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Real-Time and Full-Scale Numerical Analysis and Monitoring of Displacements in the Left Bank of the Tabellout RCC Arch Dam during Construction and Operation, Jijel Province, Algeria

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ABSTRACT

This study provides a comprehensive evaluation of the Tabellout RCC dam in Jijel Province, Algeria, a unique structure classified as a combined gravity-arch dam. It addresses critical geotechnical, hydraulic and structural stability aspects, presenting significant contributions to the field of dam engineering by advancing the understanding of the interaction between RCC layers and adjacent slopes under operational conditions. This research employs real-time, full-scale numerical modelling using "Plaxis 2D," with a particular focus on arch behavior. The study bridges a gap by integrating hydrostatic and hydrodynamic pressures measured during the initial filling phase into the model, offering insights into the dam's behavior under both static and dynamic conditions. Monitoring of RCC layers across three elevations prior to operation revealed minimal displacements, with a maximum recorded displacement of 1 mm in the critical interaction zone between the RCC and the left bank slope. Post-operation analysis demonstrated uniform deformation across elevations, with a negligible 1 mm variance, confirming the homogeneity of RCC stiffness—an essential factor for structural stability. The safety factor (FoS) analysis confirmed stability under static conditions, but highlighted vulnerabilities under seismic conditions, underscoring the need for enhanced resilience measures. This work extends findings from previous studies, particularly by validating the importance of a seismic belt at the foundation, through detailed numerical analysis and comparison with real-time monitoring data from PDL pendulums.

1 Introduction

Dams play a fundamental role in water resource management [1], especially under changing climate scenarios [2], serving critical functions such as supplying drinking water [3], generating hydroelectric power [4], mitigating flood risks,

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and regulating river flows [5]. Among the various types of dams, arch dams stand out due to their structural design, which allows them to withstand high hydraulic loads by laterally transferring forces to the abutments on the riverbanks [6]. Despite their apparent robustness, arch dams remain vulnerable to various challenges, including changing geotechnical conditions [7], seismic events [8, 9], and the effects of material aging [10].

The selection of the type and optimal location of a dam depends on the site's geology, topography, and specific characteristics [11, 12]. In Algeria, the construction of dams has significantly increased since the colonial era, with projections reaching 139 dams by 2030, highlighting their strategic importance for the country. Arch dams, in particular, are favored for their material efficiency and adaptability to varied geological conditions. However, their design requires stringent measures to ensure the stability of the abutments and arches that make up the structure.

The safety assessment of arch dams relies on continuous monitoring [13], precise numerical analyses, and rigorous modelling of the loads they are exposed to, such as hydrostatic pressures, thermal fluctuations, and seismic shocks [14]. Technological advancements, particularly the use of numerical simulation software, have enhanced our understanding of dam behaviour under various loading conditions [15, 16].

Despite these advances, the maintenance and monitoring of dams remain critical challenges to prevent failures [17], which can result from material degradation [18], inadequate design [19], or extreme environmental conditions [20]. Dam failures have potentially catastrophic consequences, underscoring the importance of regular inspections and the implementation of corrective measures to enhance the safety of these infrastructures [21].

This study fits within this context, focusing on the analysis of the Tabellout Dam, the only gravity-arch dam in Algeria, by evaluating its geotechnical and structural stability to enhance its resilience against dynamic risks such as earthquakes and geotechnical failures.

2 General Overview of the Tabellout Dam

The Tabellout Dam serves as the intermediate reservoir within the "East" system of the "Sétif-Hodna" transfer project (Figure 1).

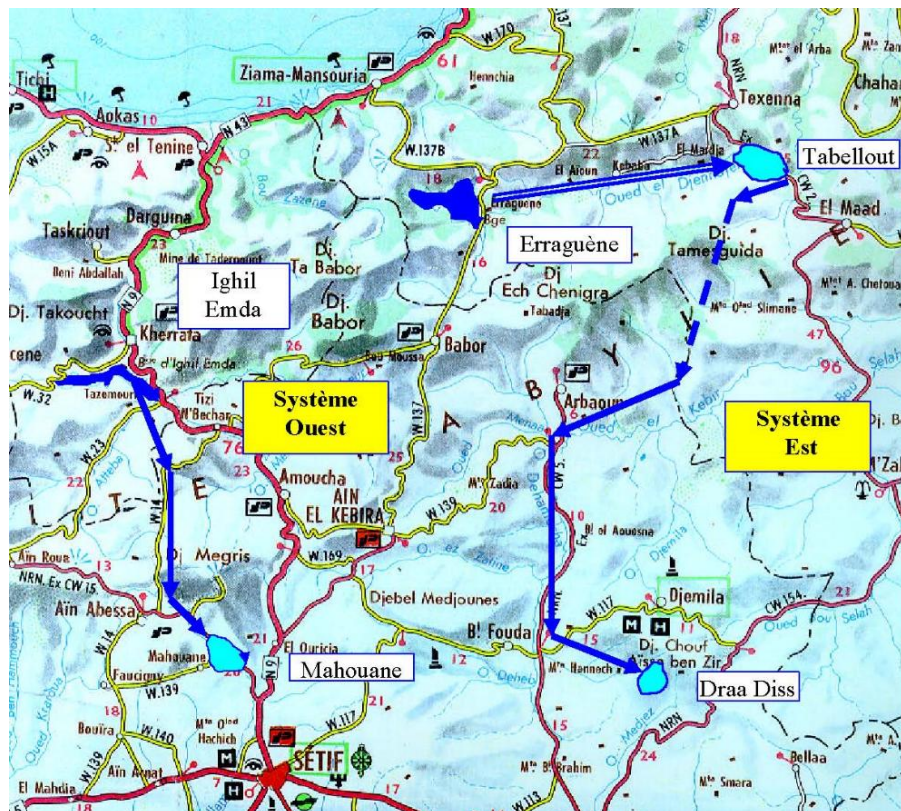


Fig. 1 – Sétif-Hodna Transfer Project - Location Map of Proposed Structures [23].

It is located on the Djendjene River, immediately downstream of its confluence on the right bank with the Raha River. This reservoir collects water transferred by gravity from the existing upstream Erraguène Dam before it is pumped into the planned downstream Draa Diss reservoir [22]. From there, the water will be distributed through networks to the El Eulma region for irrigation and potable water supply. The pumping station that extracts water from the Tabellout reservoir is situated in the eastern branch of the reservoir, which is fed by the Raha River, at the bottom of the Grou River valley, a left-bank tributary of the Raha River. The station is located approximately 2.5 km (as the crow flies) from the Tabellout Dam site. The Tabellout site is located approximately 7.5 kilometers (as the crow flies) southeast of the Texenna commune. The site is easily accessible from Texenna via the CW2 road, which connects Jijel to the north and Fedj'M'Zala to the south. At the dam site, the Djendjene River and its tributary, the Raha River, drain a catchment area of 402 km², of which 133 km² are intercepted by the existing Erraguène Dam [23].

2.1 Geological and Geotechnical Analysis of the Tabellout Dam Site

The Tabellout Dam site (Figure 2) is characterized by a foundation primarily composed of schistose phyllades with quartz veins, ranging from phyllitic to gneissic in nature [24].

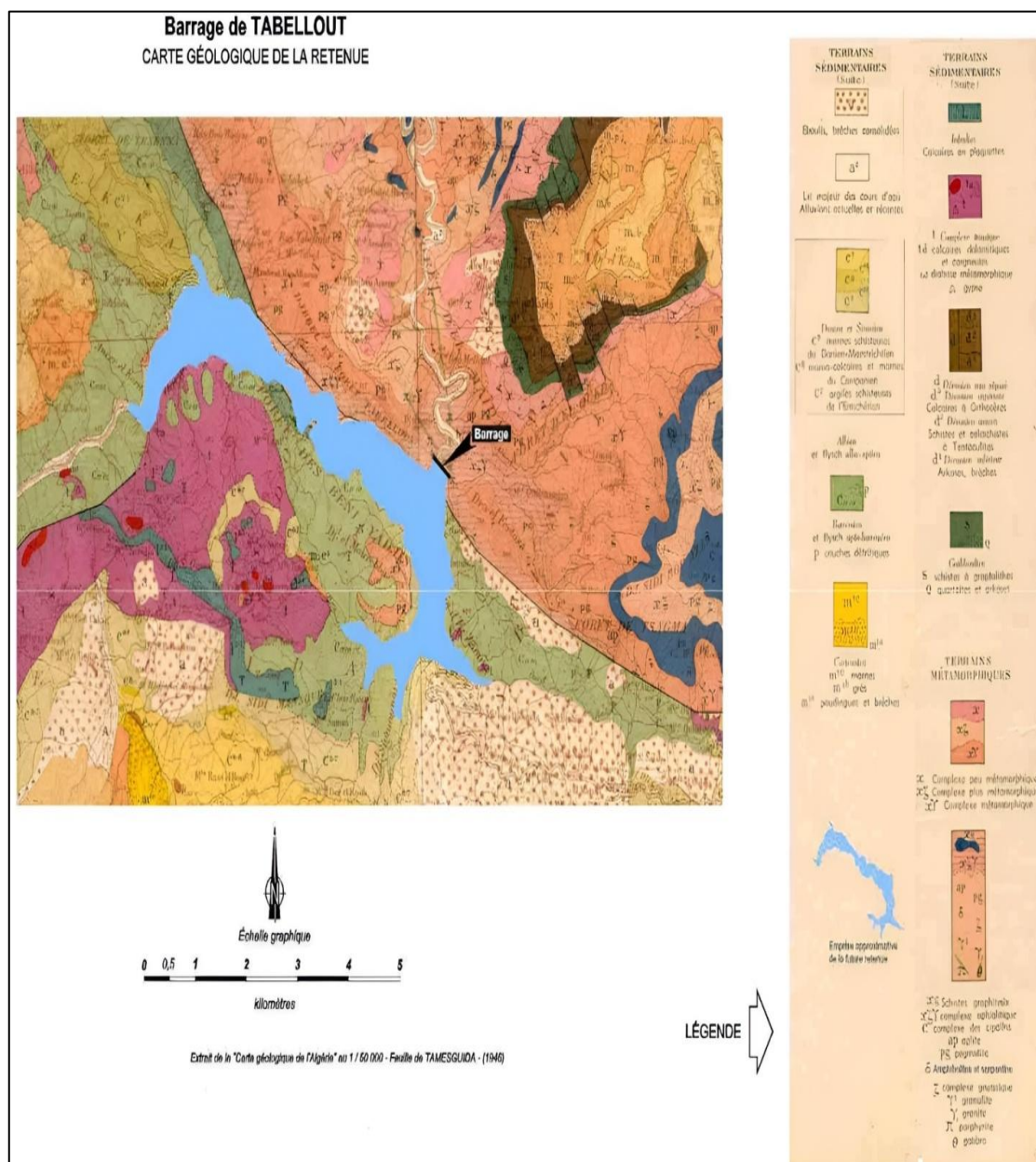


Fig. 2 – Geological Map of the Tabellout Dam Reservoir [28].

The bedrock consists of highly fractured schistose and quartzitic crystalline schists, with foliation generally oriented at 115° North-East, nearly parallel to the dam's axis [25]. The bedding dips from upstream to downstream, averaging 30° on the right bank and 15° on the left bank [26]. This unfavorable dip and the fractured nature of the rock necessitate excavation to reach less fissured bedrock and require the construction of multiple berms on the foundation slopes to maintain excavation stability [27].

The dam's location is marked by significant geological challenges, including a large rockslide on the right bank at the gorge entrance (figure 3). This led to the decision to construct a Roller-Compacted Concrete (RCC) gravity dam with minimal impact, especially given two additional landslides on the right bank—one in the middle of the gorge and another immediately downstream of a pronounced bend in the river [29]. Due to these conditions, alternative designs, such as alluvial and rockfill dams proposed by PROMON, were abandoned since the dam and the spillway's footing intersected these unstable areas. The RCC dam impact remains within the landslide zone in the middle of the gorge, necessitating complete excavation in this area, resulting in a substantial excavation depth ranging from 15 to 20 meters vertically. Outside these well-identified rockslide and landslide zones on the right bank, a SE-NW trending lineament was discovered, which intersects the rockslide on the right bank upstream and extends into the left bank, cutting through the dam's axis and the alignment of the temporary diversion tunnel. Due to safety concerns, in-situ observations on both banks were not possible, making it challenging to ascertain the origin of this feature [30]. A hypothesis of an active fault remains, which could have severe implications for the project [31].

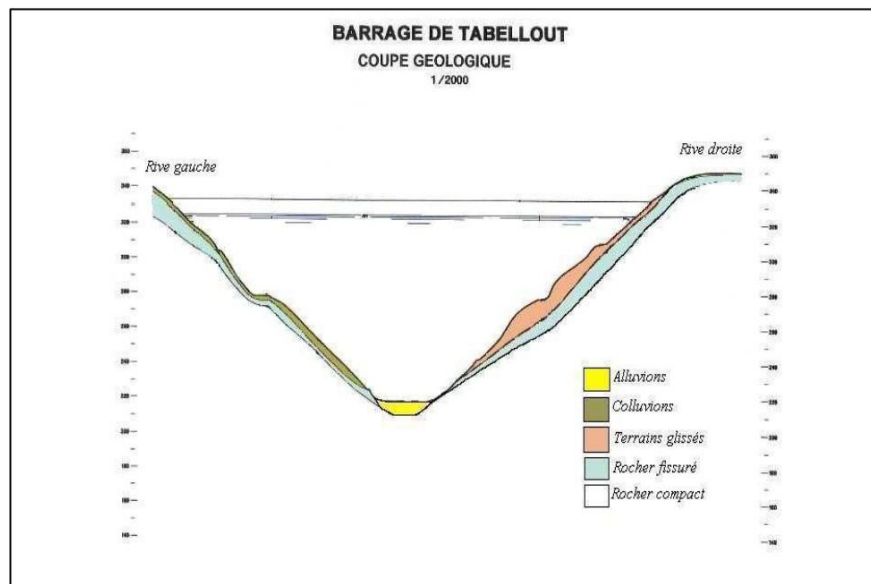


Fig. 3— Geological section of the Tabellout dam.

2.1.1 Right Bank

The bedrock is intact beyond the colluvium, superficial alteration zones, and landslides or collapsed areas. In the absence of the recommended reconnaissance galleries, it can be cautiously estimated that the landslide within the dam area has a vertical thickness of about twenty meters. At this stage of the Detailed Preliminary Design (APD), there is no entirely satisfactory explanation for the origin of this landslide (possibly an unfavorable dip of the schistosity toward the downstream side with the presence of more schistose layers?). The upstream collapse is estimated to have a thickness of around forty meters. Its origin may lie in the erosion of the slope's base by the Djendjene River, which would have removed the foot support of the massif.

2.1.2 Valley Floor

The bedrock in the valley floor is covered by coarse alluvium (blocks of quartzite, sandstone, and limestone with pebbles, gravel, and sand) with a thickness not exceeding about ten meters. The bedrock is intact and does not show any fissured and/or altered zones.

2.1.3 Left Bank

Unlike the right bank, there are no areas with landslides. The bedrock is similar to that of the right bank and the valley floor, consisting of schistose, quartzitic, sometimes phyllitic, and sometimes gneissic phyllades. Some sections are more fissured and/or fractured.

Based on the initial investigations conducted on-site, the Young's modulus of the foundation can be considered as 20,000 MPa. The Poisson's ratio of the foundation soil is taken as 0.18. According to the results obtained from core sample testing, the wet density of the rock is 2,900 kg/m³.

2.2 Topography of the Dam site

The Tabellout site is mapped topographically by the Tamesguida topographic map at a scale of 1:50,000 (Sheet 49) [28]. Based on the topographic data established by PROMON in 1990, which were found to be incomplete and inaccurate during feasibility studies conducted by EDF in December 2000, a detailed topographic survey at a 1:5,000 scale was carried out by the MATH Topography Company between 2000 and 2001, at the request of EDF. Due to the high costs associated with a full survey of the future reservoir and logistical challenges related to safety measures on site, only 50% of the total reservoir area (355 hectares from the valley floor to elevation 340.00 NGA) was surveyed. Despite these limitations, this survey allowed for necessary corrections to the PROMON survey, facilitating the development of a general plan for the reservoir and the accurate determination of the future reservoir's height-capacity curve. Additionally, during the same period, MATH conducted a topographic survey at a 1:1,000 scale over a 90-hectare area of the dam site [22]. This survey was crucial for the design studies of the dam and its ancillary structures. The dam site is located at the entrance of the narrowing Djendjene Valley, which has carved a gorge through Paleozoic metamorphic formations. At the gorge, where the dam is to be constructed, the riverbed sits at an average elevation of 217 NGA, with the minor and major stream widths averaging about 10 and 40 meters, respectively. The banks are relatively steep, sloping at approximately 40° to the horizontal, while the Djendjene River bed itself has a gentle gradient of about 1%. Approximately 150 meters downstream from the dam's base, a narrow spur rising to around 280 NGA forces the river to make a sharp 90° meander eastward [23].

2.3 Seismic risk of the Dam site

The studies conducted in 2000 for all dam sites of the Sétif Hodna transfer project identified the reference earthquake for the Tabellout site;

Tables must be embedded into the text and not supplied separately. Below is an example which the authors may find useful.

Table 1 - Characteristics of the reference earthquake for Tabellout site [23].

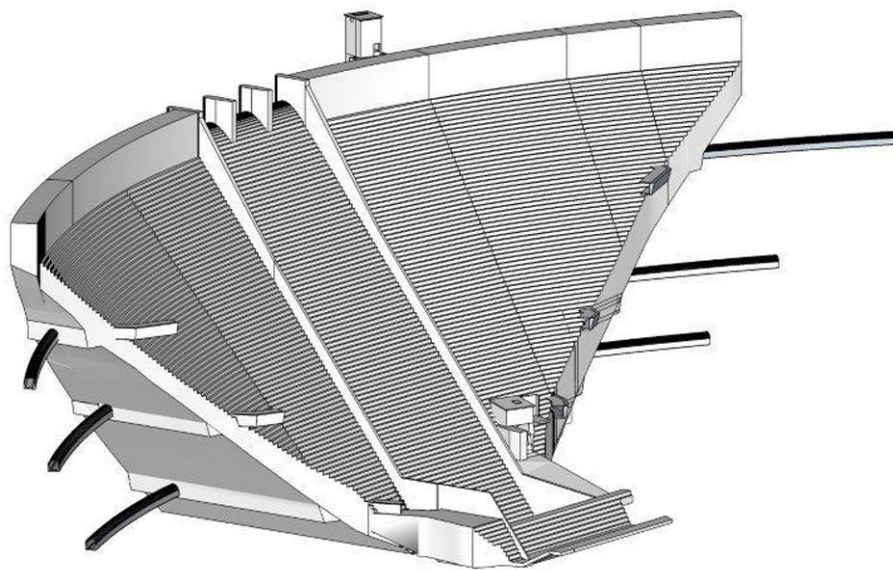
Reference earthquake	21/08/1956
Epicentral intensity I_0	VIII MSK
Magnitude M	5,54
Depth h	11 km
Distance to epicenter - D	0 km
Induced intensity on the site - I_s	VIII MSK
Maximum ground acceleration	0,20 g

A recent seismic study carried out as part of the APD (Detailed Preliminary Design) for the Boussiaba Dam [32] confirmed the characteristics of this earthquake. However, the acceleration to be considered at the Tabellout site would now be 0.163 g instead of 0.20 g. Since 2001, the spectrum library of the IRSN (Institute of Radioprotection and Nuclear Safety – France) has been updated to consider a spectrum limit value at 33 Hz instead of 25 Hz. However, the acceleration of 0.163 g is currently subject to significant uncertainties, particularly regarding the intensities and epicentral locations of earthquakes

before the 19th century. Given these uncertainties, we prefer to retain, for the dam stability studies, the same characteristics as those defined in the feasibility studies carried out in 2000, namely a maximum ground acceleration of 0.20 g.

2.4 Site Selection and Design of the Tabellout Dam

The site chosen for the dam and reservoir corresponds to the location identified during preliminary studies conducted by the PROMON consulting firm in 1990 and later confirmed by a feasibility study carried out by EDF in December 2000 [23]. The topographical and geological constraints associated with the Tabellout dam site led EDF, as early as the feasibility study phase, to select a Roller-Compacted Concrete (RCC) structure (Figure 4) as the most suitable design for the location [31]. The structure includes an integrated spillway aligned with the riverbed of the wadi. The dam's axis was modified from the alignment defined by PROMON; it was shifted as far upstream as possible from the pronounced bend of the Djendjene wadi on the left bank. This adjustment minimizes the natural obstacle posed by the bend, ensuring that it interferes as little as possible with the downstream flow from the spillway.



(a)



(b)

Fig. 4 – a) 3D Design of the Tabellout Arch-Gravity Dam [22]; b) Photo of the Tabellout Arch-Gravity Dam in RCC before its Exploitation.

2.4.1 Reservoir Capacity and Elevations

The storage capacities of the Tabellout reservoir were calculated based on a partial topographic survey of the basin at a scale of 1:5000, conducted by the MATH company during 2000-2001. The areas of the basin that were not covered in this survey were defined using previously corrected PROMON topographic data [22, 23]. The curve illustrating the variation of the reservoir volume as a function of the water level is presented in the figure (5).

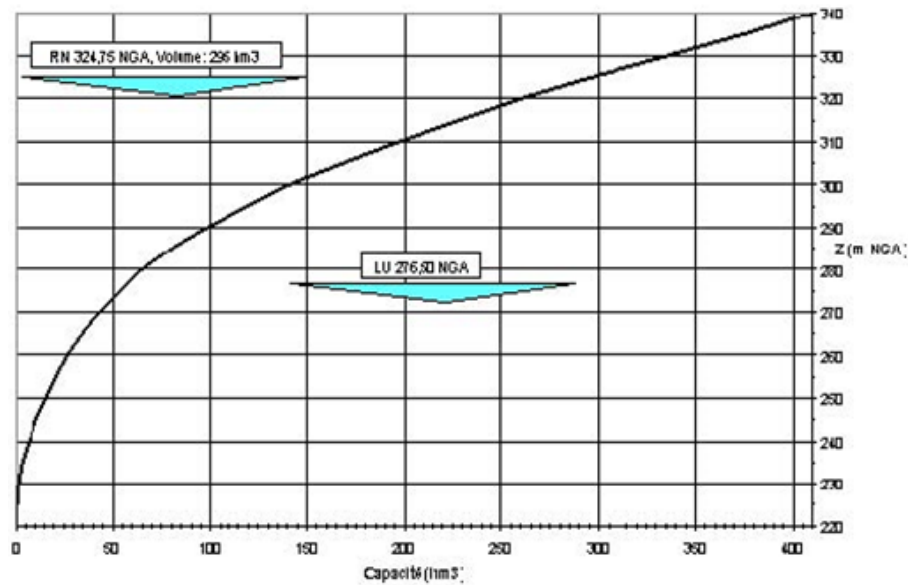


Fig. 5 – Height-Capacity Curve of the Tabellout Reservoir (excluding sedimentation).

The total storage capacity of the reservoir below the Normal Retention Elevation (NRE/ or RN) of 324.75 NGA is 294.40 million cubic meters. The dead storage capacity is 80 million cubic meters, with sediment deposition distributed such that the siltation level reaches an elevation of 276.50 NGA at the dam axis, which is defined as the Limit of Useful Exploitation (LUE/ or LU).

Table 2- summary of reservoir levels and capacities.

Crest elevation of the dam	332,00 NGA
Highest Water Level (HWL)/ or (PHE)	329,45 NGA
Highest Water Level during the passage of the Probable Maximum Flood (PMF) / or (CMP)	330,65 NGA
Normal Retention Level (NRL) / or (RN)	324,75 NGA
Usable Limit Level (ULL) / or (LU)	276,50 NGA
Total capacity	294,40 hm ³
Dead storage	80 hm ³
Usable Operating Capacity	214,40 hm ³

2.4.1.1 Spillway Capacity

The spillway is defined at elevation 324.75 NGA, corresponding to the normal retention level (NRL). It consists of an open crest 45.0 m wide, divided into three bays of equal width, separated by piers. The total length is 51 m. Downstream of the crest, there is a chute that is 51 m wide, formed by 1.20 m high steps, leading to a dissipation basin founded on rock with a length of approximately 12 m, and a Roller Compacted Concrete (RCC) threshold at elevation 219.00 NGA. A riprap layer provides a transition between the downstream foot of the RCC threshold and the natural riverbed. For the design flood with a peak flow rate of 1,953 m³/s, and considering the attenuation in the reservoir, the flow to be discharged is approximately

981 m³/s, with a theoretical maximum elevation of 329.45 NGA. The diagram below, based on the scaled model, shows the relationship between reservoir level and spillway discharge.

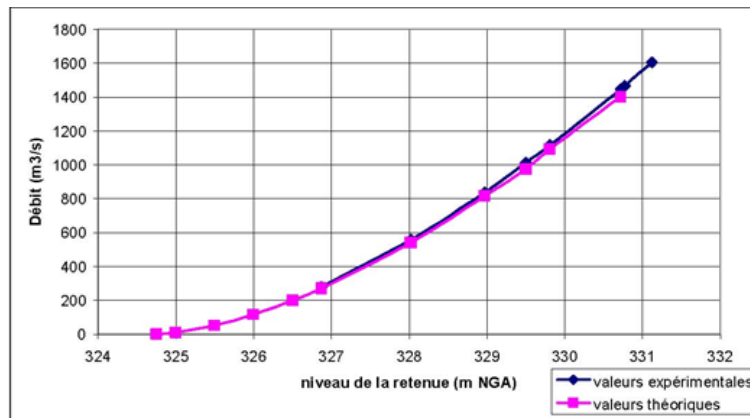


Fig. 6– Theoretical and experimental "height-discharge" laws of the spillway.

2.4.2 RCC Mix Design for the Dam Construction

Construction of the Roller Compacted Concrete (RCC) dam began on March 16, 2013, on the right bank. For blocks M1 to M5 (blocks 3, 4, and 5), the cement dosage was initially increased to 135 kg/m³ with the approval of the Directorate but was subsequently maintained at 130 kg/m³. During a coordination meeting on February 19-20, 2013, the Administration established several guidelines for RCC production, including adopting a VeBe consistency time of 19-21 seconds with a ± 1 -second tolerance (VeBe test with an approximate 12 kg surcharge), using a bonding mortar with a 20 cm slump and 10 mm thickness between layers, and utilizing Enriched RCC (RCC-E) for upstream and downstream facings with 20 l/m² of grout (figure 7) [22, 31].

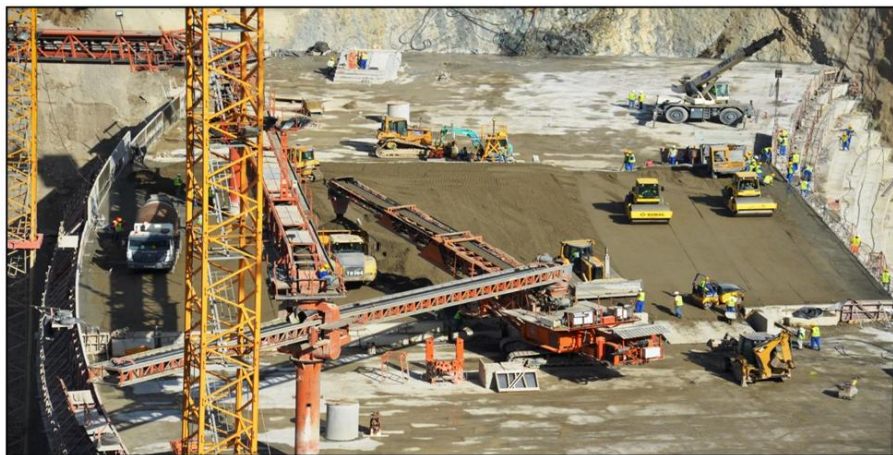


Fig. 7– RCC on Layer, with Crawler Placer and Trucks.

From May 11, 2014, until October 20, 2014, when external temperatures exceeded 29°C, a setting retarder admixture, "Plastiretard SIKA" at 1.2% of the cement weight, was incorporated as requested by the Administration [23, 31]. This was to prevent premature drying before compaction and to enhance adhesion between layers of the same block. Laboratory tests demonstrated that the retarder significantly improved workability and final strength (figure 8).

However, on June 25, 2014, instructions were issued to discontinue the retarder for the fourth layer, even if temperatures were above 29°C. The use of the retarder concluded on October 20, 2014, with the sampling of series B 574. The composition and dosage of the standard RCC formulations used until February 28, 2015, are summarized in Table (3), covering the construction of plots 1 and 2 of massif 80 (level 306), plots 3, 4, and 5 of massif 79 (level 304.8), plot 6 of massif 78 (level 303.6), and plots 7 of massif 77 (level 302.4).

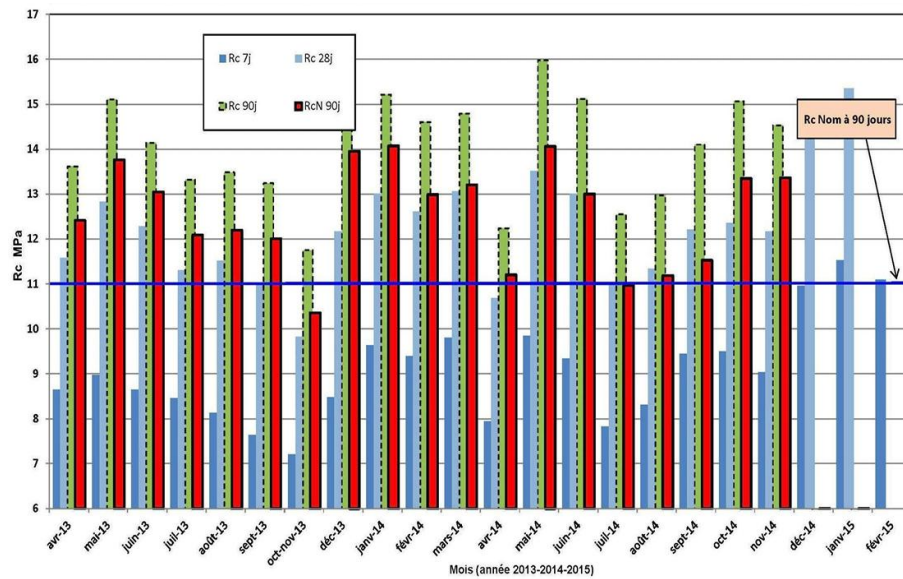


Fig. 8– Monthly Average Strengths at 7, 28, and 90 Days, and Nominal Strength at 90 Days.

Table 3- Standard RCC Concrete Mix Designs Used on Site.

Mix Design	Series Numbering	Start of manufacturing date	Cement dosage	Filler dosage	Composition of RCC (% - Kg/m ³)			
					Filler % - kg	Sand 0-5mm % - kg	Gravel 5-20mm % - kg	Gravel 20-63mm % - kg
F1- B135 T 140	B1 – B6 et B22 – B33	16/03/13	135 kg	141 kg	6,5-141	35,5-746	30,0-656	28,0-619
F2 - B130 T145*	B7-B8	02/04/13	130 kg	145 kg	6,8-145	35,2-740	30,0-656	28,0-619
F3- B130 T140	B9 – B21 et B34 – Actuel	07/04/13	130 kg	141 kg	6,5-141	35,5-746	30,0-656	28,0-619
F4 - B130 T140** 1,2% Plastiretard	B325 – B574 until 20/10/14	11/05/14	130 kg	141 kg	6,5-141	35,5-746	30,0-656	28,0-619

*Mix Design Used Only on April 2, 2013, Only if the external temperature is $\geq 29^{\circ}$

It should be noted that from May 11 to October 20, 2014, with the use of the setting retarder (Formula F4), compressive strength values increased by approximately 20% compared to RCC (Formula F3) without the retarder (Comparative table below):

Table 4- RCC Average Compressive Strength Values at 7, 28, and 90 Days Without and With Retarder.

Mix Design	Average compressive strengths (as of January 25, 2015)		
	7 days	28 days	90 days
F3-B130-T140	9.2 MPa	12.4 MPa	14.0 MPa
F4-B130-T140 (With 1.2% retarder)	11.3 MPa	14.8 MPa	17.5 MPa

Since November 2013, the company's laboratory (RAZEL) has been conducting core drilling on RCC layers after compaction (4-5 days) using a 150 mm diameter, 600 mm depth core drill (Figure 9). A "Hilti model" coring machine is used on the top layer of the block and progressively at the end of each layer. Three cores are taken—one downstream and two upstream—to obtain representative samples from the last and second-to-last layers (C4 and C3) of the block and massif. The average recovery length of the cores is approximately 50-60 cm.



Fig. 9 – a) RCC cores taken by the laboratory on Plot 1 of Massif 76 and Plot 5 of Massif 75 with a diameter of 150 mm. b) Hilti coring machine capable of reaching a depth of 60 cm on the RCC layer.

These cores allow for the assessment of the bonding condition between layers 4 and 3 of the RCC at upstream, central, and downstream positions, the density of the RCC after compaction, the texture and homogeneity of the RCC, which are influenced by the presence or absence of the retarder, and the Modulus of Deformation (Table 5). The following table summarizes the positions of the core samples, the strength values of the cores compared to the test specimens, and the modulus of deformation values of the cores:

Table 5- Results of compressive tests on cores and specimens of the RCC from the dam (4th and 3rd layers)

Reference Block	Date of Concreting	Date of Core Sampling	Date of Compressive Testing	Age at Testing (days)	Modulus of Deformation of Cores in MPa	Compressive Strength of Cores in MPa	Compressive Strength of Specimens in MPa
12	06/06/2013	25/09/2013	03/10/2013	119	-	10,5	15,7
19	22/08/2013	27/08/2013	11/12/2013	111	-	9,2	10,2
21	05/09/2013	17/12/2013	18/01/2014	135	-	10,5	16,4
26	29/09/2013	21/12/2013	28/12/2013	90	-	9,9	12,3
29	12/10/2013	23/12/2013	10/01/2014	90	-	9,1	10,3
33	31/10/2013	28/12/2013	29/01/2014	90	3431	7,1	10,9
35	06/11/2013	29/12/2013	04/02/2014	90	4568	6,9	11,5
Core samples taken after Coordination Meeting No. 33 on January 28, 2014							
30	18/03/2014	21/03/2014	16/06/2014	90	3970	8,4	12,3
36	24/04/2014	28/04/2014	23/07/2014	90	2915	8,3	12,6
38	11/05/2014	15/05/2014	09/08/2014	90	4891	9,7	16,3 + retarder
39	19/05/2014	26/05/2014	17/08/2014	90	-	11,8	15,8
39	21/05/2014	24/05/14	19/08/2014	90	-	11,7	22,6 + retarder
42	09/06/2014	12/06/2014	07/09/2014	90	4341	8,1	15,7
42	05/06/2014	09/06/2014	03/09/2014	90	4555	10,1	17 + retarder
45	19/06/2014	24/06/2014	17/09/2014	90	3737	10,5	15,8
50	31/07/2014	04/08/2014	29/10/2014	90	3708	9,0	13,8
50	30/07/2014	02/08/2014	28/10/2014	90	6296	15,1	18,6 + retarder
53	18/08/2014	23/08/2014	16/11/2014	90	3305	8,7	13,6
54	27/08/2014	31/08/2014	25/11/2014	90	7962	9,6	10,9
58	17/09/2014	20/09/2014	16/12/2014	90	6250	9,5	14,0
62	07/10/2014	11/10/2014	05/01/2015	90	6562	10,7	15,3
62	02/10/2014	06/10/2014	31/12/2014	90	3588	13,1	21,7 + retarder
63	12/10/2014	15/10/2014	10/01/2015	90	3485	8,3	16,3
63	14/10/2014	19/10/2014	12/01/2015	90	3646	12,2	17,0 + retarder
65	23/10/2014	27/10/2014	21/01/2015	90	6669	8,7	12,6
68	12/11/2014	12/11/2014	10/02/2015	90	4701	10	15,5

2.4.3 Monitoring of RCC before Exploitation: Crack Meters (Joint Monitors)

The installation of "vibrating wire crack meters" began on June 17, 2013, between plots 4 and 5 at section PM 182 at elevation +225 (Figure 10). As of February 28, 2015, the installation of crack meter KA 24, between plots 6 and 7 at section PM 82.4 (figure A1), remains pending. The reference reading will be established once the readings become stable over several consecutive days.



Fig. 10– Installation of the Crack Meter between Plot 4 and 5 (Before and After Sealing).

Starting from June 17, 2013 (Figure 11), displacement variations ranging from 0.3 mm to 0.6 mm were observed at measurement points KA1 (upstream) and KA2 (downstream) in section PM 182 (figure A1), which marks the beginning of the left bank relative to the center of the dam, at elevation +225, representing the dam's base or first tier. This trend persisted until January 1, 2014, where stability in displacement around 0.2 mm was noted. By August 23, 2024, a slight increase to 0.5 mm was detected, continuing until February 19, 2015. On January 19, 2014, a displacement initiation of 0.2 mm to 0.3 mm was recorded at measurement point KA3, located at the core of the dam in the same section and at the same first tier, but at a higher elevation of +235. In the middle of the dam, from May 10, 2014, no significant displacement was observed at KA4, at elevation +255, marking the beginning of the second tier (figure A1). This remained unchanged until November 21, 2014, when a slight movement of 0.1 mm was detected, continuing until March 1, 2015. From August 23, 2024, to March 1, 2015, similar displacement patterns were observed at KA5, located at elevation +275 in the middle of the dam. A displacement of 0.3 mm was recorded at KA6, at elevation +292 in the third tier (figure A1), from December 1, 2014, with a slight decrease by March 9, 2015. Finally, measurement point KA7, located at elevation +305 in the third tier (figure A1), showed negligible movement only between February 9 and March 1, 2015. In summary, the three main tiers showed maximum displacement values of around 0.5 mm over a two-year period, whether upstream, downstream, or in the core of the dam, before its exploitation phase.

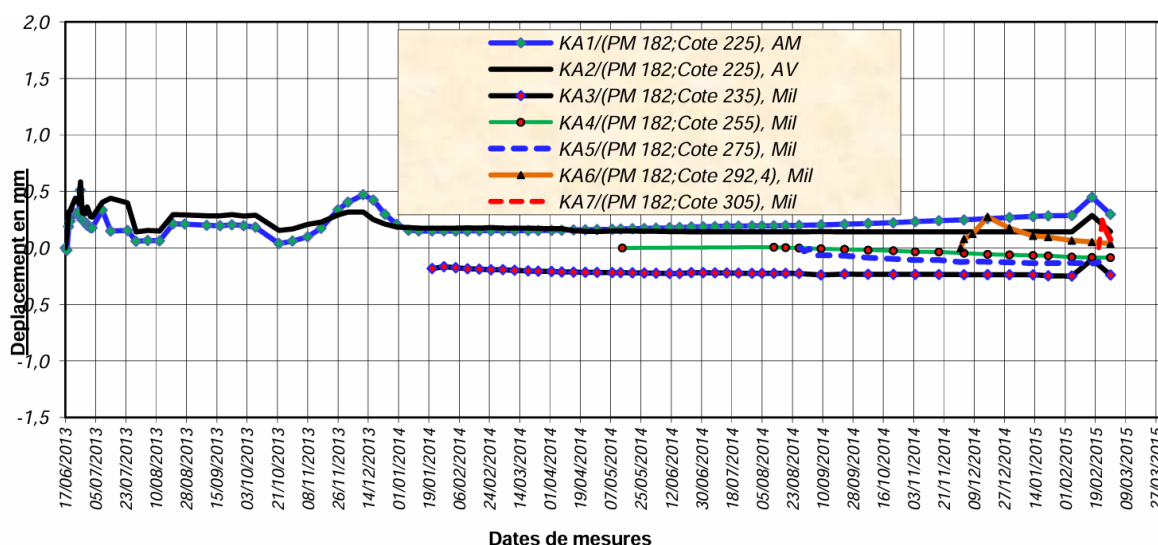


Fig. 11– Crack Meter Monitoring at PM 182, Left Bank – Crack Meters KA1-KA7: Installed Between Plot 4 and 5 at PM 182.0 on 17/06/2013, 02/01/2014, 14/05/2014, 28/08/2014, and 23/11/2014.

In PM 132 (Figure 12), no significant displacement was observed in the middle of the dam body until March 24, 2015. Only a minor displacement of 0.1 mm was recorded between May 8, 2014, and May 18, 2014, at measurement point KA15 on the first elevation at +255 meters (figure A1). A similar behavior was noted at measurement point KA16 on the second elevation at +275 meters, where a displacement of 0.1 mm was detected between August 26, 2014, and September 5, 2014, followed by no notable displacement until February 22, 2015. A comparable pattern was observed in the third elevation at measurement point KA18 (figure A1), which recorded a displacement of 0.05 mm between March 4, 2015, and March 14, 2015. However, special attention is required at measurement point KA17 on the third elevation at +292.4 meters (figure A1), which registered a significant displacement compared to previous readings, ranging from 0.85 mm on December 4, 2014, to 0.5 mm on March 4, 2015. In summary, no displacement was detected in the first two elevations, except for a notable displacement of 0.85 mm in the third elevation.

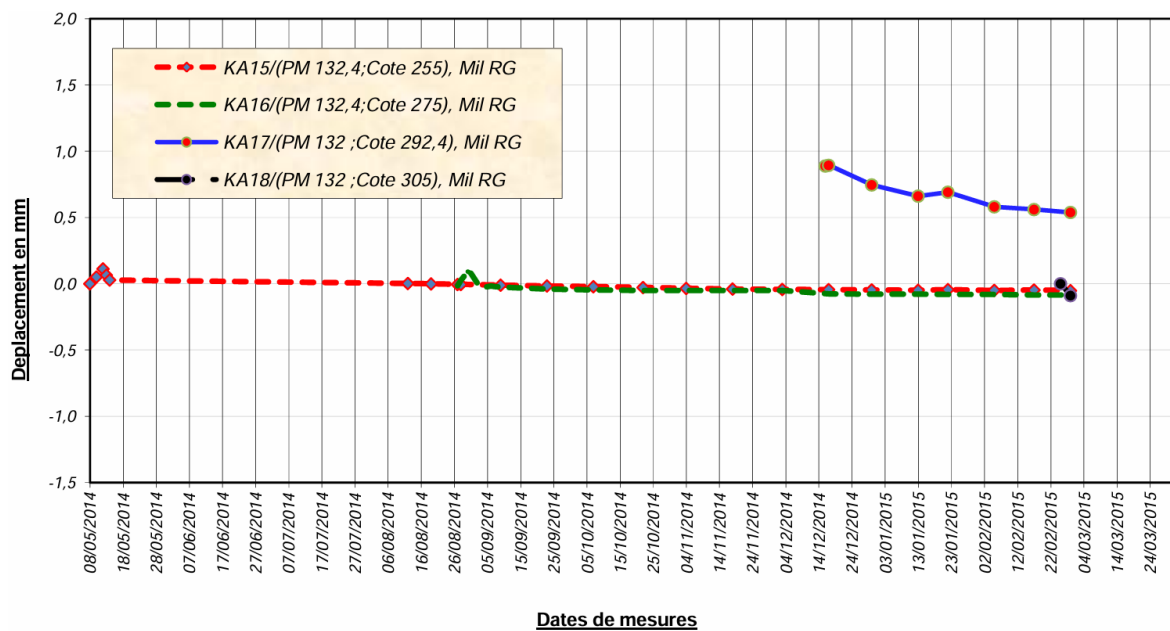


Fig. 12 – Crack Meter Monitoring at PM 132.4, Left Bank – Crack Meters KA15, KA16, and KA17: Installed Between Plot 5 and 6 at PM 132.4 on 08/05/2014, 26/08/2014, and 25/11/2014.

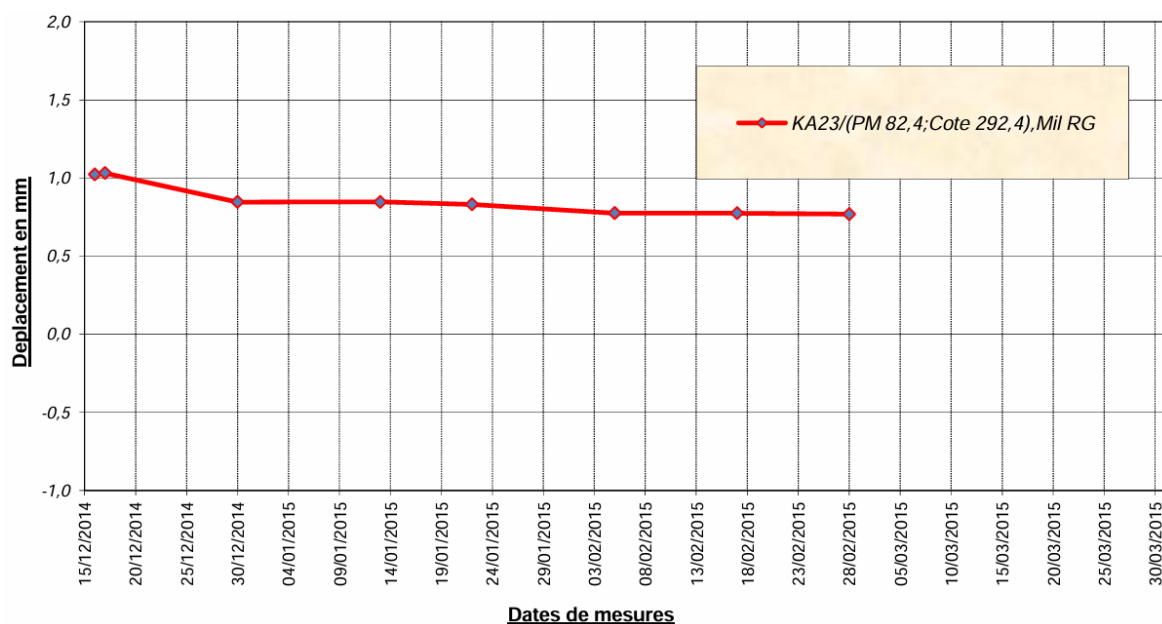


Fig. 13 – Crack Meter Monitoring at PM 82.4, Left Bank – Crack Meter KA23: Installed Between Plot 6 and 7 at PM 82.4 on 25/11/2014.

In the extremity area interacting directly with the left bank slope (figure 13), a displacement of 1 mm was observed at measurement point KA23, located in the middle of the dam at PM 82.4, 3rd elevation +292.4 (figure A1), on December 15, 2014. This was followed by a reduction to 0.8 mm from December 20, 2014, until February 28, 2015. In summary, this represents the most significant displacement compared to previous measurements. This may be attributed to the fact that this area is the most critical, as it marks the interaction zone between the RCC and the rock foundation. It is also notable that the closer we approach the rock, the greater the displacement becomes. This observation emphasizes the necessity of simulating this section to better understand the actual behavior of the dam in this critical zone.

3 Numerical Simulation

Our simulation model (figure A2) has a total width of 550 m, with an extension of 200 m downstream and 200 m upstream, and a height of 250 m. It contains a single layer of shale at a depth of 120 m in its lithology, as excavations were carried out to a depth of 20 m to reach the hard shale layer, aiming to avoid any geotechnical failure beneath the RCC dam. The dam has an arch shape with a height of 121 m and a thickness of 107.76 m at its foundation, gradually decreasing at each elevation until reaching 8 m at the top. The model is generated using a 15-node triangular mesh and is constrained by a system of boundary conditions to control the distribution of stresses and deformations, as well as to prevent undesirable effects at the model's.

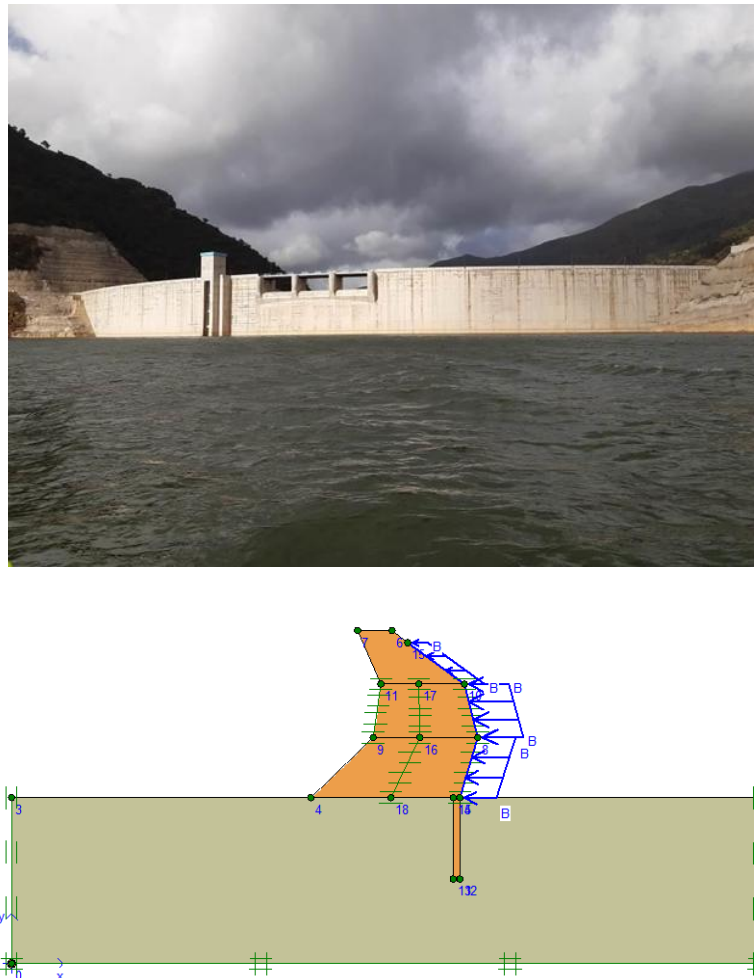


Fig. 14 – The distribution of water pressure on the dam as a function of the water level.

Our numerical modeling consists of eleven (11) main phases, accurately replicating real conditions and full-scale behavior to simulate the dam's performance in real-time and full scale:

- Phase 1: The initial plastic phase, during which the waterproofing wall anchored in the shale layer is installed over a period of ninety (90) days.

- Phase 2: The plastic phase representing the installation of the first elevation of the dam over a period of 240 days.
- Phase 3: The plastic phase representing the installation of the second elevation of the dam over a period of 240 days.
- Phase 4: The plastic phase representing the installation of the third elevation of the dam over a period of 240 days.
- Phase 5: The plastic phase representing the initial filling of the reservoir up to the first elevation over a period of 30 days. It is important to consider that the water pressures (loads in our model equal to approximately 407.90 kN/m²) on the upstream side of the dam at this level (1/3) are actual values, measured by the pressure pendulums installed within the dam at this height (see Table A1, Figure 14, and Figure A2).
- Phase 6: The plastic phase representing the reservoir filling up to the second elevation over a period of 30 days. The water pressures (loads in our model equal to approximately 493.10 kN/m²) on the upstream side of the dam at this level (1/3) are real, measured by the pressure pendulums at this height (see Table A1, Figure A2, and Figure 14).
- Phase 7: The plastic phase representing the reservoir filling up to the third elevation over a period of 30 days. The water pressures (loads in our model equal to approximately 215.80 kN/m²) on the upstream side of the dam at this level (1/3) are real and measured by the pressure pendulums (see Table A1, Figure A2, and Figure 14).
- Phase 8: The consolidation phase, adjusted to calculate the system's deformations.
- Phase 9: The consolidation phase, adjusted again to calculate further deformations of the system.
- Phase 10: The dynamic analysis phase, adjusted to calculate the dynamic effects of water on the dam.
- Phase 11: The final phase involves calculating the Φ/c reduction to determine the safety factor of the system.

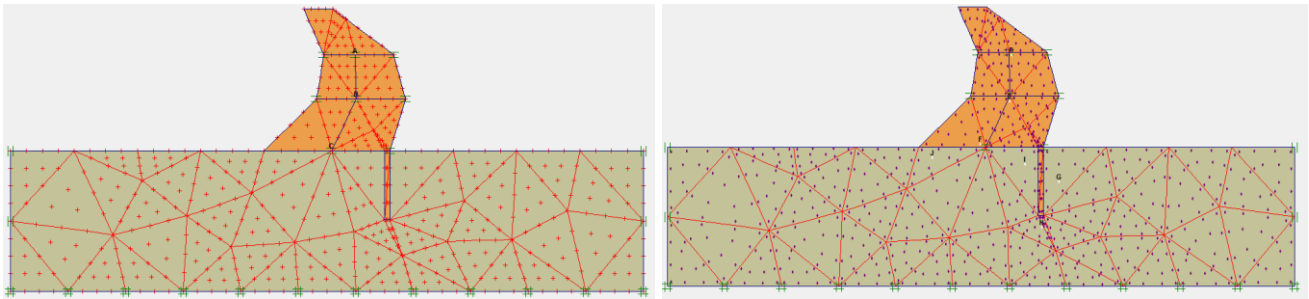


Fig. 15 – Monitoring points in our model.

In order to monitor deformations in our numerical model (Figure 15), we selected points A, B, and C within the body of the RCC dam in our model, positioned at the same locations as the horizontal displacement pendulums in the actual dam. This allows us to accurately track deformations in the dam itself, in real time and at full scale. Additionally, points D, E, and F were chosen at the same locations to monitor stresses in the RCC dam. To track stresses and deformations in the foundation soil, we selected points G and H in the shale layer.

4 Results

After the calculations, we found a total displacement of 11.06 mm in the direction from upstream to downstream (Figure 16-a), which seems logical due to the water pressure exerted on the dam, indicating this is a horizontal displacement. We observed that the main displacement occurs within the RCC dam itself, as well as in the dam's foundation where interaction with the supporting soil (shale) takes place, with a significant reduction in displacement as the depth of the lithology increases, which we consider to be vertical displacement. There is also vertical movement in the soil behind the dam (upstream), with displacement values ranging from 5 to 3 mm up to halfway down the cut-off wall. This is the effect of the reservoir water,

which logically creates tangential pressures on the soil, causing slight settlements. This variation is also notably decreasing from the downstream side to below the dam itself, possibly due to the effect of the dam's own weight.

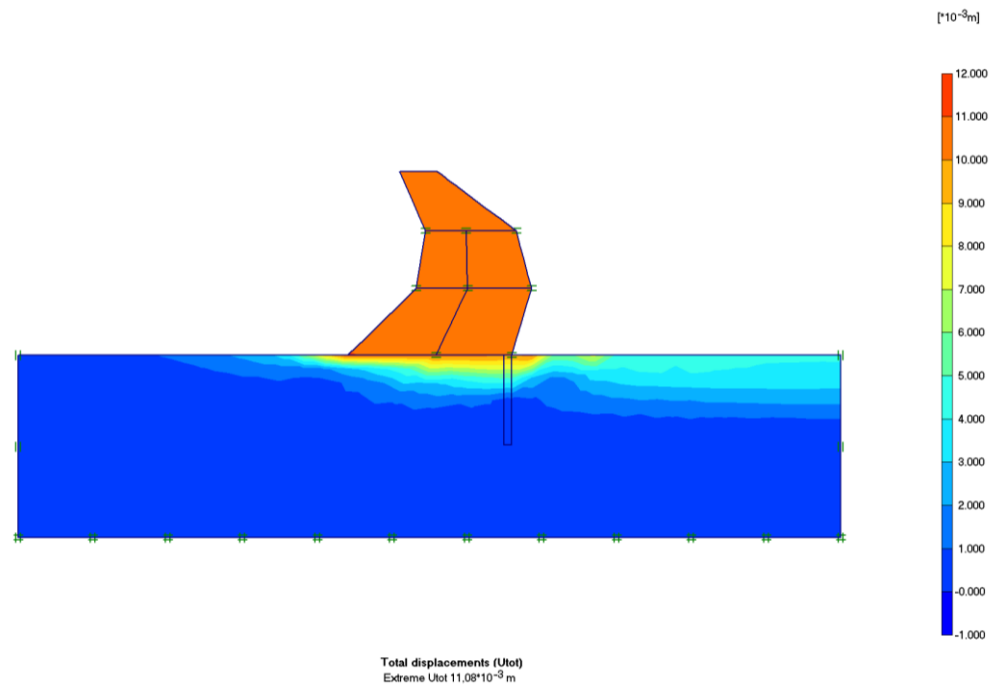


Fig. 16 (a) – total displacement of the dam.

Refer to figure (16-b), which clearly shows the horizontal displacement of 11.02 mm, primarily observed in the RCC dam and in the soil interacting with it, varying between 9 and 7 mm. This displacement gradually decreases with depth beneath the dam, reaching a value of 1 mm at mid-height of the cut-off wall.

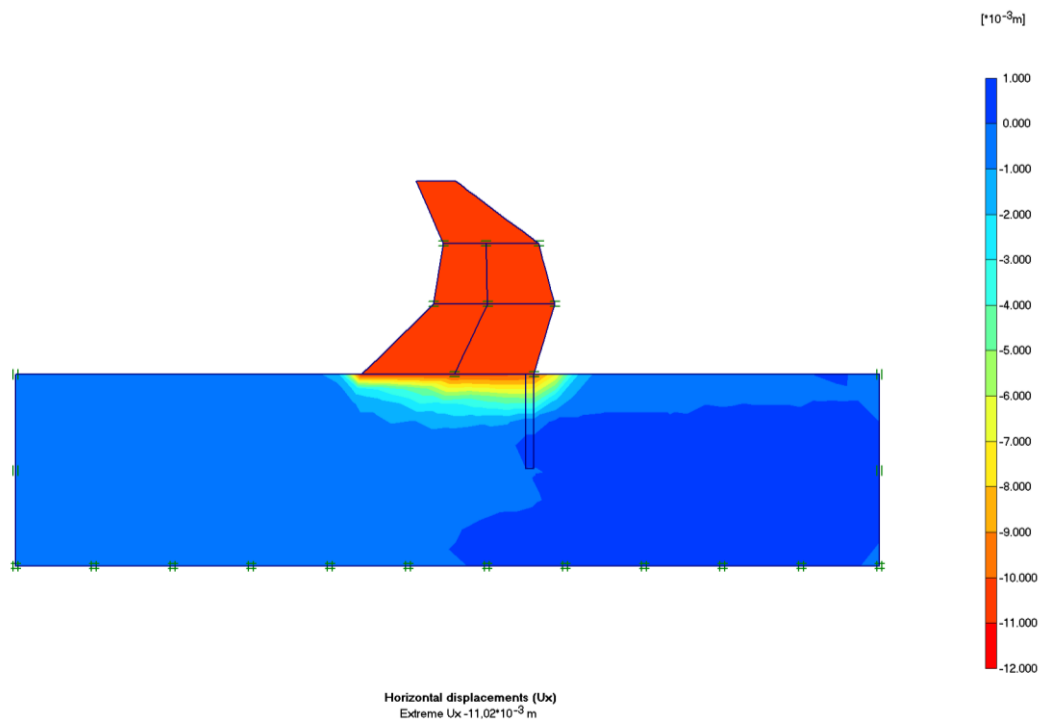


Fig. 16 (b) – horizontal displacement of the dam.

In comparison with the actual measurements of the dam's displacement (Table A2, Figure 17) over a three-month period, from January 14, 2024, to March 10, 2024, we found the following values:

- Pendulum 1-1 recorded horizontal displacement ranging from 0.08 mm to 1.48 mm.
- Pendulum 1-2b recorded horizontal displacement ranging from 0.22 mm to 0.46 mm.
- Pendulum 2-3 recorded horizontal displacement ranging from 0.46 mm to 4.06 mm, respectively.

The pendulums (Figure 17) are primarily designed for measuring horizontal movements in dams, engineering structures, and high-rise buildings. For the Tabellout Dam, the engineering firm equipped the dam with 13 direct pendulums, consisting of a wire anchored at the top of the dam and tensioned by a suspended mass at the bottom. This mass is free within a basin filled with a damping fluid. Additionally, 2 inverted pendulums were installed, with the wire anchored at a fixed point beneath the dam and tensioned by a float at the top. In both cases, the wire represents a vertical reference line.

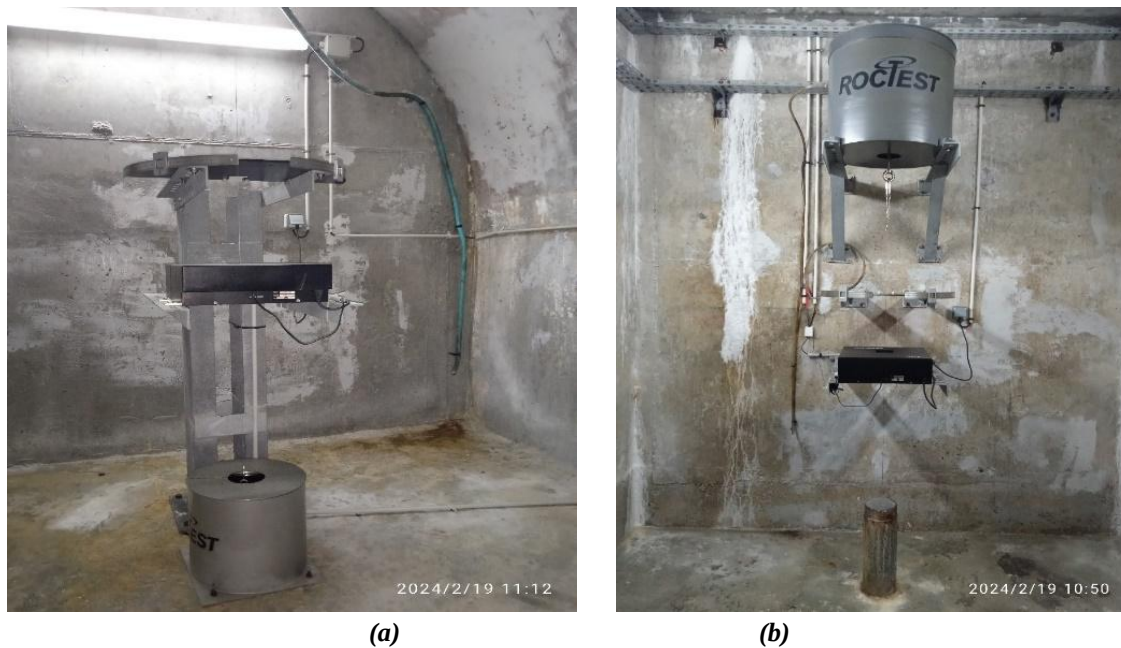


Fig. 17 – (a) direct pendulum, (b) inverted pendulum.

If we break down the stages of the impoundment into three elevation levels, with each elevation corresponding to a pendulum to monitor horizontal displacements in real time, the first elevation shows a horizontal displacement of 2.67 mm (Figure 18-a), as represented by Pendulum 2-3, which records a value of 3.08 mm (Table A2-a), resulting in a difference of 0.41 mm. This is considered to be nearly consistent.

The second elevation shows a horizontal displacement of 0.87 mm (Figure 18-b), as represented by Pendulum 1-2b, which records a value of 0.57 mm (Table A2-b), resulting in a difference of 0.30 mm. This is considered to be nearly consistent.

The third elevation indicates a horizontal displacement of 1.05 mm (Figure 18-c), represented by Pendulum 2-3, which measures a value of 2.56 mm (Table A2-c), resulting in a difference of 1.51 mm. This is also considered to be nearly consistent.

Consequently, the results (Figure 18-d) are very satisfactory in terms of horizontal displacement, demonstrating a significant level of compatibility, which greatly enhances the credibility of our numerical model.

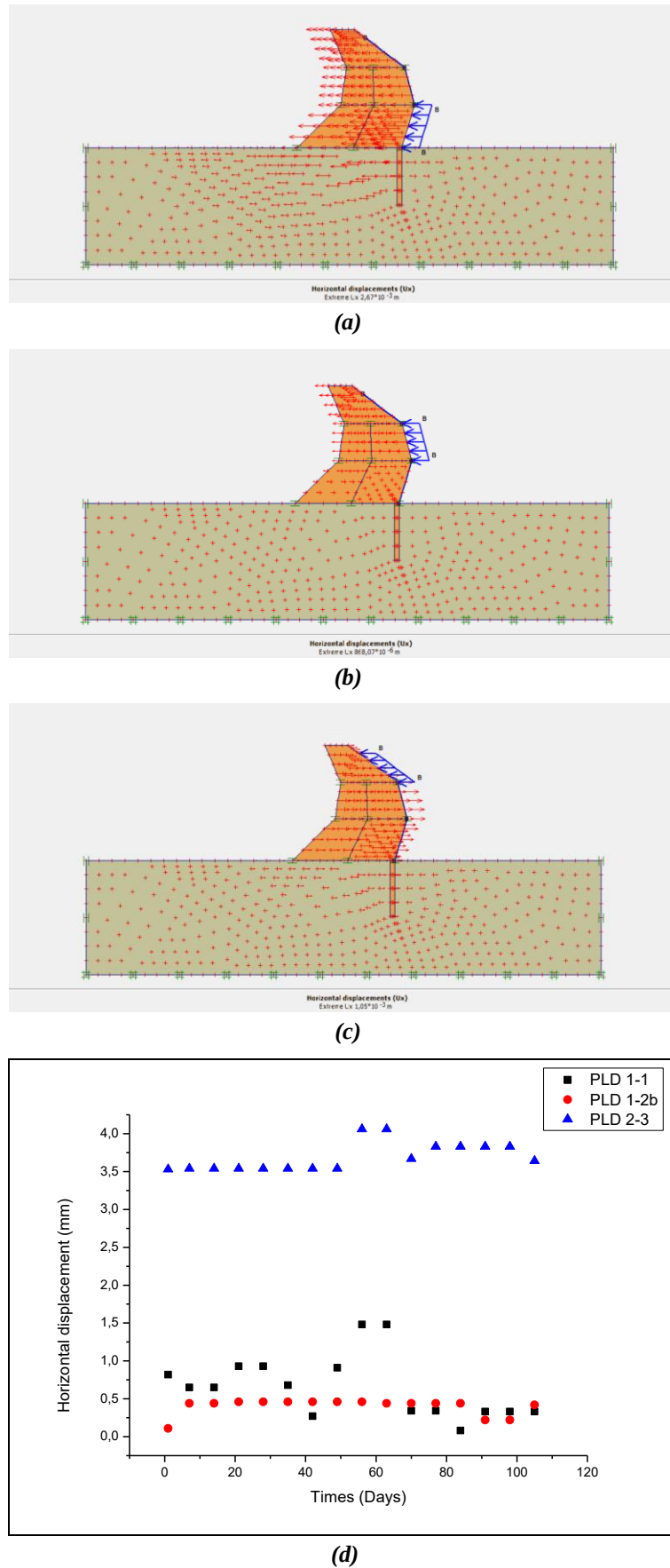


Fig. 18 – horizontal displacement of the dam in the level of (a) the 1st elevation (b) the 2nd elevation (c) the 3rd elevation (d) Real horizontal displacement measured at the three different elevations.

In terms of vertical displacement (Figure 19), we found a maximum value of 8.54 mm in the soil adjacent to the dam wall on both the upstream and downstream sides. Following this, there is a progressive decrease in settlement within the schist, ranging from 6 mm to 3 mm with depth until reaching the midpoint of the upstream side of the cutoff wall, and varying between 6 mm and 1.5 mm near the base of the dam towards the downstream side, extending to about one-quarter (1/4) of the cutoff wall height. Regarding the vertical displacement within the RCC dam itself, it ranges from 0 mm in the upper half of the first and second elevations on the upstream side to 1.50 mm in the remaining sections of the RCC dam.

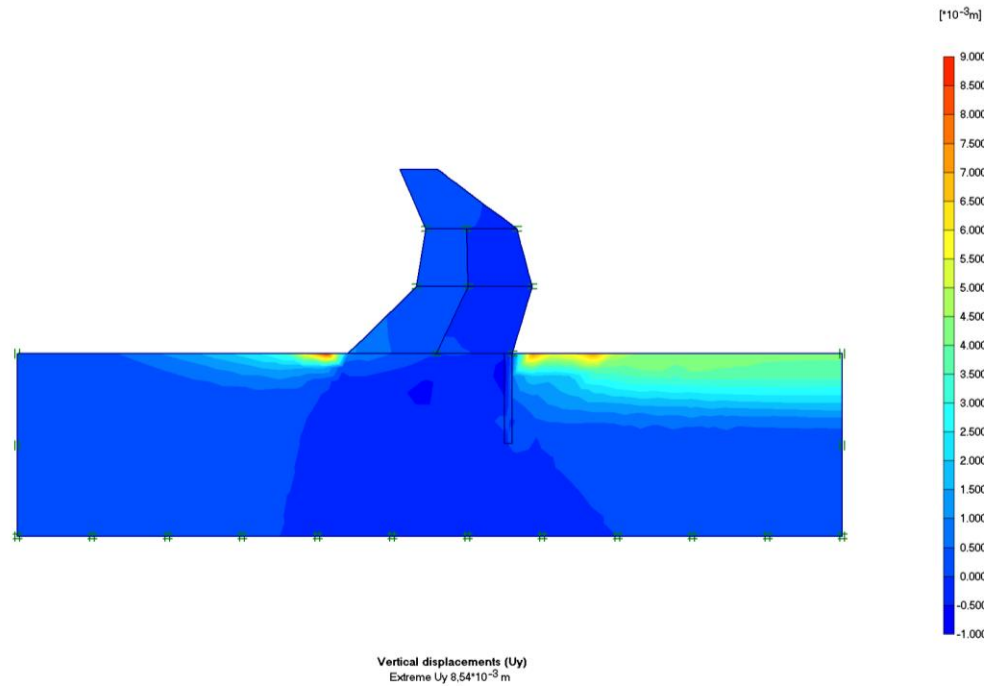


Fig. 19 – the vertical displacement of the dam.

In comparison with the actual measurements of displacement of the dam itself (Table A2) over a three-month period, from January 14, 2024, to March 10, 2024, we found the following values:

- For pendulum 1-1, a vertical displacement ranging from 1.69 mm to 2.60 mm.
- For pendulum 1-2b, a vertical displacement ranging from 0.09 mm to 1.16 mm.
- For pendulum 2-3, a vertical displacement ranging from 0.00 mm to 0.36 mm, respectively.

By detailing the phases of the impoundment at three elevation levels, each elevation is represented by a pendulum to realistically monitor vertical displacements:

- First elevation: It shows a vertical displacement of 1.15 mm (Figure 20-a), represented by pendulum 2-3, which indicates a value of 0.26 mm (Table A2). The difference is 0.89 mm, which we consider to be nearly compatible.
- Second elevation: It shows a horizontal displacement of 0.068 mm (Figure 20-b), represented by pendulum 1-2b, which indicates a value of 0.83 mm (Table A2). The difference is 0.76 mm, which we consider to be nearly compatible.
- Third elevation: It shows a horizontal displacement of 0.25 mm (Figure 20-c), represented by pendulum 2-3, which indicates a value of 0.07 mm (Table A2). The difference is 0.518 mm, which we consider to be nearly compatible.
- Consequently, the results (Figure 20-d) are highly satisfactory in terms of vertical displacement, showing significant compatibility, which enhances the credibility of our numerical model.

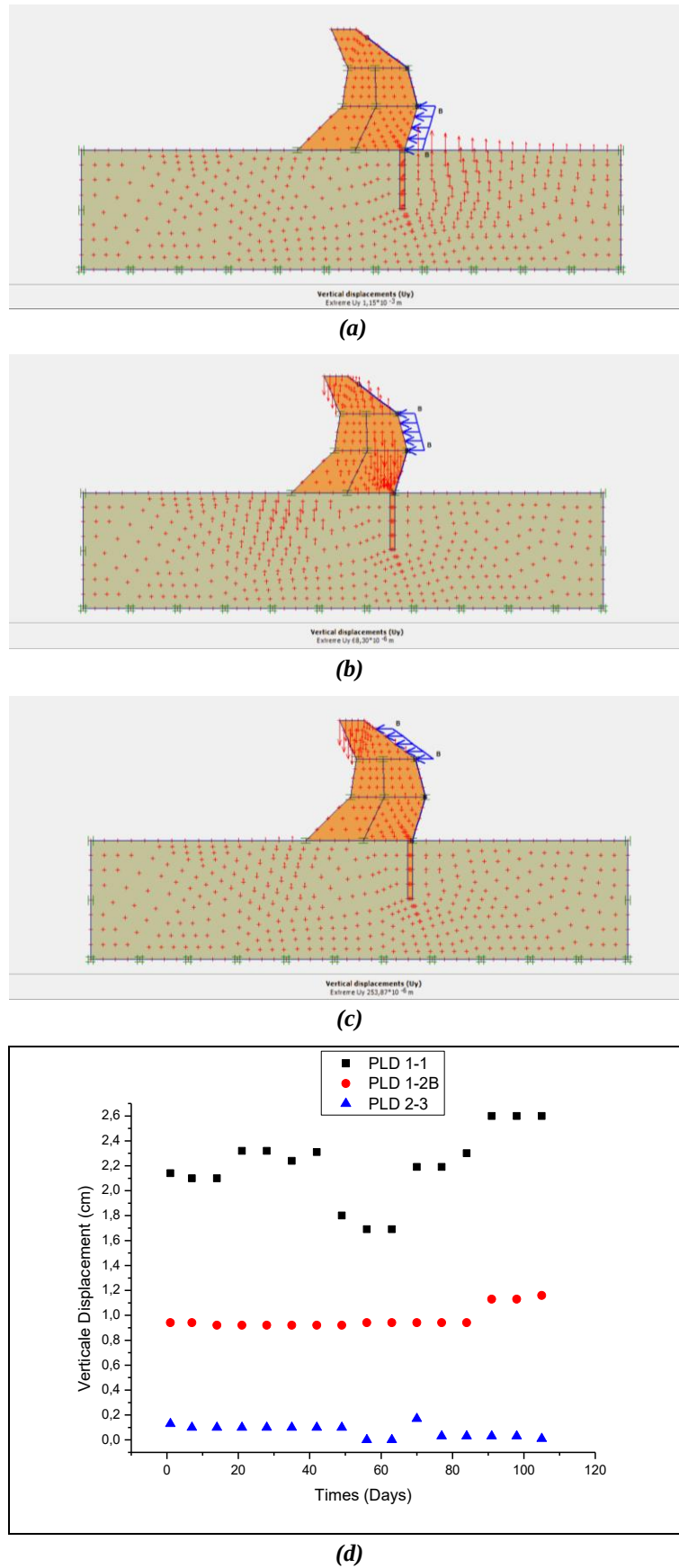


Fig. 20 – vertical displacement of the dam in the level of (a) the 1st elevation (b) the 2nd elevation (c) the 3rd elevation (d) Actual vertical displacement measured at the three different elevations.

The three curves (Figure 21) representing the first elevation (yellow), second elevation (red), and third elevation (blue) demonstrate a total deformation of 11 mm in the third elevation and 10 mm in both the second and first elevations, resulting in a difference of 1 mm. This similarity in the behaviour of the three levels of the dam indicates a uniform rigidity throughout the entire RCC body.

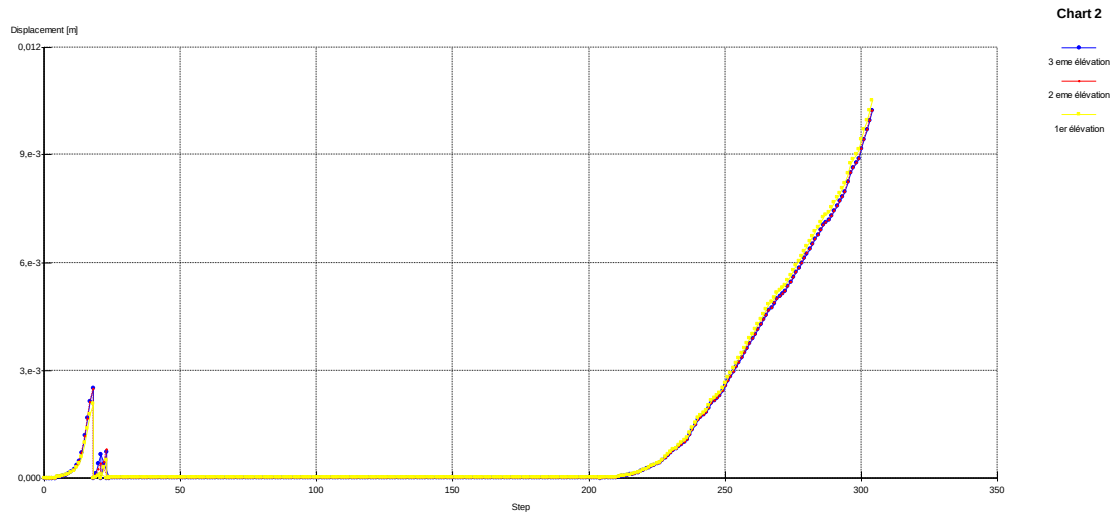


Fig. 21 – total displacement of the numerical simulation in the three different elevations.

We observed that the Mohr-Coulomb plastic points in our model (Figure 22) are located solely beneath the dam itself, which is typically attributed to the significant effect of the self-weight of the structure. In contrast, there are no plastic points in the soil on the upstream and downstream sides. This result indicates that the zone of plastic deformation is primarily concentrated beneath the dam, where the stresses due to the weight of the structure are highest. This implies that the foundation of the dam must be meticulously designed to support these loads. Furthermore, the absence of plastic points in the soil on both the upstream and downstream sides suggests that these areas do not experience sufficient stresses to reach the plasticity threshold according to the Mohr-Coulomb criterion, which is a positive indicator of the overall stability of the dam and its interaction with the surrounding soil.

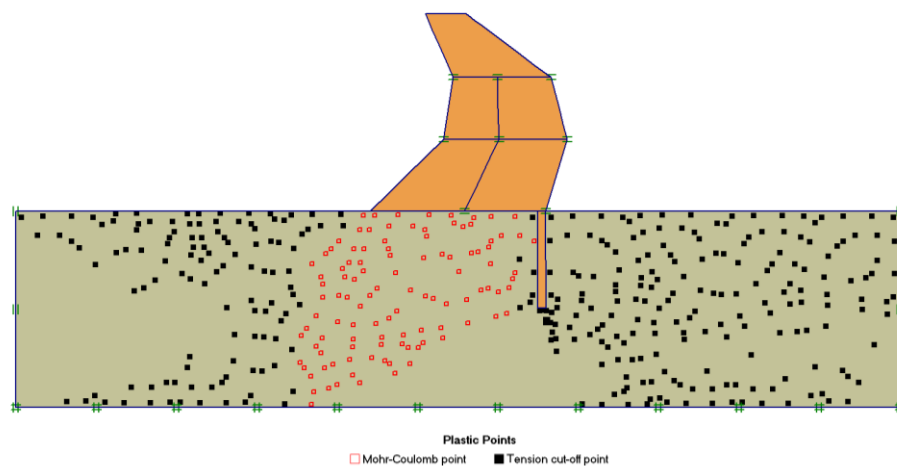


Fig. 22 – the Mohr-Coulomb plastic points in our model.

Finally, regarding the assessment of the overall stability of the RCC dam and our soil-structure system, we chose to compare the safety factor (FS) value to determine whether it is greater than or less than 1.5. This threshold was selected because, for structures that are significant in terms of their design and self-weight, it is essential to maintain a substantial margin above the value of 1, which represents the boundary between failure and stability. Upon reviewing Figure 23, which

illustrates the static safety factor (in blue) and the dynamic safety factor (in red, under seismic conditions), we observe the following:

- Under static conditions, the safety factor reaches a value of 2.45, which is well above 1.5, indicating a high level of stability.
- Under dynamic conditions, we found a limiting safety factor of 1, suggesting potential instability in the event of an earthquake or significant tectonic movement in the geological area of the Tebellout dam.

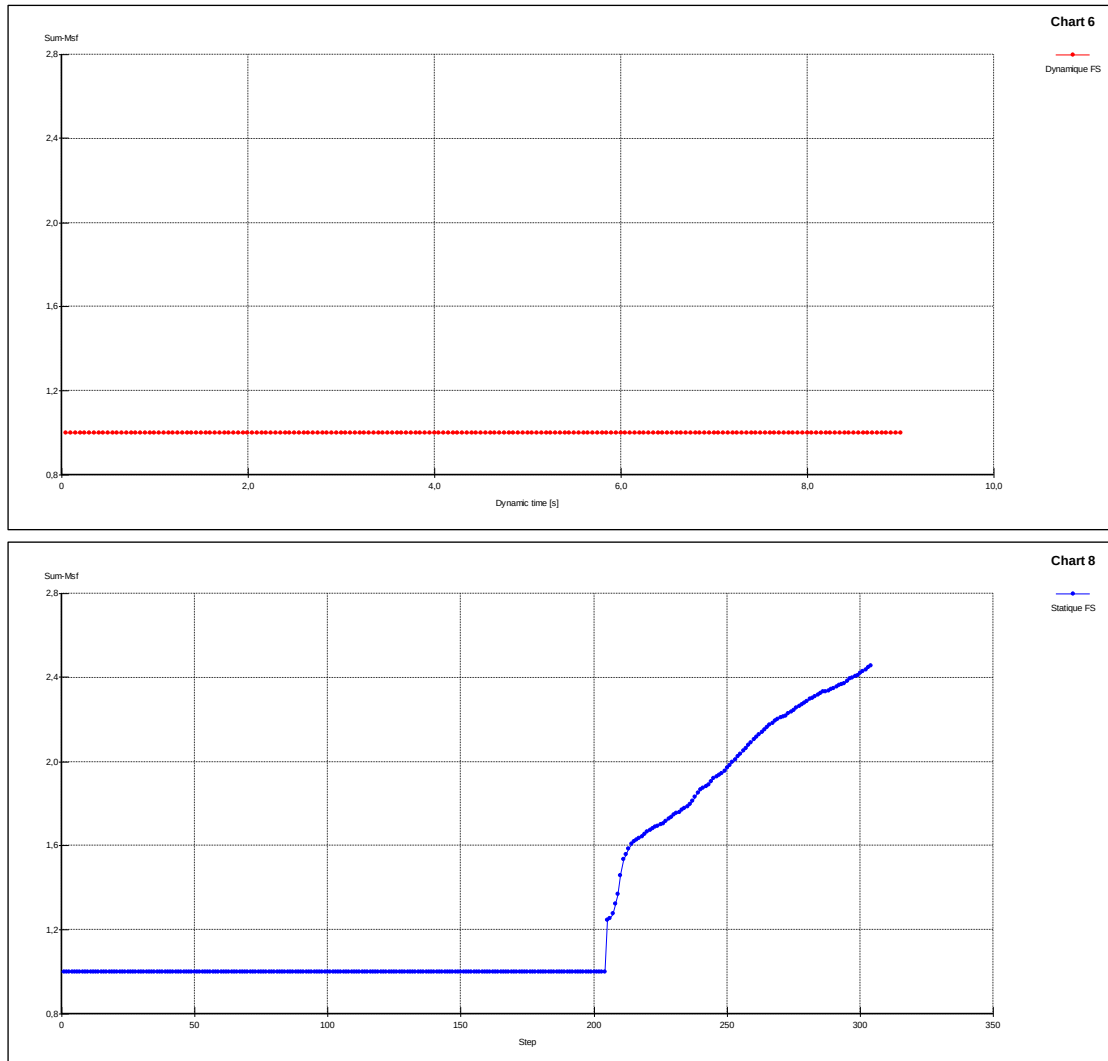


Fig. 23 – Safety factors were evaluated in static state (in blue) and in dynamic state (in red).

5 Discussion

The difference in deformation between the elevations is only 1 mm, indicating a remarkable uniformity in the behaviour of the dam. This uniformity suggests a homogeneous rigidity within the roller-compacted concrete (RCC) dam, which is crucial for structural stability. Uniform rigidity ensures that forces and loads are evenly distributed throughout the structure, thereby reducing the risk of weak points that could lead to structural failures.

The differences observed between the modelling results and the actual measurements, although present, remain within acceptable margins. The variations may be attributed to simplifications or assumptions made in the numerical model. These results indicate that the numerical modelling is generally reliable but must be continuously validated and adjusted with monitoring data to enhance accuracy.

The results of deformation analyses, safety factors, and plastic behaviour provide a comprehensive overview of the stability and performance of the RCC dam. Uniform rigidity and stability under static conditions are strengths, while vulnerability under dynamic conditions highlights areas for improvement. The comparison with actual measurements confirms the overall reliability of the modelling while emphasizing the importance of continuously integrating monitoring data for accurate and robust analyses.

The comparison of safety factors in these two states shows that while the dam is highly stable under static conditions, it exhibits vulnerability under dynamic conditions. This information is critical for planning and designing seismic risk mitigation measures (Figure 24), such as reinforcing the structure or improving construction techniques to enhance dynamic resistance.

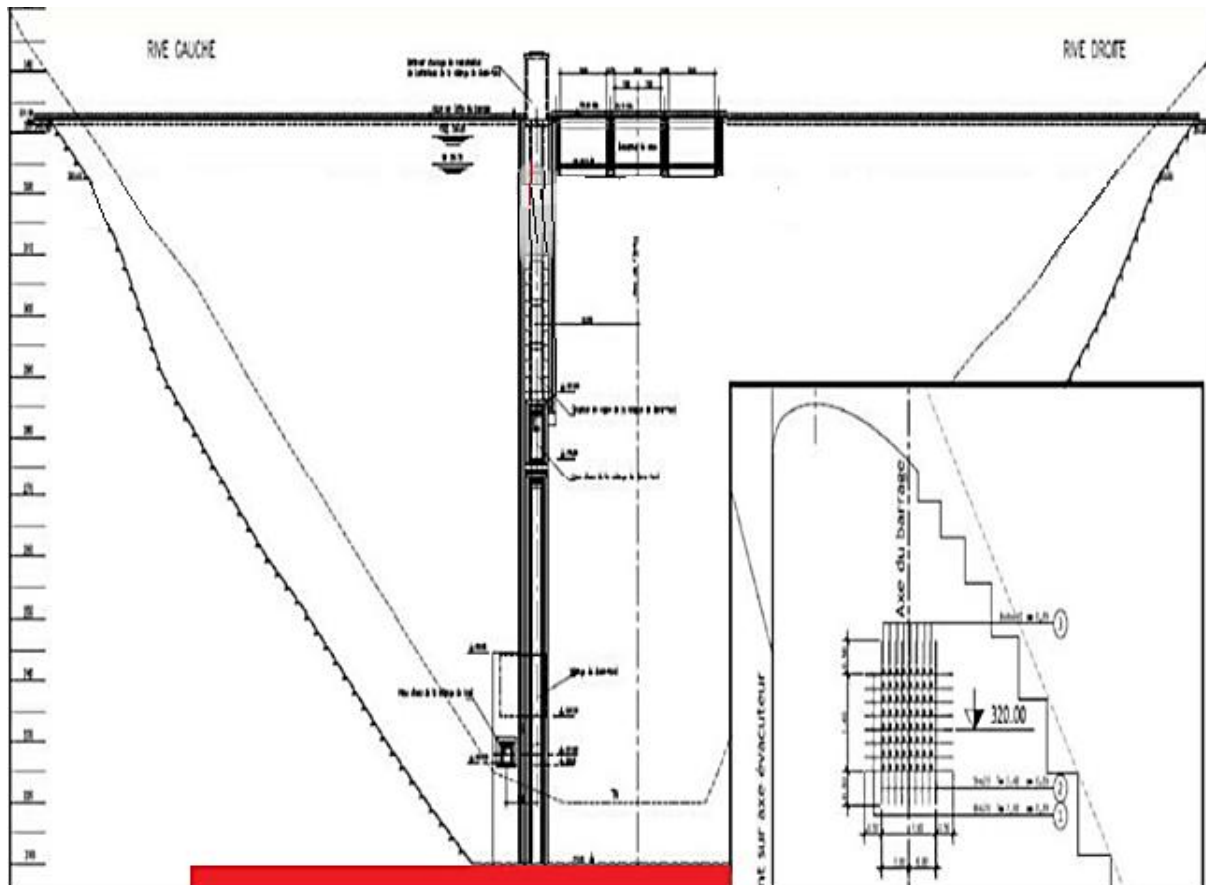


Fig. 24 – Schematic of the seismic belt.

The Tabellout dam is equipped with a seismic belt designed to absorb and dissipate seismic energy in order to reduce potential damage caused by earthquakes. This design helps prevent significant differential displacements between adjacent foundations (piano effect). The seismic belt consists of special materials and mechanisms that allow the dam to flex and move in a controlled manner during an earthquake, thereby reducing pressure on the dam's main structure.

6 Conclusion

The results obtained from numerical modeling and real measurements allow for several important conclusions regarding the stability and performance of the Roller-Compacted Concrete (RCC) dam:

- **Uniform Rigidity:** The deformations observed in the three elevations (first elevation in yellow, second elevation in red, and third elevation in blue) show a total deformation of 11 mm for the third elevation and 10 mm for the first and second elevations, with a difference of only 1 mm. This uniformity in deformations indicates a homogeneous rigidity throughout the entire body of the dam, which is essential for the even distribution of loads and the prevention of weak points.

- **Static and Dynamic Stability:** In static conditions, the factor of safety reaches 2.45, well above the critical threshold of 1.5, indicating high stability under normal static conditions. In dynamic conditions, the factor of safety is 1, which is just at the stability limit. This value highlights a potential vulnerability in the event of an earthquake or significant tectonic movements, suggesting that seismic risk mitigation measures should be considered.
- **Plastic Behavior:** Plastic points according to the Mohr-Coulomb criterion are concentrated solely under the dam due to the high stresses generated by the self-weight of the structure. The absence of plastic points in the soils on the upstream and downstream sides is a positive sign, indicating that these areas do not experience sufficient stresses to reach plasticity, thereby enhancing the overall stability of the dam.
- **Validation through Real Measurements:** The comparison between deformations obtained from numerical modelling and real measurements shows acceptable differences, confirming the overall reliability of the numerical model. However, the observed variations emphasize the importance of continuously validating and adjusting the model with empirical data to improve its accuracy.

In summary, the RCC dam exhibits uniform rigidity and high stability under normal static conditions. However, the observed vulnerability under dynamic conditions highlights the need to strengthen the structure to enhance its seismic resistance. Although the numerical modelling is reliable, it must be continuously refined with real measurements to ensure an accurate and robust assessment of the dam's performance.

Acknowledgements

We extend our heartfelt gratitude to the staff of the ANBT at the Tebellout Dam in Jijel Province, Algeria, for their invaluable support and collaboration throughout this research. Their assistance in conducting the monitoring was instrumental to the successful completion of this study.

Appendix A.

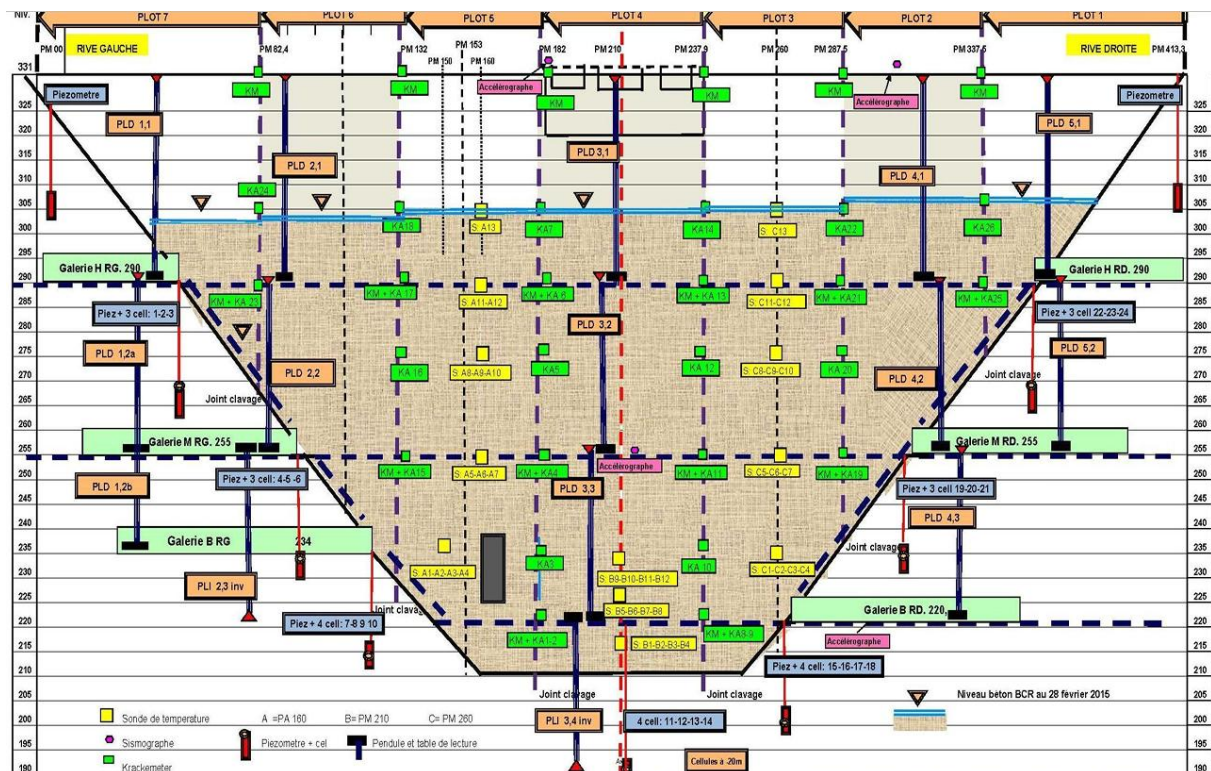


Fig. A1 – Synopsis of the positioning with technical note of the monitoring device in the Tabellout dam”, implemented 11/30/2014.

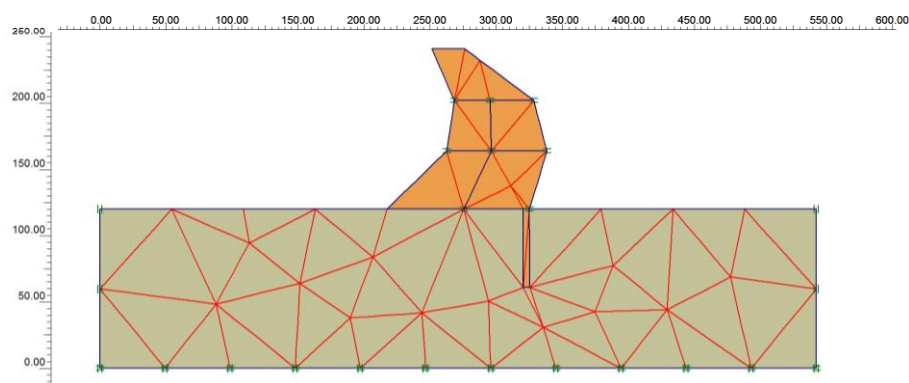
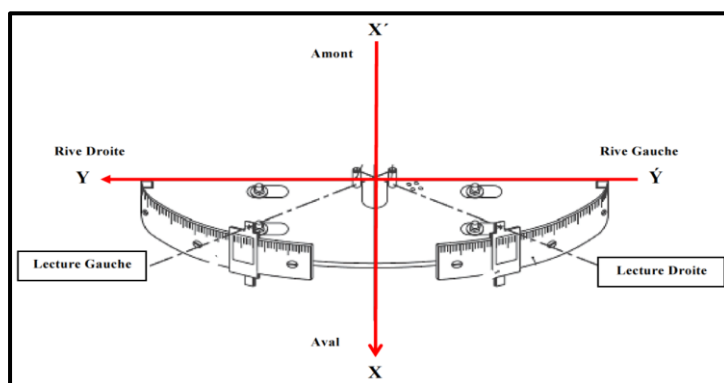
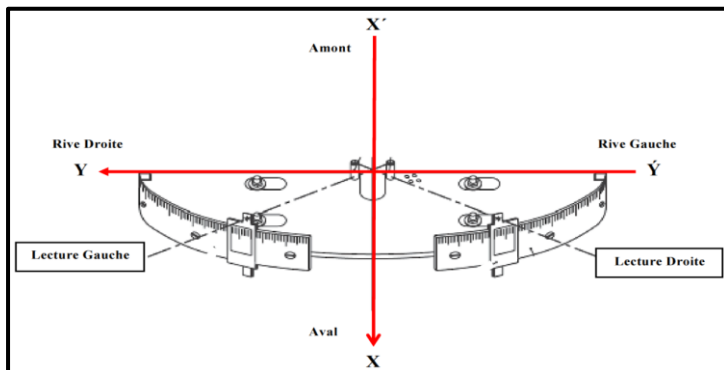


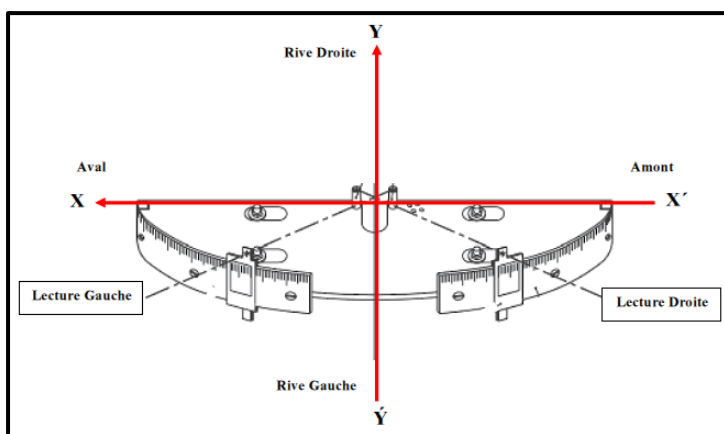
Fig. A2 – Designated model



(a) Direct Pendulum 1-1



(b) Direct Pendulum 1-2b



(c) Inverted Pendulum 2-3

Fig. A3 –The pendulums where we took the measurements of the displacements.

Table A1 - Monitoring of pressure cells at the three main elevations

Cell	C1: elevation 3			
Curve Title	C1/(PM 61,3 ; Cote 269,5), Amont Galerie d'exhaure haute rive gauche			
PM : 61,3; Cf. Factor: -5,3021E-01; Cote Z cell: 269,5; Initial Lecture L0: 3998,1; Plot : 7				
Date	Lecture (UL)	Pressure (KPa)	Piezo metric Level (m NGA)	T°C
28/06/2015	3998,1	0,000	269,50	25,1
15/01/2024	3563,5	230,429	293,00	11,0
22/01/2024	3552,5	236,262	293,59	11,0
29/01/2024	3568,3	227,884	292,74	11,0
05/02/2024	3589,7	216,538	291,58	11,0
12/02/2024	3591,0	215,848	291,51	11,0
19/02/2024	3577,2	223,165	292,26	11,0
26/02/2024	3574,7	224,491	292,39	11,0
29/02/2024	3532,4	246,935	294,68	11,0
01/03/2024	3522,9	251,956	295,19	11,0
02/03/2024	3539,1	243,366	294,32	11,0
03/03/2024	3554,2	235,360	293,50	11,0
04/03/2024	3566,4	228,892	292,84	11,0
07/03/2024	3602,2	209,910	290,90	11,0
12/03/2024	3594,9	213,781	291,30	11,0
Cell	C4: elevation 2			
Curve Title	C4/(PM 105,73; Cote 234), Amont Galerie d'exhaure moyenne rive gauche			
PM : 105,73; Cf. Factor: -7,2369E-01; Cote Z cell : 234; Initial Lecture L0 : 4030,9; Plot : 2				
Date	Lecture (UL)	Pressure (KPa)	Piezo metric Level (m NGA)	T°C
03/02/2015	4030,9	0,000	234,00	17,0
04/02/2015	3900,7	94,224	243,61	18,1
15/01/2024	3316,9	516,715	286,69	12,8
22/01/2024	3310,3	521,491	287,18	12,8
29/01/2024	3325,5	510,491	286,05	12,8
05/02/2024	3350,8	492,182	284,19	12,8
12/02/2024	3349,6	493,050	284,28	12,8
19/02/2024	3342,0	498,550	284,84	12,8
26/02/2024	3335,8	503,037	285,29	12,8
29/02/2024	3274,2	547,616	289,84	12,8
01/03/2024	3266,2	553,406	290,43	12,2
02/03/2024	3289,8	536,327	288,69	12,2
03/03/2024	3313,5	519,175	286,94	12,8
06/03/2024	3379,0	471,774	282,11	12,8
07/03/2024	3379,3	471,556	282,08	12,8
Cell	C7: elevation 3			
Curve Title	C7/ incliné : (PM 132;Cote 214), Amont Galerie d'exhaure basse rive gauche			
PM : 132; Cf. Factor: -1,0653E+00; Cote Z cell : 214; Initial Lecture L0 : 4128,2; Plot : 6				
Date	Lecture (UL)	Pressure (KPa)	Piezo metric Level (m NGA)	T°C
13/04/2014	4128,2	0,000	214,00	
15/01/2024	3732,3	421,752	257,01	16,2
22/01/2024	3728,5	425,800	257,42	16,2
29/01/2024	3735,1	418,769	256,70	16,2
05/02/2024	3742,8	410,567	255,87	16,2
12/02/2024	3745,3	407,903	255,59	16,2
19/02/2024	3739,6	413,976	256,21	16,2
26/02/2024	3740,8	412,697	256,08	16,2
29/02/2024	3724,5	430,062	257,85	16,2
01/03/2024	3713,2	442,100	259,08	16,2
02/03/2024	3718,4	436,560	258,52	16,2
03/03/2024	3725,2	429,316	257,78	16,2
04/03/2024	3729,9	424,309	257,27	16,2
07/03/2024	3744,0	409,288	255,74	16,2
12/03/2024	3742,0	411,419	255,95	16,2

Table A2 - Horizontal and vertical displacement measurements measured by pendulums 1-1, 1-2b and 2-3 respectively

Date measured	Hook Level	Arrival Coordinate	Cable Length (m)	Table Level	Circles Lectures (mm)		Angles Calculated		Coordinates (mm)		Displacement from zero lecture (mm)		Displacement from water launch (mm)	
					Right Circle (d)	Left Circle (g)	Right Angle (D)	Left Angle (G)	X (mm)	Y (mm)	X (mm)	Y (mm)	X (mm)	Y (mm)
23/04/2016	331,7	290,3	41,4	291,35	633,20	273,10	0,87	0,83	34,23	1,31	0,00	0,00	#N/A	#N/A
31/12/2018	331,7	290,3	41,4	291,35	636,4	244,4	0,86	0,74	30,74	3,70	-3,49	2,39	0,00	0,00
14/01/2024	331,7	290,3	41,4	291,35	624,9	258,8	0,90	0,78	33,41	3,45	-0,82	2,14	2,68	-0,25
21/01/2024	331,7	290,3	41,4	291,35	624,4	259,8	0,90	0,79	33,58	3,40	-0,65	2,10	2,84	-0,30
28/01/2024	331,7	290,3	41,4	291,35	624,4	259,8	0,90	0,79	33,58	3,40	-0,65	2,10	2,84	-0,30
04/02/2024	331,7	290,3	41,4	291,35	624,4	257,4	0,90	0,78	33,30	3,63	-0,93	2,32	2,56	-0,07
11/02/2024	331,7	290,3	41,4	291,35	624,4	257,4	0,90	0,78	33,30	3,63	-0,93	2,32	2,56	-0,07
18/02/2024	331,7	290,3	41,4	291,35	623,7	259	0,90	0,79	33,55	3,55	-0,68	2,24	2,81	-0,16
25/02/2024	331,7	290,3	41,4	291,35	621,4	260,6	0,91	0,79	33,97	3,62	-0,27	2,31	3,23	-0,08
29/02/2024	331,7	290,3	41,4	291,35	619,1	268,4	0,92	0,82	35,14	3,11	0,91	1,80	4,40	-0,59
01/03/2024	331,7	290,3	41,4	291,35	617,3	271,5	0,92	0,82	35,71	2,99	1,48	1,69	4,97	-0,71
02/03/2024	331,7	290,3	41,4	292,35	617,3	271,5	0,92	0,82	35,71	2,99	1,48	1,69	4,97	-0,71
03/03/2024	331,7	290,3	41,4	292,35	619,4	264	0,92	0,80	34,57	3,49	0,34	2,19	3,84	-0,21
04/03/2024	331,7	290,3	41,4	293,35	619,4	264	0,92	0,80	34,57	3,49	0,34	2,19	3,84	-0,21
05/03/2024	331,7	290,3	41,4	293,35	620,6	261,5	0,91	0,79	34,15	3,61	-0,08	2,30	3,41	-0,09
06/03/2024	331,7	290,3	41,4	293,35	620	258,9	0,91	0,79	33,90	3,91	-0,33	2,60	3,16	0,21
07/03/2024	331,7	290,3	41,4	293,35	620	258,9	0,91	0,79	33,90	3,91	-0,33	2,60	3,16	0,21
10/03/2024	331,7	290,3	41,4	293,35	620	258,9	0,91	0,79	33,90	3,91	-0,33	2,60	3,16	0,21

Date measured	Hook Level	Arrival Coordinate	Cable Length (m)	Table Level	Circles Lectures (mm)		Angles Calculated		Coordinates (mm)		Displacement from zero lecture (mm)		Displacement from water launch (mm)	
					Right Circle (d)	Left Circle (g)	Right Angle (D)	Left Angle (G)	X (mm)	Y (mm)	X (mm)	Y (mm)	X (mm)	Y (mm)
23/04/2016	291,20	233,95	57,25	235,10	643,20	270,50	0,84	0,82	32,84	0,57	0,00	0,00	#N/A	#N/A
31/12/2018	291,20	238,95	52,25	235,10	643,2	269,5	0,84	0,82	32,73	0,66	-0,11	0,09	0,00	0,00
14/01/2024	291,20	238,95	52,25	235,10	636	267,8	0,86	0,81	33,28	1,51	0,44	0,94	0,55	0,85
21/01/2024	291,20	238,95	52,25	235,10	636	267,8	0,86	0,81	33,28	1,51	0,44	0,94	0,55	0,85
28/01/2024	291,20	238,95	52,25	235,10	636	268	0,86	0,81	33,30	1,49	0,46	0,92	0,57	0,83
04/02/2024	291,20	238,95	52,25	235,10	636	268	0,86	0,81	33,30	1,49	0,46	0,92	0,57	0,83
11/02/2024	291,20	238,95	52,25	235,10	636	268	0,86	0,81	33,30	1,49	0,46	0,92	0,57	0,83
18/02/2024	291,20	238,95	52,25	235,10	636	268	0,86	0,81	33,30	1,49	0,46	0,92	0,57	0,83
25/02/2024	291,20	238,95	52,25	235,10	636	268	0,86	0,81	33,30	1,49	0,46	0,92	0,57	0,83
29/02/2024	291,20	238,95	52,25	235,10	636	268	0,86	0,81	33,30	1,49	0,46	0,92	0,57	0,83
01/03/2024	291,20	238,95	52,25	235,10	636	267,8	0,86	0,81	33,28	1,51	0,44	0,94	0,55	0,85
02/03/2024	291,20	238,95	52,25	235,10	636	267,8	0,86	0,81	33,28	1,51	0,44	0,94	0,55	0,85
03/03/2024	291,20	238,95	52,25	235,10	636	267,8	0,86	0,81	33,28	1,51	0,44	0,94	0,55	0,85
04/03/2024	291,20	238,95	52,25	235,10	636	267,8	0,86	0,81	33,28	1,51	0,44	0,94	0,55	0,85
05/03/2024	291,20	238,95	52,25	235,10	636	267,8	0,86	0,81	33,28	1,51	0,44	0,94	0,55	0,85
06/03/2024	291,20	238,95	52,25	235,10	636	265,8	0,86	0,81	33,06	1,70	0,22	1,13	0,32	1,04
07/03/2024	291,20	238,95	52,25	235,10	636	265,8	0,86	0,81	33,06	1,70	0,22	1,13	0,32	1,04
10/03/2024	291,20	238,95	52,25	235,10	634,9	266,6	0,87	0,81	33,25	1,73	0,42	1,16	0,52	1,07

Date measured	Hook Level	Arrival Coordinate	Cable Length (m)	Table Level	Circles Lectures (mm)		Angles Calculated		Coordinates (mm)		Displacement from zero lecture (mm)		Displacement from water launch (mm)	
					Right Circle (d)	Left Circle (g)	Right Angle (D)	Left Angle (G)	X (mm)	Y (mm)	X (mm)	Y (mm)	X (mm)	Y (mm)
23/04/2016	220,5	256,8	36,3	256,4	636,00	266,80	0,86	0,81	1,64	33,24	0,00	0,00	#N/A	#N/A
31/12/2018	220,5	256,8	36,3	256,4	640,2	267,4	0,85	0,81	1,18	32,88	0,46	0,36	0,00	0,00
14/01/2024	220,5	256,8	36,3	256,4	655,1	284,8	0,80	0,87	-1,89	33,11	3,53	0,13	3,07	-0,23
21/01/2024	220,5	256,8	36,3	256,4	655	285	0,80	0,87	-1,90	33,14	3,54	0,10	3,08	-0,26
28/01/2024	220,5	256,8	36,3	256,4	655	285	0,80	0,87	-1,90	33,14	3,54	0,10	3,08	-0,26
04/02/2024	220,5	256,8	36,3	256,4	655	285	0,80	0,87	-1,90	33,14	3,54	0,10	3,08	-0,26
11/02/2024	220,5	256,8	36,3	256,4	655	285	0,80	0,87	-1,90	33,14	3,54	0,10	3,08	-0,26
18/02/2024	220,5	256,8	36,3	256,4	655	285	0,80	0,87	-1,90	33,14	3,54	0,10	3,08	-0,26
25/02/2024	220,5	256,8	36,3	256,4	655	285	0,80	0,87	-1,90	33,14	3,54	0,10	3,08	-0,26
29/02/2024	220,5	256,8	36,3	256,4	655	285	0,80	0,87	-1,90	33,14	3,54	0,10	3,08	-0,26
01/03/2024	220,5	256,8	36,3	257,4	657,1	288,4	0,80	0,88	-2,42	33,24	4,06	0,00	3,60	-0,36
02/03/2024	220,5	256,8	36,3	258,4	657,1	288,4	0,80	0,88	-2,42	33,24	4,06	0,00	3,60	-0,36
03/03/2024	220,5	256,8	36,3	258,4	654,4	287	0,81	0,87	-2,04	33,40	3,67	-0,17	3,21	-0,52
04/03/2024	220,5	256,8	36,3	259,4	656,1	287	0,80	0,87	-2,20	33,21	3,83	0,03	3,37	-0,33
05/03/2024	220,5	256,8	36,3	259,4	656,1	287	0,80	0,87	-2,20	33,21	3,83	0,03	3,37	-0,33
06/03/2024	220,5	256,8	36,3	259,4	656,1	287	0,80	0,87	-2,20	33,21	3,83	0,03	3,37	-0,33
07/03/2024	220,5	256,8	36,3	259,4	656,1	287	0,80	0,87	-2,20	33,21	3,83	0,03	3,37	-0,33
10/03/2024	220,5	256,8	36,3	259,4	655	286,1	0,80	0,87	-2,01	33,25	3,64	-0,01	3,18	-0,37

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