2022, the data is somewhat inconsistent; however, from 2022 onwards, the measurements show greater consistency. Nevertheless, it is possible to identify a gradual increase in piezometric levels when comparing the initial data with the most recent.

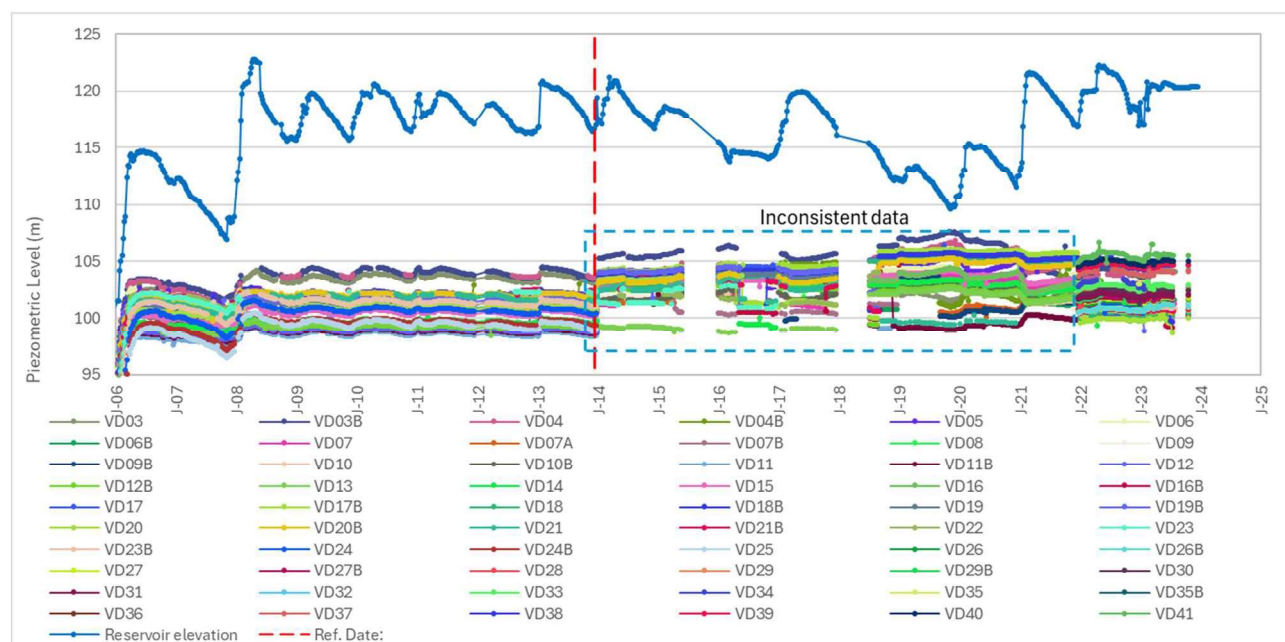


Figure 6 - Historical piezometric levels downstream of the dam, between 2006 and 2023

Concerning the flow rates measured in the relief wells - there are a total of 74 devices in operation at right bank, distributed between stakes 0+200 and 2+025 - these devices show a downward trend, as can be seen in **Figure 7**.

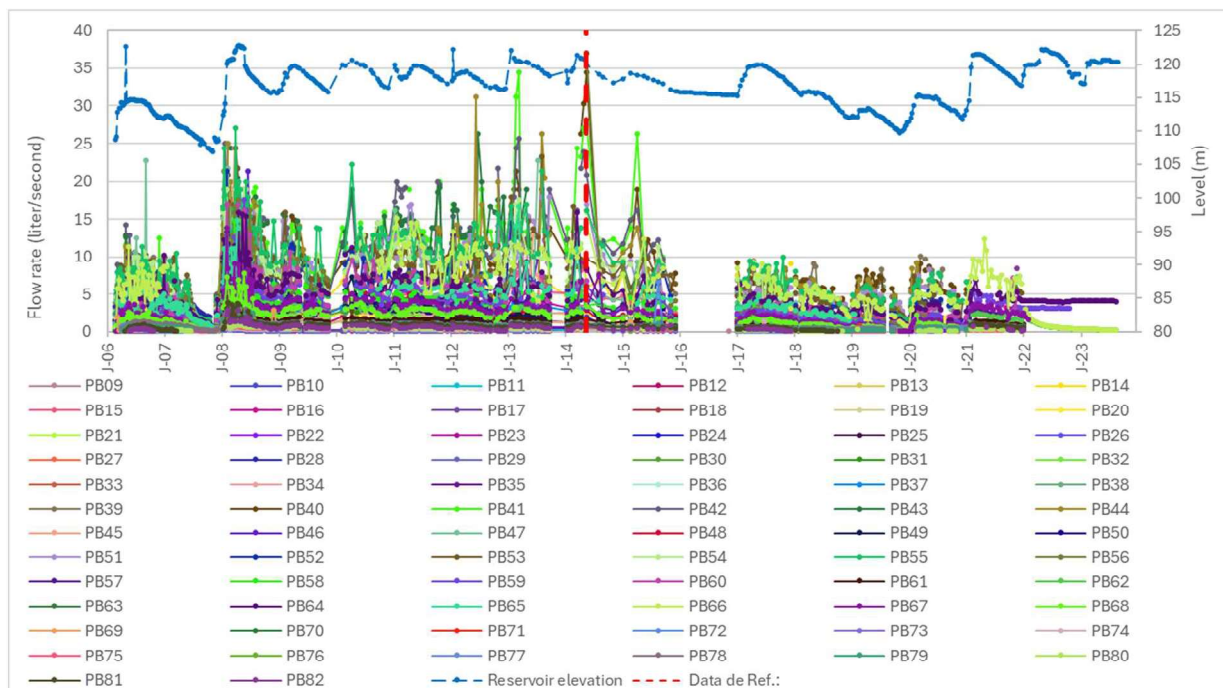


Figure 7 - History of the flows in the relief wells, between 2006 and 2023

Figure 8 shows the location and the values of the measured flows on 2020-10-20, when the reservoir was at an elevation of 113.12 m. The flows are significantly higher in the central area of the right bank (pattern that repeats for other reading dates), in contrast to the piezometric levels, which are higher at the extremities. This phenomenon may be associated with the clogging of drains near the areas with higher piezometric levels.

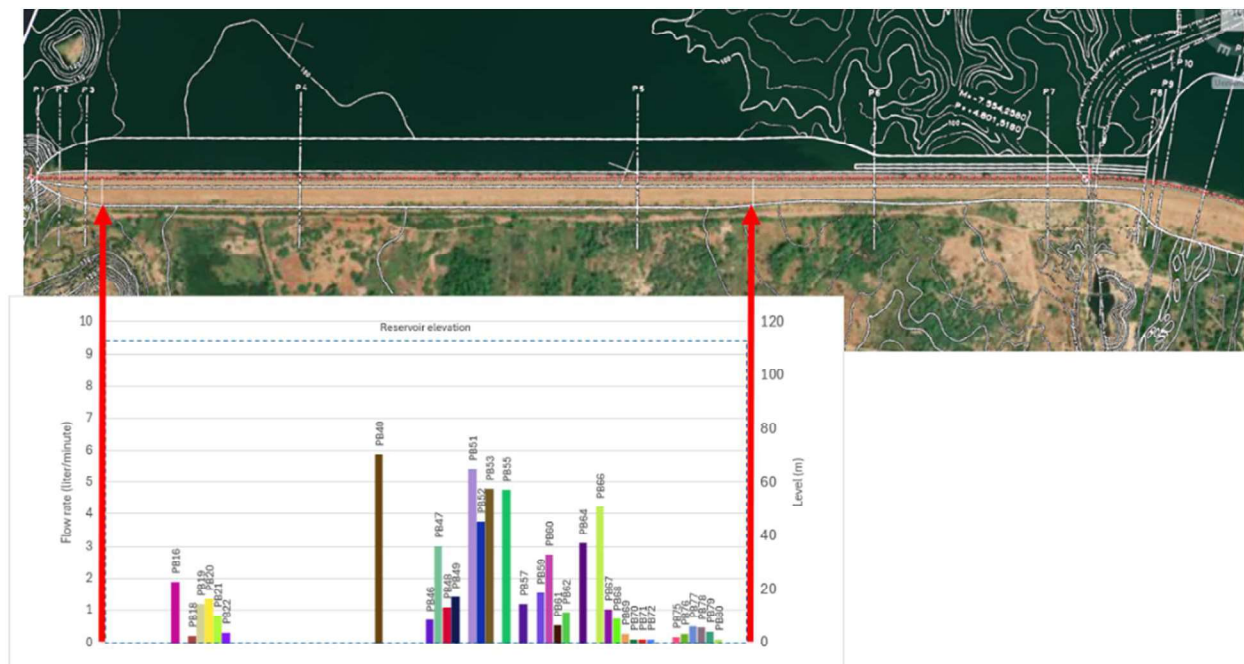


Figure 8 - Measured flows in the relief wells on 20/10/2020

For the analysis of the total flows percolating through the foundation of the dam on the right bank, periods were selected in which readings were taken from at least 60 relief wells. **Figure 9** presents a graph of the total flow observed in these wells, showing a directly proportional relationship between flow behaviour and reservoir levels. Based on the most reliable data series, the trend curve that best represents the relationship between flows and reservoir levels was analysed. As shown in **Figure 10**, the estimated flow for current reservoir levels is approximately 344 l/s. At the Normal Retention Level (125 m), the flow is estimated at 784 l/s, and at the Maximum Flood Level (128.5 m), the flow is projected to reach around 1,394 l/s.

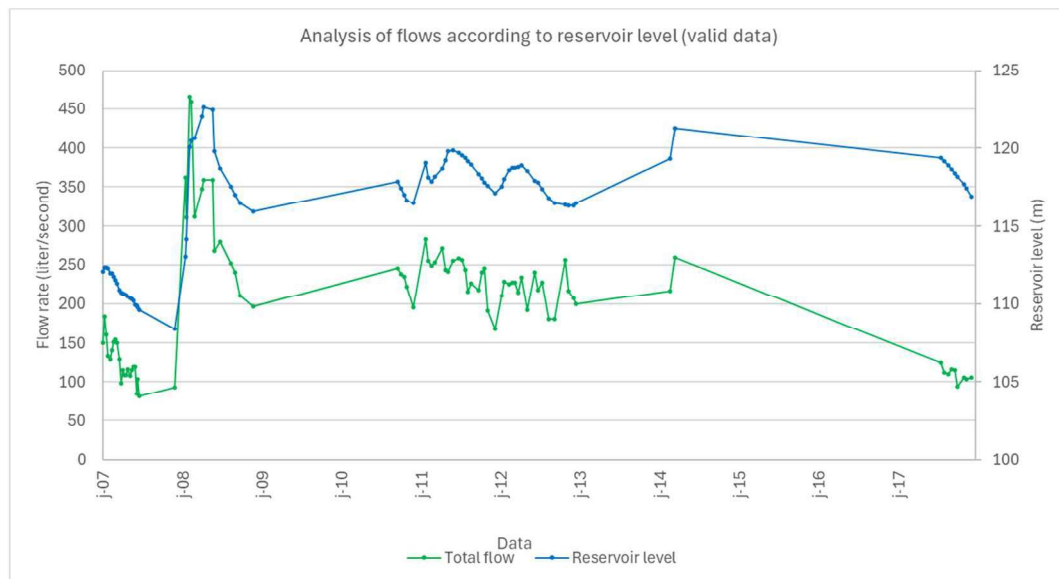


Figure 9 - Total flows on the right bank versus reservoir water level

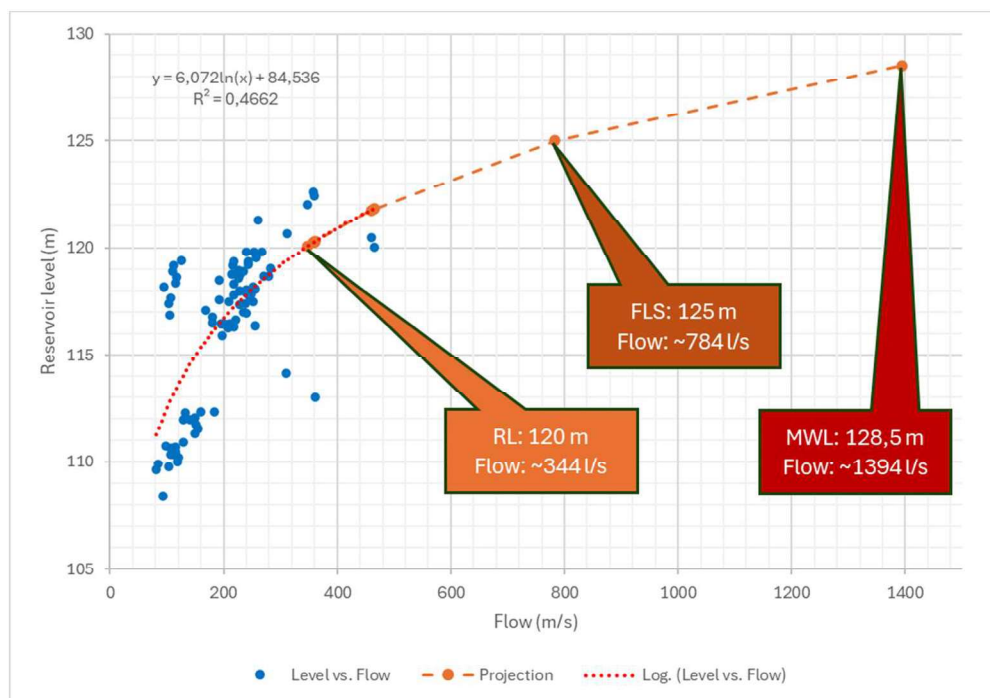


Figure 10 – Extrapolated flows downstream of the dam on right bank

Considering that the wells are distributed over approximately 1,900 meters and the flow occurs along this entire length, a specific flow rate of about 25 l/min/m is observed at a reservoir level of 125 m, and around 44 l/min/m at a level of 128.5 m. These values represent a potentially hazardous condition, further aggravated by the fact that these are average values, as significantly higher flow rates are observed in sections with greater inflows to the relief wells

2.4. Dam performance and failure modes

In what concerns the results of the site inspections [4], there are currently no indicators of anomalous behaviour in the dam body that threatens its safety. However, the monitoring data show that there are preferential seepages through the foundation on the right bank, water levels at the toe of the dam exceeding natural ground levels, and significant total and partial flows. The medium and long-term effects of these conditions on the foundation soils and the dam body cannot be underestimated, as they may trigger internal erosion processes that could compromise the integrity of the dam-foundation system, potentially resulting in the downstream release of a catastrophic flood wave.

Although preferential water pathways through the foundation have been identified since the first filling of the reservoir, the monitoring data proves that they remain unresolved despite stabilization and drainage interventions, including stabilizing berms, filter/drainage zones at the toe of the dam, and the installation of additional relief wells. Despite the large number of relief wells installed at the downstream toe of the dam on the right bank, around 100, there are still uncontrolled preferential seepage paths.

The most common failure mechanisms in earth dams, in order of importance, are overtopping erosion (usually due to inadequate or failed operation of spillways), internal erosion, and loss of integrity due to foundation failure. Although most dam failures occur within the first 10 years of operation, around 70%, a still significant percentage, 30%, happens during the later operational period.

For the Massingir Dam, from a risk assessment perspective, it is important to note that the reservoir has not yet reached full capacity. The water level has only exceeded 120 m (5 m below the Normal Retention Level) for brief periods, primarily during flood events. Additionally, for reservoir water levels above elevation 121, even if occasional and occurring over short periods, resurgences appear at the dam's toe, at the transition between the central valley section of the dam and the right bank dike.

The estimated inflow rates at the base of the dam on the right bank, based on monitoring data, are approximately 790 l/s at level 125 m and 1,400 l/s at level 128.5 m. These values imply the need for implementing effective impermeabilization solutions and temporarily limiting the maximum operating level until these measures are carried out.

Level 121 was established for the temporary maximum operating level at Massingir reservoir. This level must be validated using the observational method. Once this level is reached in the reservoir, the inflows to the relief wells should be monitored weekly (or, if feasible, twice a week) for a period of two months. If the flow reading remains constant, elevation 121 can be temporarily used for normal operation of the reservoir. If an increase in inflow is observed while the reservoir level remains at elevation 121, this value should be reduced by 1 m (to elevation 120) and the validation procedure should be repeated.

Additionally, in the event of floods that temporarily raise the water level in the reservoir, supplementary measurements of the inflows to the relief wells should be taken, and the increase in flows should be analyzed for flood levels. This will enable timely decision-making, if necessary, through the operation of the main spillway gates or the bottom outlets.

3. HYDRAULIC AND OPERATIONAL SAFETY

3.1. Characteristics of appurtenant structures

The main spillway features a 475 m-long concrete chute with a 3% slope, transitioning from a width of 128 m to 100 m, then expanding to 170 m at its end. The ogee-type crest is set at elevation 115.0 m and controlled by six radial gates measuring 18.0 m in width and 10.5 m in height. The downstream stilling basin includes energy dissipation components such as baffle blocks and an end sill.

The auxiliary spillway, located on the upper left bank, includes a 151.9 m-long crest at elevation 120.0 m, fitted with 14 Hydroplus fuse gates, each 10.85 m wide and 5.85 m high. This spillway operates progressively for reservoir levels exceeding 127.5 m.

The bottom outlet system comprises two conduits, each 7 m in diameter and 300 m long, capable of discharging 800 m³/s per conduit. The conduits include radial gates for flow regulation and connect to a stilling basin for energy dissipation.



Figure 11 – Downstream view of the spillway crest and detail of a spillway gate

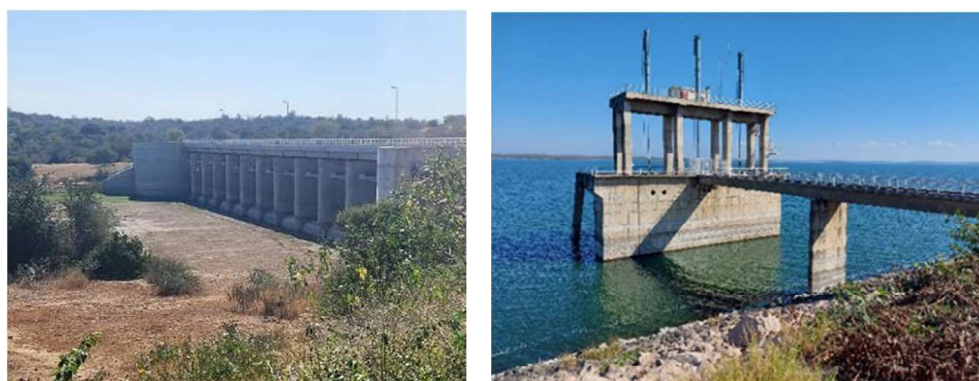


Figure 12 – View of the Auxiliary Spillway

Figure 13 – Bottom outlet intake tower

3.2. Hydraulic and operational safety assessment

The Mozambican dam safety regulation MDSR requires design floods with a 2,000-year return period and verification floods with a 5,000-year return period for Class I embankment dams like Massingir. Prior to the construction of the auxiliary spillway, past studies assessed the dam's performance for the 10,000-year flood and the Probable Maximum Flood (PMF), revealing that the main spillway alone was insufficient to prevent water levels from approaching the embankment dam crest (130.5 m). While the installation of the auxiliary spillway has significantly enhanced the dam's flood discharge capacity, further hydrological and hydraulic studies are needed to verify its compliance with MDSR standards.

Key safety concerns include the non-operational status of the spillway gantry crane, bottom outlet, and remote-control system, all critical for safe flood management. Thus, the following equipment must be refurbished in a short term.

- The gantry crane requires complete redesign, followed by supply and installation. A new gantry crane specification guiding the future tender must be done compatible with the current civil structure and the hydromechanical equipment to be maneuvered.
- The Bottom Outlet and Water Intake Systems were non-operational when the inspection took place due to gate seal problems. Meanwhile, both bottom outlets have been put into operation. However, to ensure that these outlets are restored to full functionality, it is necessary to proceed with in a reasonable short period with the following steps:
 - A thorough inspection to all equipment,
 - Replacement of obsolete or deficient equipment and components.

The remote-control system, installed in 2006, has been non-functional since 2008. It is recommended to either repair this system or implement a new, reliable remote-control mechanism to improve operational efficiency and comply with Mozambican regulatory requirements.

Additionally, downstream erosion in the outlet channel requires frequent monitoring to prevent potential structural deterioration.

3.3. Electric equipment and installations safety assessment

The Massingir dam is equipped with a range of electrical installations and equipment that have been in operation for several years, show signs of wear, and are located in humid environments.

The difficulty of replacing protective equipment in the event of a breakdown or damage is a reality, compounded by long waiting times for the purchase and delivery of replacement materials. In some cases, the equipment is not even replaced because the market doesn't have similar equipment to offer. .

During our site inspection, we observed that the facilities critical to the electrical operation of the Massingir dam, such as the HV/LV substation and the generator room, were poorly maintained or in deteriorating condition. As a result, we recommend replacing the equipment, fully renovating the buildings, and enhancing safety within these areas. Additionally, exterior cleaning around these buildings is crucial for fire prevention, particularly due to their proximity to the HV/LV substation, generator, and control room.

Access to the Massingir dam control room is through the generator room, and its proximity results in mechanical and electrical noise, compromising people's safety. The generator room should be a dedicated technical space with separate access, restricted to qualified technicians. The generators and switchboards need to be urgently replaced or repaired, and the technical room should be fully renovated.

The SCADA supervision system at the Massingir dam has not been installed. It is recommended to implement a Supervision System that enables technicians to remotely monitor (either locally or from a distance) a range of events and operations, as well as record critical events for planning repairs and inspections. Remote operation of the Massingir dam should be conducted with caution and always with the presence and expertise of the Massingir dam team.

The electrical panels are in working order and generally well-maintained inside. However, they are equipped with long-standing equipment that is difficult to replace, and the cabinets are showing signs of corrosion.

The power cables will have to be replaced as they have been in place since the Massingir dam began operating. New signal cables will have to be installed.

The lighting, sockets and fire safety installations should be renewed or installed.

The CCTV system should be implemented together with the control system.

It is also very important to carry out regular electrical checks, operations and inspections. The lack of records and the absence of an electrical project is commonplace. There should be a space dedicated to the technical archive with all the documents on the electrical activities carried out, from design, maintenance, inspections and equipment manufacturers' manuals.

Continuous training in the areas of electrical systems, instrumentation, automation, supervision, and IT should be prioritized. Additionally, the creation of a technical space for recording operations and a dedicated electrical workspace should be considered.

It is also recommended that the entire electrical installation be new, renovated in a phased manner to maintain the proper functionality of the Massingir dam.

4. CONCLUSIONS AND RECOMMENDATIONS

After 47 years of operation of the Massingir Dam, considering its history of issues since the beginning of its operation, as well as the analysis of the dam's design criteria and calculations, a comprehensive review of all safety checks of the dam-foundation system is strongly recommended based on the methods and models currently available in dam engineering and aligned with the MDSR. Freeboard calculations and the minimum crest elevation of the dam - which is not constant throughout its entire length - must also be reviewed and, if necessary, a design for raising the entire crest of the dam should be developed.

These calculations should be supported by a geotechnical exploration campaign to characterize the material properties, and by monitoring data to be collected following the rehabilitation of the actual monitoring systems in progress. In fact, the presence of a significant number of out-of-service monitoring devices limits the overall assessment of the safety implications of excessive and preferential seepage through foundation.

Regarding internal erosion mechanisms, it is recommended to use specialized detection techniques to monitor changes in the seepage network, such as temperature, resistivity, or electrical current measurements. This data will be crucial for informing the design of impermeabilization and flow control solutions for the dam foundation, namely in the right bank. It will also be important to assess percolation through the foundation in the central valley area and in the left bank, where the inflow rates to the relief wells are not being recorded.

From the analysis of all the information consulted and collected, and considering the extensive stabilization and drainage works at the toe of the dam on the right bank – stabilizing berms, filter/drainage zones at the toe of the dam, and an extremely high number of relief wells, as well as impervious treatment of the foundation by injection of cement grouts in some sections of longitudinal development – the solution that appears to be most suitable for controlling the excessive flows percolating through the foundation and reducing the risk of internal erosion is a diaphragm wall.

The foundation of the right bank dike consists of two distinct alluvial zones: an upper clayey layer and a lower sandy layer with gravel. The alluvium rests on a Cretaceous substratum, whose upper fringe is decompressed and weathered. The impermeabilization of these alluvial deposits cannot be achieved through cement grout injection, as it lacks the ability to penetrate the pores.

The detailing of the diaphragm wall solution (characteristics, depth, execution and control techniques), as well as the selection of its location in the cross-sectional profile to optimize execution lengths and minimize operational impacts, requires additional baseline information and detailed design studies. Together with the design of the foundation impermeabilization solution, the dam Observation Plan should be reviewed and complemented accordingly.

Complementary hydrological studies should also be undertaken to establish the maximum peak flows and hydrographs for floods with return periods of 2,000 years and 5,000 years. These updated studies, together with flood-routing and hydraulic analyses, are critical for assessing the dam's capacity to safely manage extreme flood events and ensuring compliance with MDSR requirements.

Concerning the appurtenant structures, updated flood-routing studies, a new and functional spillway gantry crane, gate remote-control system and maintenance of hydromechanical components are essential to ensure regulatory compliance and safe operation.

Regarding the hydromechanical equipment the following must be refurbished:

- The gantry crane requires complete redesign, followed by supply and installation.
- The bottom outlet inspections and replacement of obsolete or deficient equipment and components.
- The remote-control system, installed in 2006, has been non-functional since 2008.

The safety assessment studies for the Massingir dam culminated in the definition of a set of studies and projects, topographical and geological-geotechnical surveys, and rehabilitation interventions aimed at mitigating risks and ensuring the dam's compliance with the current safety regulations and their associated safety requirements. A work schedule and a preliminary budget estimate were established, along with implementation priorities and terms of reference for carrying out the studies, projects, and supporting works [5].

Table 3 presents the list of studies to be carried out and their priority classification and **Table 4** the list and priority classification of the surveys to support the studies and the rehabilitation interventions.

Table 3 – Priority classification for the studies and projects

Studies to support the implementation of both structural and non-structural measures.	Priority Classification
1. TECHNICAL ARCHIVE OF THE PROJECT	
1.1 Identification and organization of technical documents and data for the various phases of the dam's lifecycle	1
1.2 Elaboration of the Dam Safety Plan	3
2. COMPLEMENTARY HYDROLOGICAL AND HYDRAULIC STUDIES	2
3. COMPLEMENTARY DAM-FOUNDATION STUDIES	
3.1 Geological-geotechnical investigation program	1
3.2 Comprehensive review of all safety checks of the dam-foundation system (global stability analysis under static and seismic conditions, and seepage studies through the dam and foundation)	2
3.3 Detail design for the foundation waterproofing solution (cut-off wall), including report, calculations, technical specifications, drawings, and budget estimate	3
3.4 Possible detail design for the dam crest raising, including report, calculations, technical specifications, drawings, and budget estimate	3
4. HYDROMECHANICAL EQUIPMENT (Design and Technical Specifications)	1
5. ELECTRICAL EQUIPMENT AND INSTALLATIONS (Design and Technical Specifications)	1

1	< 3 months
2	< 6 months
3	< 9 months

Table 4 – Priority classification for the topographical and geotechnical surveys and for the rehabilitation works

Implementation of structural and non-structural measures.	Priority Classification
1. DRONE-BASED TOPOGRAPHIC SURVEY OF THE DAM	1
2. DRONE/LIDAR and SONAR/ADCP-BASED TOPOGRAPHIC AND BATHYMETRIC SURVEYS OF DOWNSTREAM VALLEY	1
3. PROGRAM OF ADDITIONAL INVESTIGATION WITH IN SITU AND LABORATORY TESTS TO CHARACTERIZE THE MECHANICAL AND HYDRAULIC PROPERTIES OF THE DAM'S EMBANKMENTS AND FOUNDATION, INCLUDING DETECTION TECHNIQUES OF INTERNAL EROSION PHENOMENA	1
4. MONITORING DEVICES	
4.1 Mapping of dam's monitoring devices in operation/local repairs	1
4.3 Installation of the monitoring devices specified in the revised observation plan	2
5. DAM-FOUNDATION REHABILITATION WORKS	3
6. INSTALLATION OF WARNING AND ALERT SYSTEMS, COMMUNICATION MEANS, AND OTHERS DEFINED IN THE INTERNAL EMERGENCY PLAN	3
7. INTERVENTIONS IN THE HYDROMECHANICAL EQUIPMENT	2
8. INTERVENTIONS IN THE ELECTRICAL EQUIPMENT AND INSTALLATIONS	2

1	< 4 months
2	< 12 months
3	< 24 months

REFERENCES

- [1] MDSR (2017), "Mozambique Dam Safety Regulation"
- [2] COBA, LNEC and SALOMON (2024), "Technical Report. Massingir dam", Product 2 of the *Consulting Services for Dam Safety Assessment of Pequenos Libombos and Massingir Dams*
- [3] COBA, 1974, Drawings from the Technical Assistance to construction.
- [4] COBA, LNEC and SALOMON (2024), "Inspection Report. Massingir dam", Product 2 of the *Consulting Services for Dam Safety Assessment of Pequenos Libombos and Massingir Dams*
- [5] COBA, LNEC and SALOMON (2024), "Safety Assessment Report. Massingir dam", Product 3 of the *Consulting Services for Dam Safety Assessment of Pequenos Libombos and Massingir Dams*