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Performance Analysis of the Ituango Dam, Based On Geotechnical Instrumentation and Models

Zorany S. Zapata [1], María C. Sierra[2], Joshua Naranjo[3]
[1]Geotechnical Engineer at Integral S.A.
Medellín, Colombia
zszapata@integral.com.co; mcsierra@integral.com.co
[2]Lead Geotechnical Engineer at Integral S.A.
[3]Geotechnical Engineer at Integral S.A.
Medellín, Colombia
jnaranjo@integral.com.co

Abstract **-** The performance of the Ituango Dam is analyzed in this document by comparing the results of geotechnical instrumentation with analytical and numerical models. Ituango Hydropower Plant Project has an Earth Core Rockfill Dam with modifications in its upper 50 meters. These modifications include a bentonite cement cutoff wall. The analyses focus on the behavior of pore pressures, settlements, and total stresses to identify the level of performance of the dam fills, the foundation, and important elements such as the cutoff wall indicated above. The field measurements (considering their range of statistical variation) are compared with the outcomes from analytical and finite element models in 2D and 3D. The geotechnical performance analysis of the dam corresponds to the current state, 3 years after its construction was completed. Through this research, it was found that the degree of correlation between field measurements and numerical calculations is high and, therefore, the measured variables are within what was expected. This information has also been of particular importance for the identification of anomalous behaviors, which complements the project's risk management plan.

Keywords**:** Dam, rockfill, instrumentation, numerical models, settlements stresses, pore pressures.

1. Introduction

Rockfill dams' performance analysis by comparing the instrumentation data with models of behavior is a practice that has been applied for many years. For instance, recent cases are presented in [1] about Albagés dam located in Spain, [2] whose offered as a case study the Marvak Dam in Iran [3] where the performance of the Sabalan Dam located in Iran is investigated, among others.

In addition, the way how this data can be used to define thresholds that help to identify outliers and the individual actions to be implemented has been presented in references such as [4].

Consequently, this article focuses on analyzing the degree of calibration between actual and simulated measurements using different types of models aimed to recognize the instruments with the greatest deviation from what was expected.

The above considers the main measures of pore pressures in the dam fill, pore pressures in the bedrock, settlements, and total stresses in the earth fill the Ituango Colombia dam. The data considered correspond to those obtained during the last three years, where the reservoir has remained at the level 407,2 meters above sea level-m.a.s.l. with variations up to 2,0 m.

2. General Description of the Project

Ituango Hydropower Plant Project (HPP) is located at the northwest of Colombia, department of Antioquia, 170 kilometers from the Medellín city. Its dam has a maximum height of 225 m - 230 m from the bed of the Cauca River. The crest has a length of 550 m and 18 m of width. The volume of materials employed for its construction was 20 million cubic meters. A plant view of the Ituango Dam is given in Fig. 1.

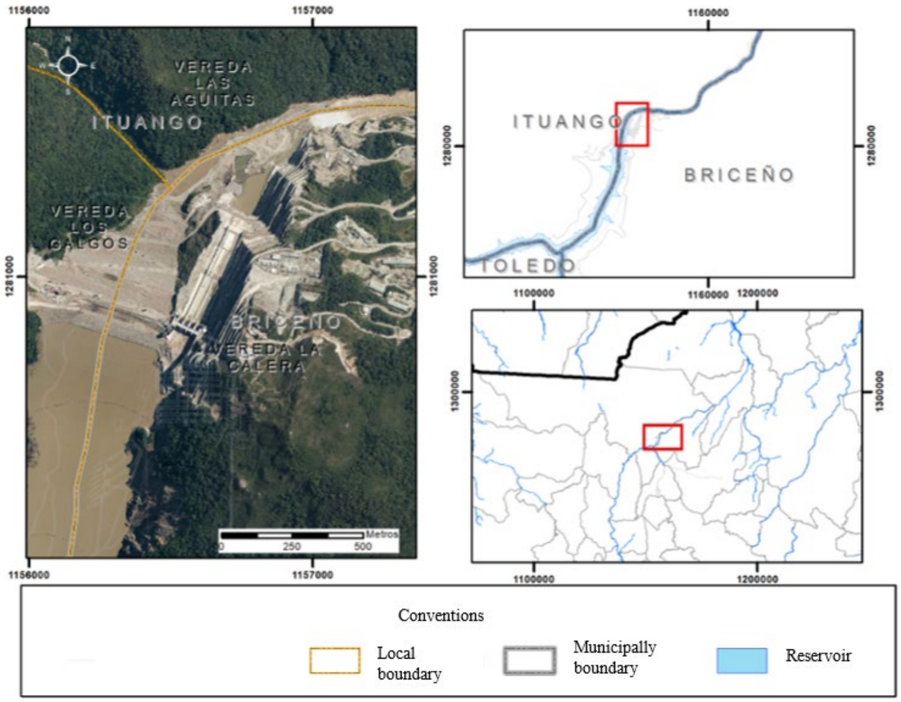

Fig. 1: Location of the Ituango Dam.

Likewise, the main section is shown in Fig. 2 which corresponds to km 0+480 (the highest part of the dam).

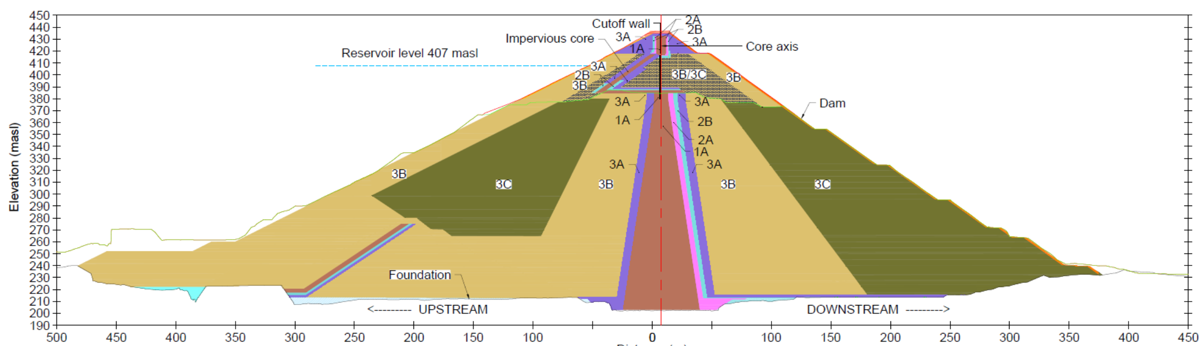

Fig. 2: Highest section in km 0+480 of the Ituango dam.

3. Geotechnical instrumentation

It is important to understand what kind of variables are monitored at the Ituango HPP dam, as well as the installation point of each sensor. The instrumentation of this dam was defined according to the probable models of failure. This article refers to the main sensors for the measurement of changes in the pore pressures, total stresses, and settlements, which are also verified using analytical and numerical models.

Vibrating wire piezometers were installed in the core 1A and near the cutoff wall (both upstream and downstream), foundation/riverbed rock mass (upstream and downstream of the deep grout curtain) and in the abutments (downstream of the deep grout curtain) to track the effectiveness of whole dam waterproofing system. These instruments are identified as PCV-PRE. The general location in plant of this instrumentation is shown from Fig. 3.

Piezoelectric cells (CA-PRE) were installed for the monitoring of deep vertical settlements both in the lower core 1A and in the downstream rockfill. On the other hand, magnetic extensometers (EM-PRE) allow the monitoring of vertical settlements in the cutoff wall and in the upper core 1A. With the pressure cells (CP-PRE) the total stresses inside the lower core 1A are monitored. The location of these sensors can be found in Fig. 3.

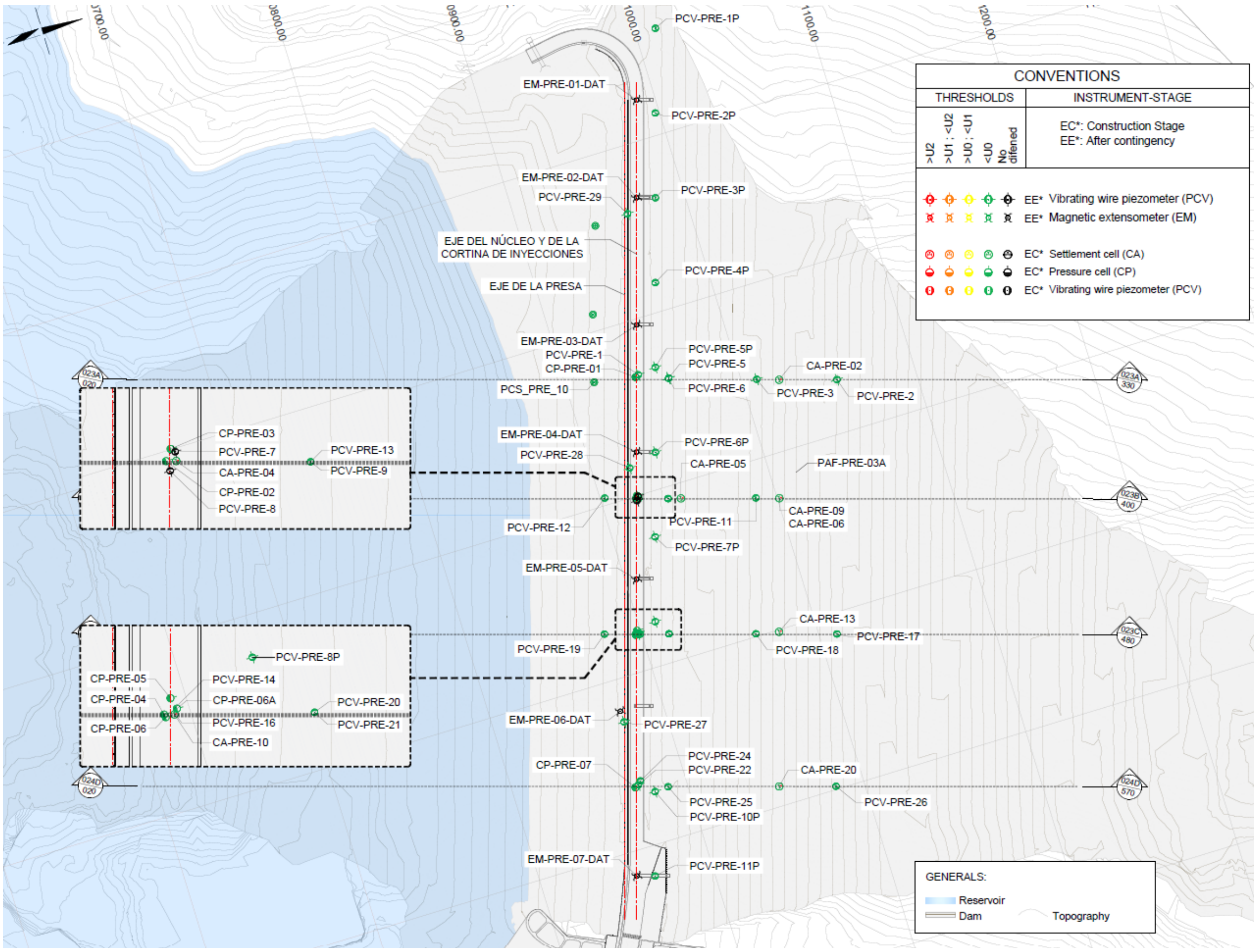

Fig. 3: Instrumentation of the Ituango dam- piezometers.

4. Results of the instrumentation and comparison with the models

This section summarizes the main results of the geotechnical instrumentation of the dam (pore pressures, settlements, and stresses). Based on all the records obtained up to August 2022, the main findings, and the degree of calibration of these with respect to different analytical and numerical models will be highlighted.

Fig. 5 shows the piezometric records core located below level 385 m.a.s.l and the foundation. This chart shows how three years after the dam was completed, the variations in the readings exhibited a tendency to stabilize with changes associated only with the reservoir (in the last three years the reservoir has varied between levels 406 m.a.s.l and 409 m.a.s.l, its average level has been 407,2 m.a.s.l).

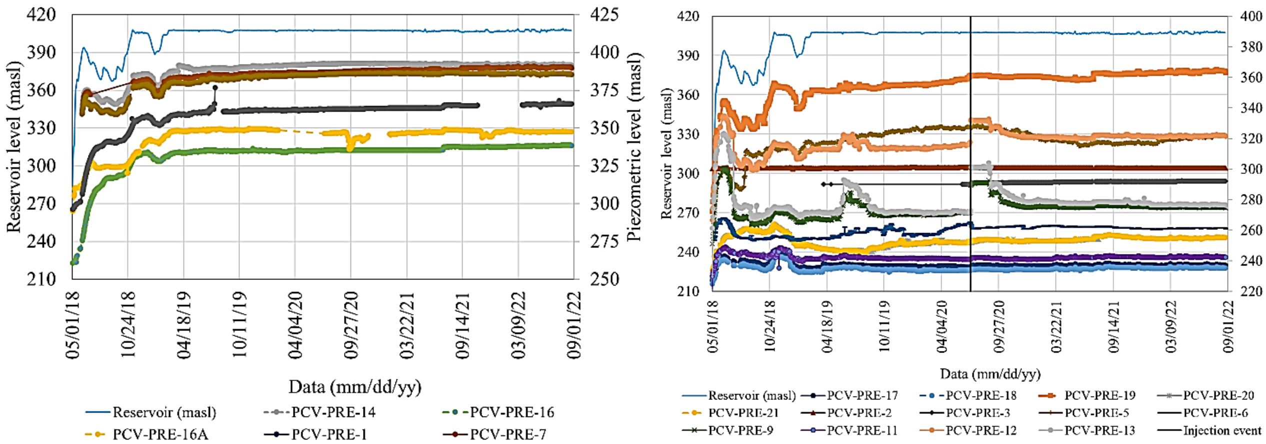

Fig. 5: Historical records of piezometers located in the core below 385 m.a.s.l (left side) and foundation (right side).

The same happens with the piezometers of the foundation. The main changes in the PVCs located on the downstream side of the deep grout curtain are only due to injection processes that have been carried out in nearby galleries, and in a particular case, the PCV-PRE-5 and 6 are highlighted, after the reservoir reached its normal operating level in the last three years. These two sensors were installed in the same borehole, downstream of the deep injection curtain, near the abscissa km0+330, km+0400 and gallery 250 MI (drainage and injection gallery located in the left abutment through the longitudinal axis of the dam, level 250 m.a.s.l). The readings in sensors 5,6,12 and13 have been impacted by the performance of the deep injection curtain of the left abutment, therefore, it was decided to implement a concrete lining on the west side of the 250 MI gallery and a reinforcement in the grout curtain as well.

The piezometric levels on the upstream side of the cutoff wall are listed in Fig. 6. According to these readings, this piezometric level remains between 5 to 4 m.c.a below the level of the reservoir, while a constant piezometric level has not been detected on the downstream side of the cement bentonite wall. This shows the effectiveness of the actions taken to waterproof the sector between 385 m.s.a.l and 418 m.a.s.l.

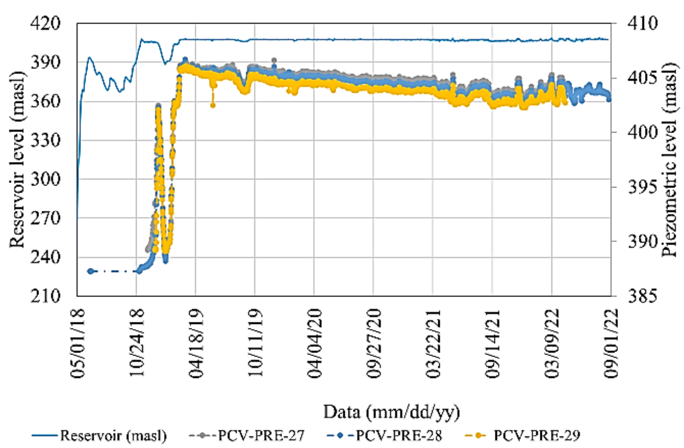

Fig. 6: Historical records of piezometers on the upstream side of the cutoff wall.

As mentioned before, in different parts of the lower earth core and the downstream rockfill settlement cells were installed. According to the Fig. 7 (left side) the current settlement in the lower core does not exceed 200 cm. However, in the readings of these equipment erratic variations have been observed that are due to the precision range, to the loss of glycol, etc. In consequence, during this research, the data were considered only until they were consistent.

On the other hand, the same Fig. 7 (right side) where the behavior of the pressure cells is shown (vertical component), the data shows that this parameter presents less variation over time and with a tendency to stabilization during the last 3 years. Likewise, it has been identified that the relationship between the horizontal and the vertical stresses K remains constant in the time, after the dam fills finished. In the highest section, the K remains between 0.4 and 0.5. Towards the abutments this ratio decreases to values close to 0.3. At the bottom of the valley, that ratio remains close to 0.5. There is no loss of stresses where this type of sensors has been installed. Measures of total stresses and pore pressures support each other as variations for sensors installed in the same sector follow the similar tendency. Similar stress ratio values were found by [5] and, [6].

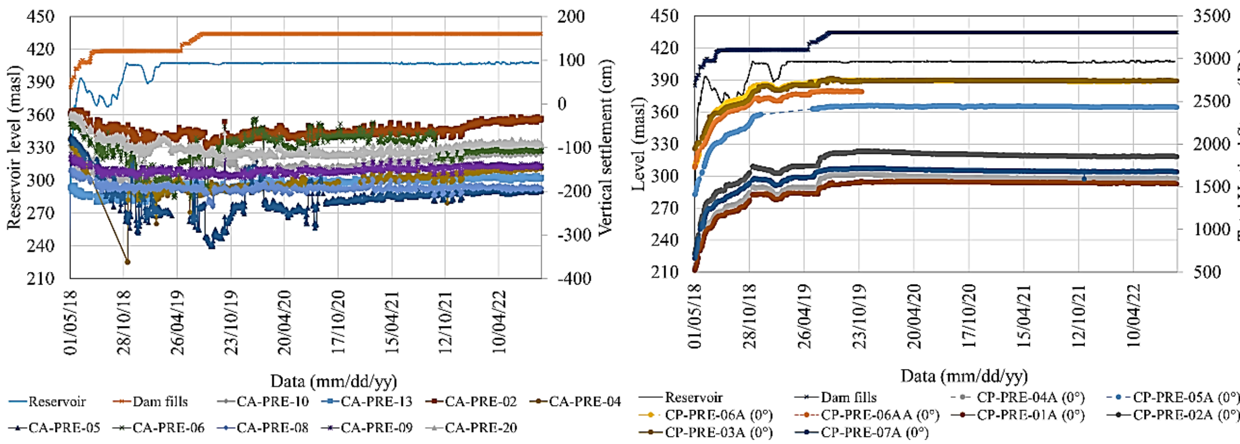

Fig. 7: Historical records of settlement cells (image on the left) and vertical pressure-stress cells (image on the right).

Moreover, considering the data from the magnetic extensometers (Fig. 8) it is noted that the crest of the dam settled around 50-60 cm in the highest section. This vertical displacement corresponds to the settlement experimented only by dam fills built between level 418 m.a.s.l to 435 m.a.s.l. Also, with this data, it was observed that the transition between the upper core 1A and the top of the cutoff wall settled at a rate like the crest. On the other hand, the settlements in the datum which represent the movement of the foundation of the cutoff wall (supported by the upper 5,0 m of the lower core 1A) were of the order of 10-20 cm. This means that the cement bentonite wall was shortened vertically to around 40 cm. Bearing in mind that the cutoff wall has a total height of 38 m, this shortening represents a vertical deformation of the order of 1,1%.

The vertical deformation of 1,1% is within the capacity of the cement bentonite material since with an extensive program of laboratory tests (triaxial tests executed at different states of confining pressure, different hydraulic gradients, and at different curing ages, among other types of tests) it was found that with deformations of the order of 6-10% the cement bentonite material still maintains the expected permeability value (approximately 5e-8 m/s).

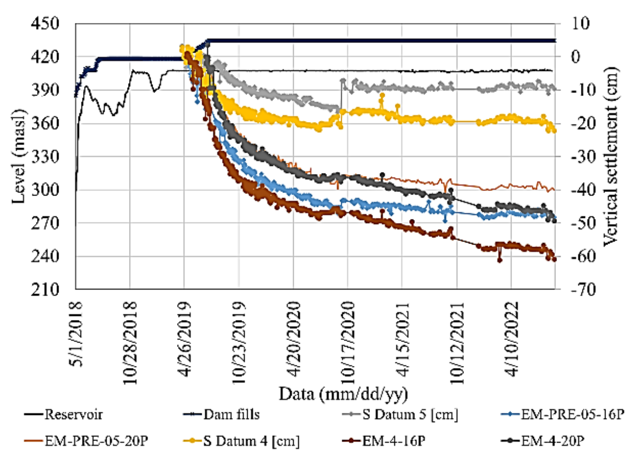

Fig. 8: Historical record of magnetic extensometers 4 and 5 (the datum sensor corresponds base of the cutoff supported by the lower core 1A, the 16P sensor corresponds to the plate closest to the cutoff-upper core transition 1A and, the 20P sensor represents the plate closest to the crest of the dam).

Correlations are periodically established between the data shown before and the analytic models, numerical 2D and 3D models of the Ituango HPP dam. Numerical models were built with software such as Rocscience RS2® for 2D analysis and Midas GTS NX® for 3D analysis. For that purpose, a linear regression analysis was implemented between the real and the estimated values; also, the coefficient of determination R2 is calculated. This coefficient of determination varies between 0 and 1 with values close to 1 being a sign of a perfect correlation between the measures. Thus, according to Fig. 9, by August 2022 the coefficient of determination R2 between the field readings of piezometric levels in the dam fills, with the numerical models, is of the order of 0,96 which is considered a strong correlation. In the lower core, readings of sensor 8 present greater deviation with respect to the simulated for which a possible wear of the sensor is being investigated. Likewise, a high correlation based on a coefficient of determination R2 of 0,89 is also evident considering the piezometer level in the dam foundation. In the dam foundation, sensors 5 and 6 present high deviations with respect to the numerical calculations, and for that reason, actions were applied to extend the security margin as described before.

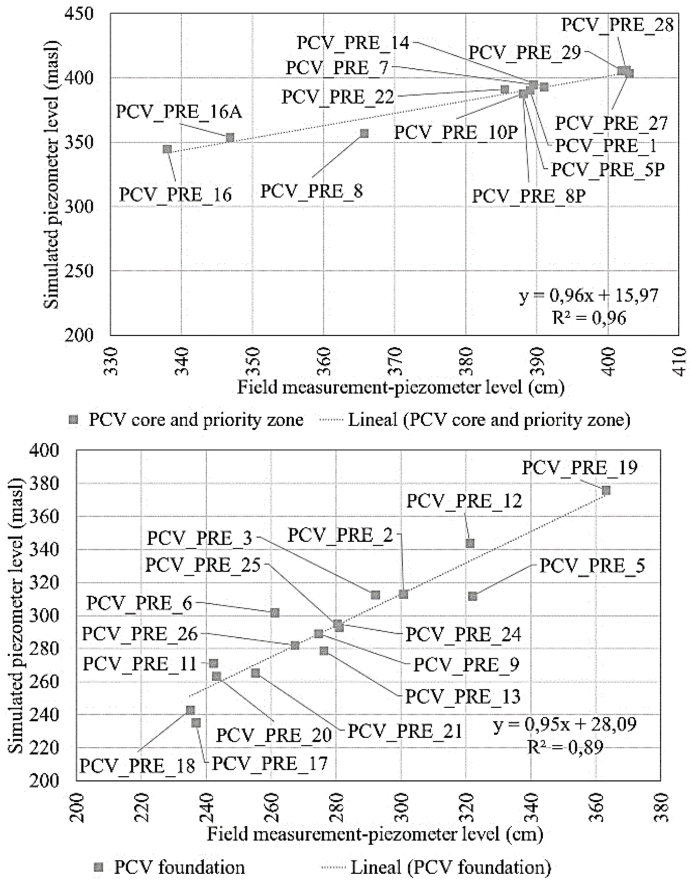

Fig. 9: Level of correlation between piezometric field readings in the dam fill (left side) and foundation (right side) with numerical modeling.

Fig. 10 (left side) shows how the readings of the settlement cells have the largest deviation of the dam instrumentation system due to the difficulties with their precision range, etc., as stated above. Therefore, in this analysis, only the consistent data up to where a correct operation was detected in the equipment were considered. Also, following the same Figure 10 (right side), the real total stresses have a strong correlation with the analytical estimates which R2 is 0,95.

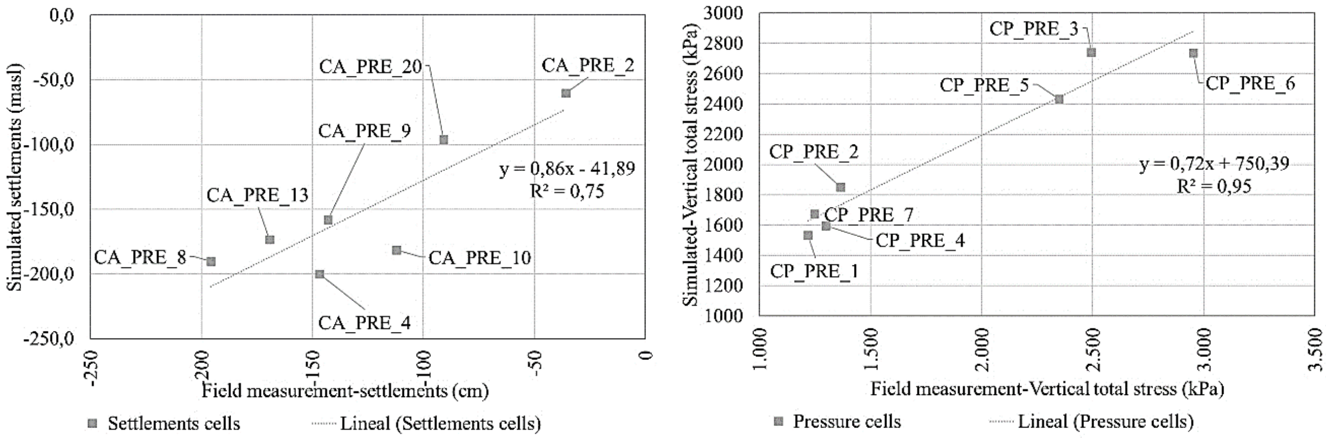

Fig. 10: Level of correlation between core settlement readings (left side) and total vertical core stresses (right side) with numerical modeling.

This comparison between field measurements and numerical simulations is made periodically (frequencies varies from biweekly to annually), for the Ituango dam. Additionally, the annual diagnosis is complemented by the statistical analysis of all variables. Using the range of statistical variation of each variable and the values simulated by numerical methods, the alert thresholds of each sensor are reviewed. These thresholds are defined as:

$$Threshold0 = x\sigma + \mu \quad (1)$$

$$Threshold1 = y\sigma + \mu \quad (2)$$

$$Threshold2 = z\sigma + \mu \quad (3)$$

In the listed equations, μ is the maximum value between the average observed data and the expected according to the numerical models (the latter, if available). For the definition of the value μ the degree of precision of the equipment is also considered since variations in the readings due to this aspect are expected, without that representing a change product of the geomechanical behavior of each involved material. The value σ corresponds to the standard deviation of the observed data. The variables x, y and z represent coefficients equal to one, two, or three.

Supported on thresholds defined by the previous methodology, with the response actions established for each threshold, and the alarm level of the emergency plan, the risk management of this dam is completed. Thresholds response actions include the review of the reliability of the data, review of the equipment, readings correlation with nearby sensors, and increasing the frequency of readings to obtain a correct measure after outliers were identified. In extreme cases after a complete analysis of the dam, an emergency plan with higher alert levels could be activated to control or reduce the risks.

4. Conclusion

Ituango HPP dam has been found to be stable considering the results from its geotechnical instrumentation. The performance of the foundation, the dam fills, the cement bentonite cutoff wall, etc. is adequate according to the capabilities of each material. Pore pressures on the upstream and downstream side of the deep injection curtain are within expectations and considering these analyses actions have also been determined to extend the safety margin. The pore pressures in the dam fills are also commensurate with the hydraulic capacity of the materials that constitute the waterproofing system. This study helped to determine to what extent the measurements of the settlement cells in the core can be considered reliable. The vertical settlement in the cutoff wall is adequate for the geomechanical capacity of the cement bentonite material. Finally, the total stresses in the core were verified and they are consistent with the load conditions acting on the dam, they showed little variation over time and the stress relationships are coherent with the effect of the valley in the redistribution of stresses inside the dam fills.

In conclusion, the examination of the historical behavior of each variable measured by geotechnical instrumentation installed in a dam and its correlation with numerical behavior models is a valuable tool for the risk management of this type of structures, since it allows to have the sensitivity on the values that can be expected in the readings and / or understand how the trends of the data should vary under different conditions of loading. Based on the permanent analysis following an established methodology, it is possible to identify which field readings do not correspond to what is expected and what actions may be required to reduce the level of risks.

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