STUDY OF THE STRUCTURAL BEHAVIOR OF PIRAPORA DAM AFFECTED BY ALKALI-AGGREGATE REACTION

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Abstract

The Pirapora Dam, built in 1956, is a gravity dam consisting of pillars (counterfort) and a wide base wall, whose stability is mainly ensured by its own weight. In the 1990s, pathological manifestations were recognized in the dam concrete structure, due to Alkali-Aggregate Reaction (AAR).

For proper comprehension of the situation presented by the dam, its structural behavior was simulated in a representative three-dimensional mathematical model, based on the Finite Element Method (FEM). In order to provide a reliable analysis of the actual dam structural behavior, a calibration of the model was performed using modal analysis, using the natural frequencies of the real structure obtained by dynamic structural tests, so that the natural frequencies of the theoretical model could match with the real natural frequencies (experimental).

To elaborate the mathematical model the geometry of the structure and materials properties were considered, obtained through laboratory testing of extracted concrete samples of the structure, as well the dynamic structural tests.

The calibrated numerical model of the dam aims to monitor and validate the results of existing instrumentation, predict the structural response and the AAR effects in the coming years and provide the basis to simulate the mitigation measures of the AAR effects and complementation of the existing instrumentation in the dam.

The results obtained with the structural modeling and the deteriorating state verified in inspections in the structure allowed the evaluation of the dam's behavior aiming to preserve the life cycle and safety of the structure.

Keywords: alkali aggregate reaction (AAR), Finite Element Method (FEM), Structural Modeling, Structural Monitoring, Dynamic Structural Test

1 INTRODUCTION

Pirapora Dam is located in the municipality of Pirapora do Bom Jesus and was built in 1956 to retain the Juqueri River's flow and, through successive settlements in Edgard de Souza, Traição and Pedreira, utilize them for power generation at Henry Borden.

It is a gravity dam made in reinforced concrete, with roughly 85 meters in length at the crest and approximately 25 meters in height. The maximum capacity of Pirapora reservoir is 75,034,000 m³. Figure 1 illustrates Pirapora dam.

The occurrence of expansive reactions at Pirapora Dam was diagnosed in the 1990s, following the expansion of the dissemination of this phenomenon in technical media.

Visual symptoms of the occurrence of expansive concrete reactions at Pirapora Dam are concentrated mainly in spillways and foothills and in the region of trunnion beams (downstream side). The study was guided by the concern regarding the possibility of advancement of a pathological scenario that may harm the operation of floodgates. The full study comprises the following steps:

1. Collection and analysis of data from the project, construction, operation, and instrumentation;
2. Visual inspection, registration of anomalies in structures and implementation of non-destructive testing;
3. **Dynamic tests to determine the mechanical properties of the structures;**
4. **Mathematical models and calibration with experimental results;**
5. Structural safety evaluation;
6. Characterization of AAR parameters and constituent materials;
7. **Development of a three-dimensional mathematical model and dam behavior simulation;**
8. Evaluation of alternatives for mitigation;
9. Simulation using mathematical models calibrated for possible interventions in structures;

10. Basic project for implementation of the adopted solution;
11. Preparation of a long-term monitoring project.

This article aims to present the study of the structural behavior of Pirapora Dam, as affected by AAR, discussing steps 3, 4, and 7.

2 DYNAMIC TESTS

To perform the dynamic test, a network of accelerometer-type sensors was installed in the spillway walls in order to obtain the structure's natural frequencies and modes of vibration. The data obtained from the instrumentation are needed to calibrate the mathematical model used to evaluate the performance of the existing structure. Figure 2 shows the instrumented points.

3 MATHEMATICAL MODEL

First, a three-dimensional drawing of Pirapora Dam was developed. Following that, a mathematical model was developed in a computer program, as shown in Figure 3, based on the Finite Element Method (FEM), aiming to determine the structure's main modes of vibration. The complete model of the dam and rock mass consists of approximately 230,000 solid elements.

To represent the actual behavior of the structure, a three-dimensional numerical model was developed considering the structural arrangement, ground support, physical properties of the concrete that makes up the dam, and the masses associated with the structure. The physical properties of the concrete were obtained by conducting laboratory tests of samples taken from the structure.

Figure 4 shows that the finite element mesh is finer in the elements of interest, while a coarser mesh was made for the ground. This was done to make the model lighter and streamline its processing.

3.1 Mathematical Model Calibration

The numerical model of Pirapora Dam was calibrated to adjust the natural frequencies of the model with the natural frequencies resulting from the experimental modal analysis. The calibrated numerical model makes possible a more reliable analysis of the actual dam behavior, enabling the evaluation of the dam's structural safety and a simulation of possible interventions in the structure. Figure 5 illustrates the deformed configuration for the first mode of the numerical model calibrated.

Table 1 presents the comparison of the first four theoretical and experimental modes of vibration after calibration of the mathematical model, in which a variation less than 2% can be observed.

3.2 Simulation of Pirapora Dam Behavior subjected to Alkali-Aggregate Reaction (AAR)

The main purpose of the Structural Behavior Simulation is to evaluate the acting forces, including increases caused by the expansion of concrete due to the AAR and safety verification available in the current state of the structure.

Based on the analysis of the Simulation results, there was an increase of displacement and the final tensions due to 58 years of expansion of the concrete, compared to displacements and stresses due to permanent loads.

The AAR is an expansive reaction, causing tensile stresses in the concrete elements at an average of 5 MPa. Therefore, the confining stresses may result in reducing the expansion of the compression force direction, thus avoiding the formation of cracks and reducing water circulation within the concrete. The figures below present the data used.

Then, the expansion rate of concrete over time was obtained. The rate used is shown in Figure 6 and was obtained from the instrumentation with multiple rod extensometers.

Some viscoelastic parameters of concrete are changed due to alkali-aggregate reaction, increasing fluency, and relaxation of tensions and also reducing the elasticity over the course of time. Figures 7, 8 and 9 show the values used for each year of numerical simulation.

4 ANALYSIS

Results for displacements and stresses were obtained based on the concrete expansion loading as of 2014. The diagram presents data relating to the behavior of displacements and stresses over time, in which 0 refers to a state obtained with permanent loads, hydrostatic loads, and concrete shrinkage. Displacement results were also compared to those measured in the rod extensometers and stresses with the mapping of cracks.

4.1 Displacement Results for Expansion loading

Figure 11 shows displacement results in X, Y, and Z directions, obtained for the expansion load in verification node No. 9766. Figure 10 shows the key nodes of the analysis, where we marked the point of interest that generated the diagram in Figure 11.

4.2 Displacement Results for Expansion loading

Figure 13 shows the normal stress results in directions X, Y, and Z, obtained for the expansion load in node 97615. Figure 12 shows the location of the points analyzed.

4.3 Analysis of Results

The results obtained qualitatively show the impacts of concrete expansion due to the AAR in Pirapora Dam's structural behavior concerning displacements, stresses, and deformation.

These results showed a high increase in displacements and final stresses, after 58 years of expansion, compared to displacements and stresses resulting from own weight loads, hydrostatic loads, and concrete shrinkage. Consequently, the anomalies existing in the structures can be explained by the occurrence of AAR.

The final displacement in the dam crest in direction Z (vertical) was 60 mm, in the node corresponding to the EM-001 rod extensometer, indicating a vertical expansion rate of 30 $\mu\varepsilon$/year, while the displacement increase in direction Y (parallel to flow) was roughly 6 mm. For the node corresponding to the EM-002 rod extensometer, vertical displacement (Z) was 38 mm, indicating a vertical expansion rate of 21 $\mu\varepsilon$/year, while the displacement increase in direction Y (parallel to flow) was roughly 4 mm.

The analysis of the dam instrumentation data and the displacement results of the mathematical model showed that that the EM-001 rod extensometer had an accumulated vertical displacement of 15mm in 16 years, while the vertical displacement obtained in the simulation for Node 7413 was 15.9 mm in the same period. For the EM-002 rod extensometer, it was observed that the accumulated vertical displacement was 9.6 mm in 16 years, compared to 10.1 mm observed in Node 9766 after the model expansion simulation. The close relation among displacements noted in the instrumentation and the results obtained in the expansion simulation shows that the model is calibrated, qualitatively representing the expansion process to which the structure was subjected over time due to AAR action.

The relative displacements of the tops of the pillars showed low values, but with a progressive behavior, requiring a more refined analysis after future expansion projection to check for possible interference in the operation of floodgates.

The maximum stresses observed occur in points verified on the crest of spillways, as well as upstream, confirming what was observed in the mapping of cracks, carried out during the visual inspection.

5 CONCLUSIONS

This article aims to present the results obtained from the analysis and the conclusion regarding the simulation of Pirapora Dam's behavior after the application of the concrete expansion load due to the AAR.

The analysis of results shows that an increase in displacements and final stresses, in particular in directions X and Z, after application of 58 years of concrete expansion compared with the displacements and stresses due to permanent loads, hydrostatic loads, and concrete shrinkage. This fact shows that the pathological manifestations identified in the structure can be explained by the occurrence of AAR.

This analysis did not include verifications of the dam structure stability regarding floating, tipping, and sliding.

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TABLE 1: Comparison of experimental and numeral frequencies.

Mode N°	Natural Frequencies (Hz)		Vibration mode type	Theoretical / Experimental
	Experimental	Theoretical		
1	12.16	12.43	Pillars P1, P2 and P3, in the dam axis directions	1.02
2	12.42	12.65	Pillars P1 and P2, in the dam axis direction	1.02
3	12.68	12.67	Pillars P1 and P2, in the water flow and dam axis directions	1.00
4	12.93	13.19	Pillar P3 in the dam axis direction	1.02

FIGURE 1: Downstream side and upstream side of Pirapora Dam.

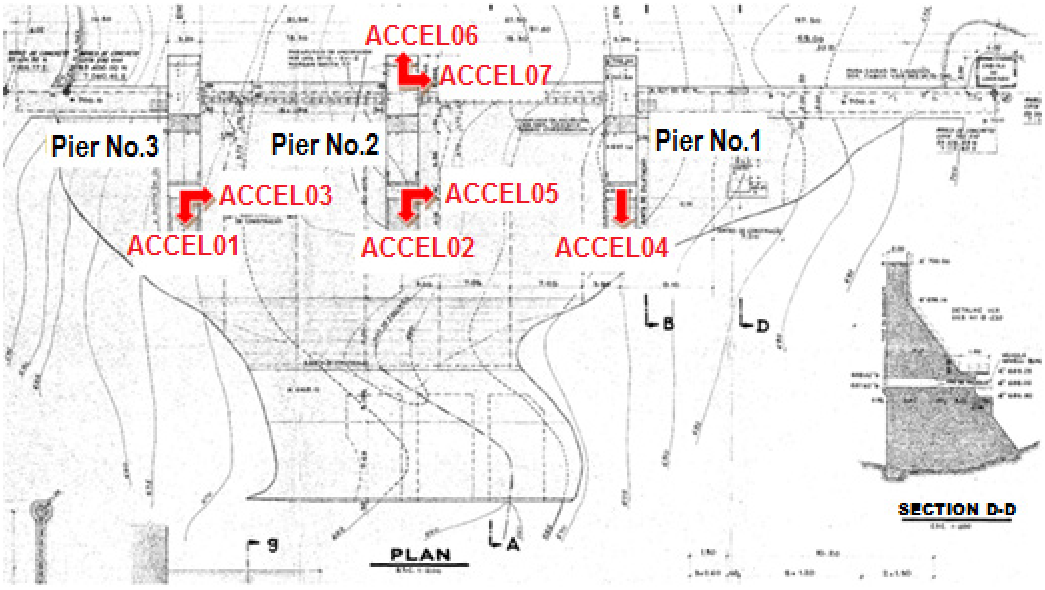

FIGURE 2: Location of accelerometers.

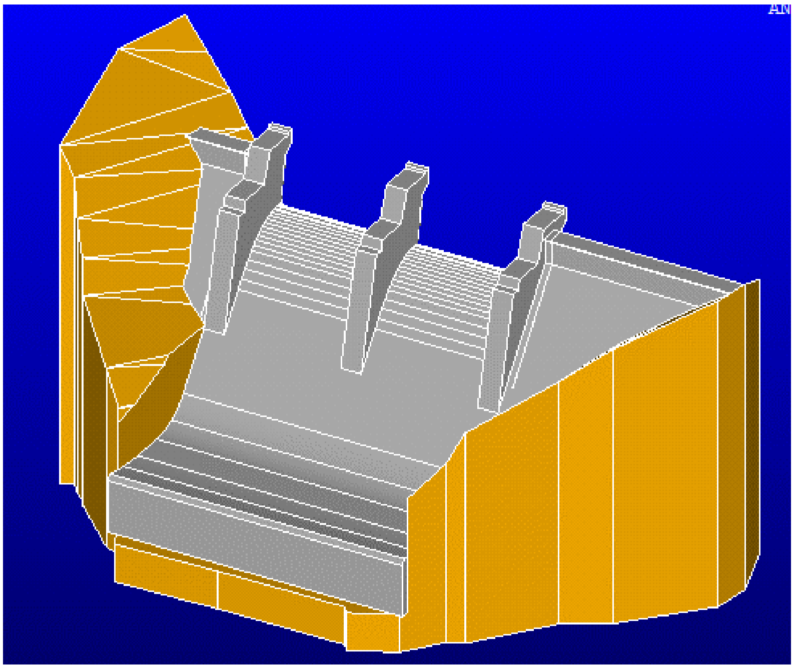

FIGURE 3: 3D view of the mathematical model.

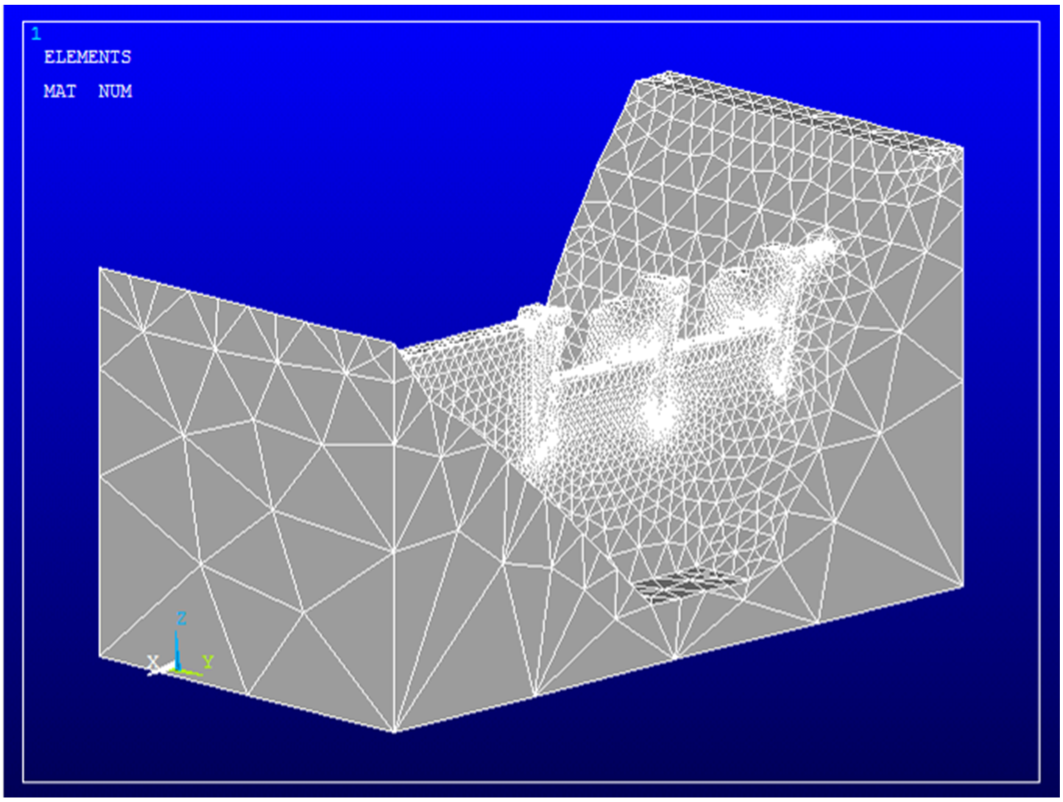

FIGURE 4: View of the model's FEM mesh.

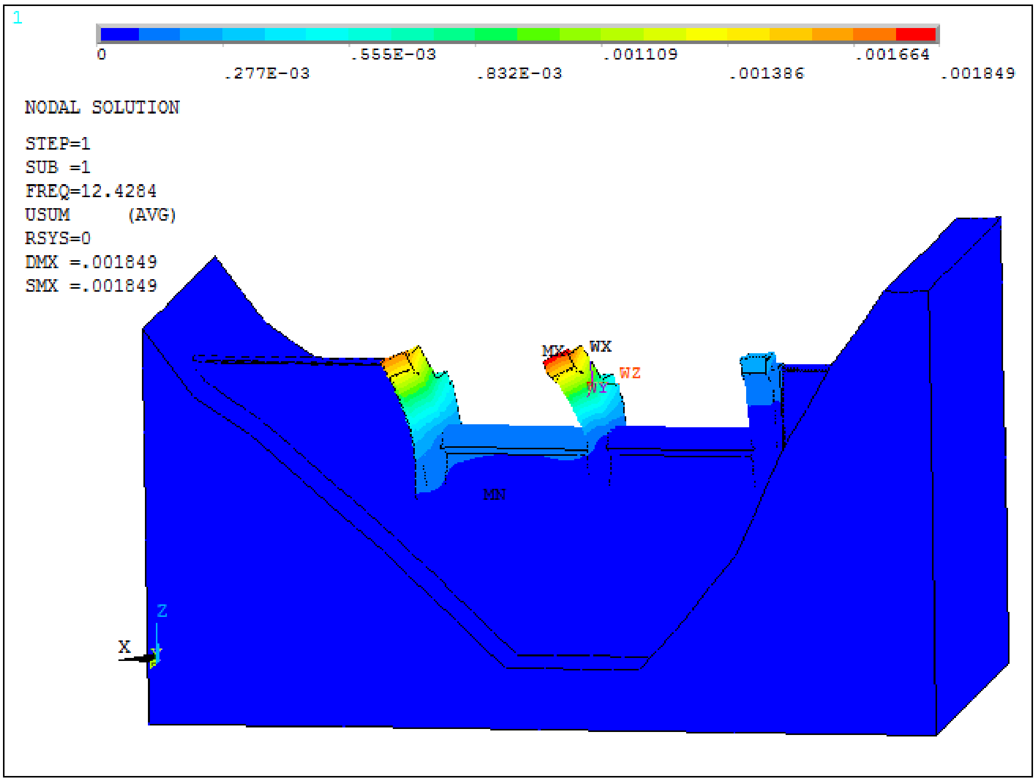

FIGURE 5: View of the first modal deformation of the model.

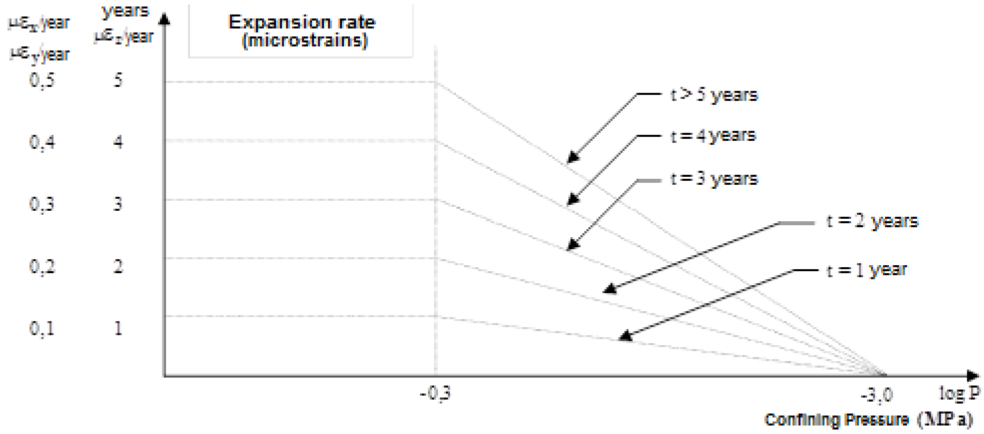

FIGURE 6: Growth rate variation with time.

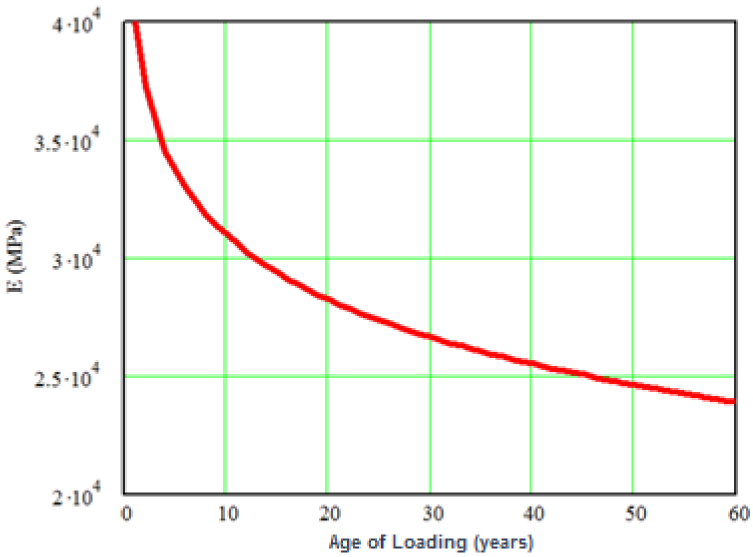

FIGURE 7: Modulus of Elasticity behavior over the years.

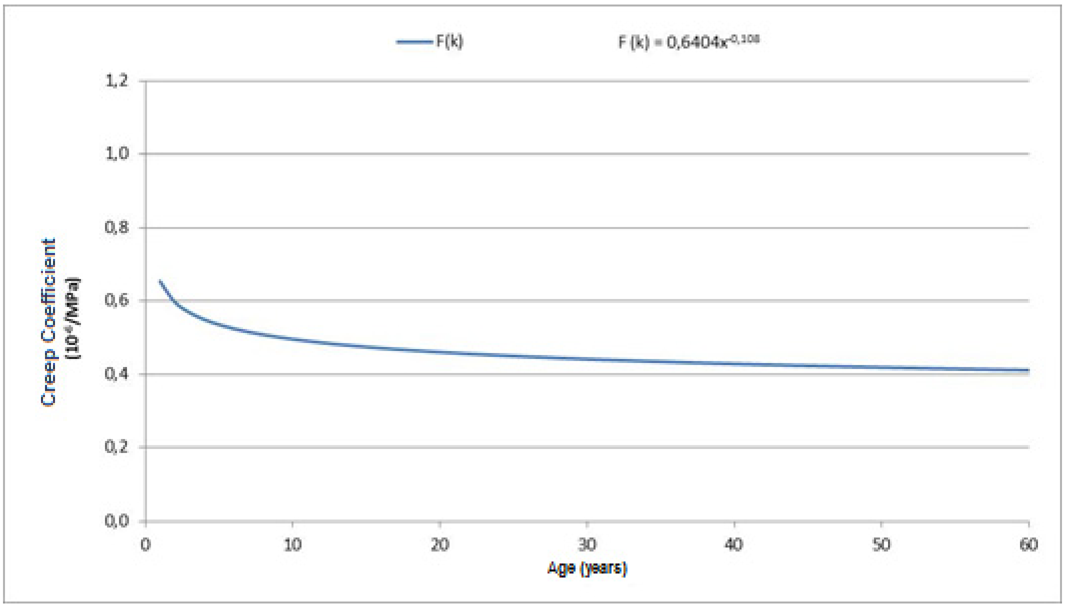

FIGURE 8: Creep coefficient behavior over the years.

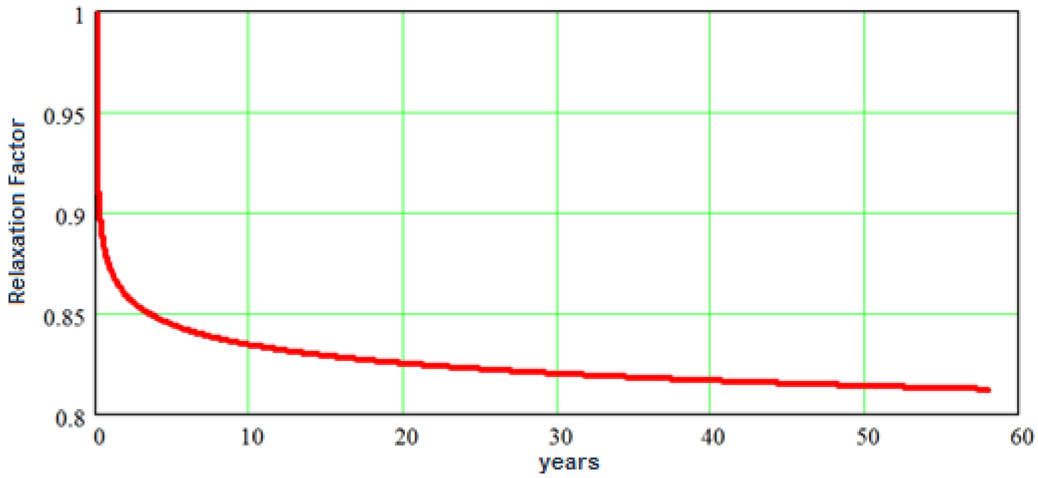

FIGURE 9: Relaxation curve for loading applied after 1 year.

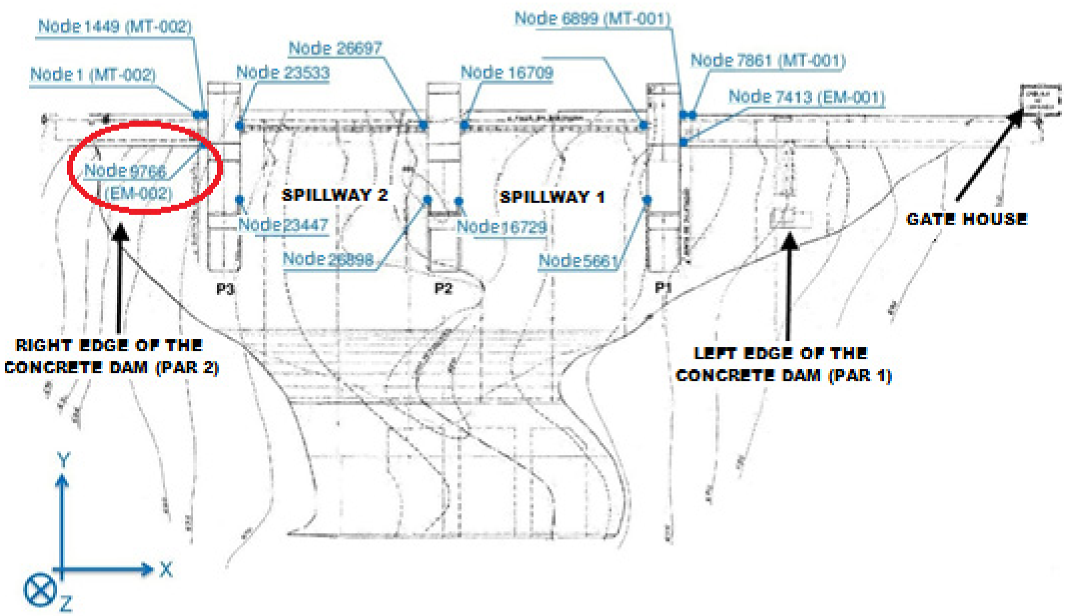

FIGURE 10: Location of the displacement verification nodes.

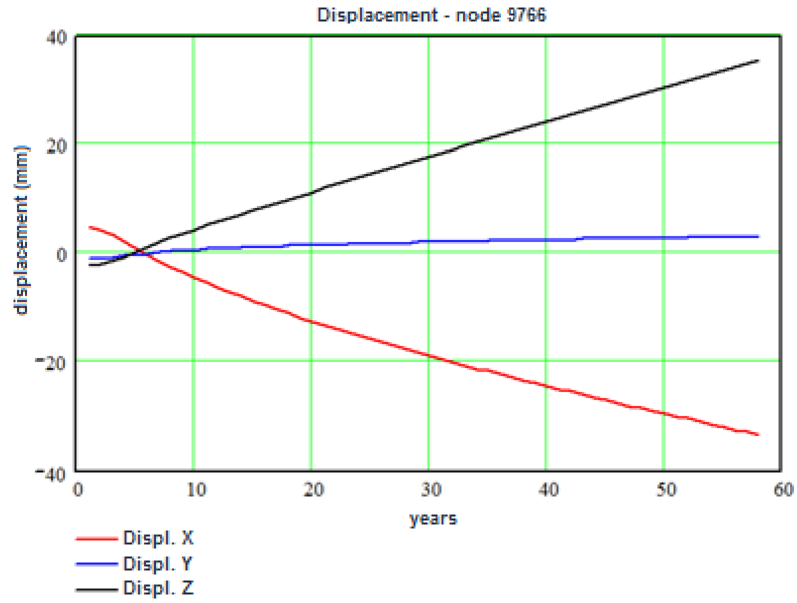

FIGURE 11: Node 9766 behavior graph – Displacements.

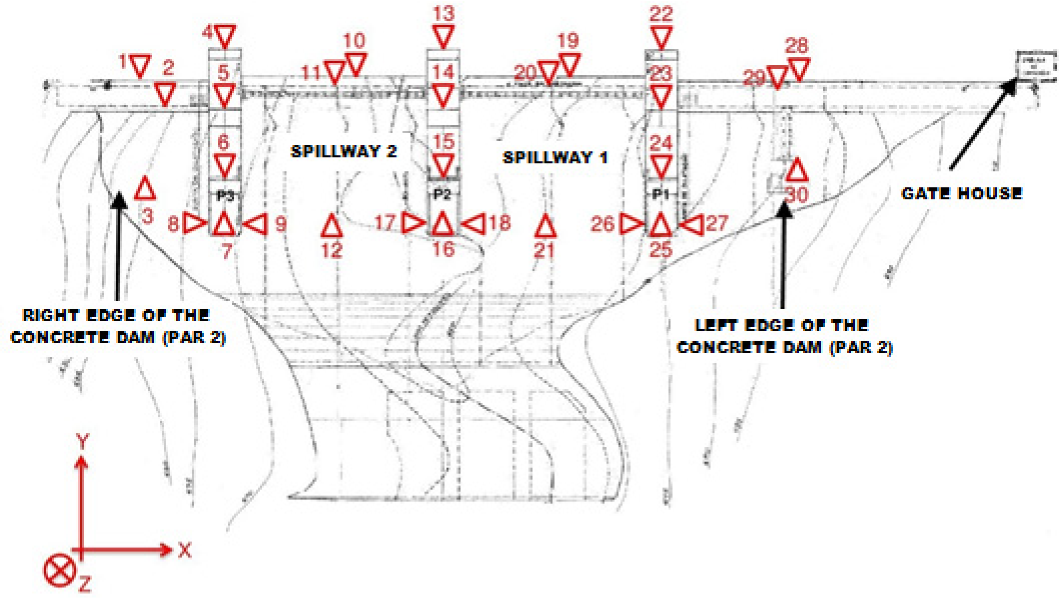

FIGURE 12: Location of the stress verification points.

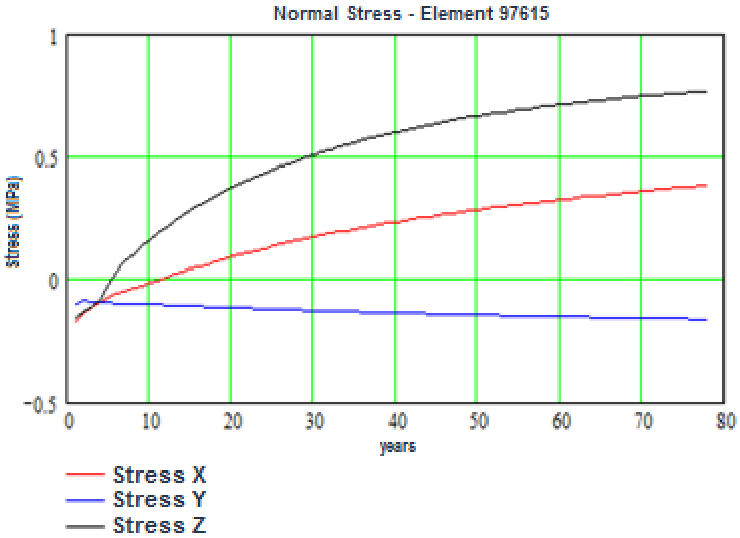

FIGURE 13: Node 97615 behavior graph – Stresses (point 22).