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MONITORING SEEPAGE FLOW THROUGH CARUACHI LEFT EMBANKMENT DAM DURING INITIAL RESERVOIR FILLING

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The construction of the Caruachi Dam was completed in early 2003 and is the third dam developed for the Lower Caroni River Hydroelectric Power Development Project located in eastern Venezuela. Most of the left embankment dam is built on an overburden consists of interbedded layers of alluvium, Kaolin and decomposed Gneiss. Since the reservoir level reached the normal operating level in March 2003, the groundwater table at some locations downstream of the left dam has risen to within a short distance from the ground surface. The collected pore pressure data have shown that the conditions inside the dam are relatively normal and stable as anticipated. The collected data will be used to develop seepage simulation models for assessment of the present and future seepage conditions with respect to the performance of the dam. In this paper, the seepage conditions of the left dam as indicated by the collected piezometric data are presented. The approach being considered for developing the seepage models is also described.

1 Introduction

Caruachi Dam is part of the Lower Caroni River Hydroelectric Development Project located in the eastern Venezuela, near the confluence of the Caroni River and the Orinoco River. The project consists of four dams, namely, Guri (9,715 MW), Macagua (2,968 MW), Caruachi (2,196 MW) and Tocoma (2,160 MW) (see Fig. 1). The first three dam projects have been completed and the Tocoma dam is in the early stage of construction. Caruachi power station generates electricity as a “run-of-the-river” hydro project by discharging 4,800 m^3/s of water through 12 Kaplan units. Figure 2 shows the main components of Caruachi Project including a 1,200 m long right concrete faced rockfill dam, a 50 m high main concrete gravity dam with a integrated spillway and a power house, and the 4,200 m long left earth and rockfill dam (left dam). The 176 m wide three-bay nine-gate spillway has a maximum discharge capacity of 30,000 m^3/s.

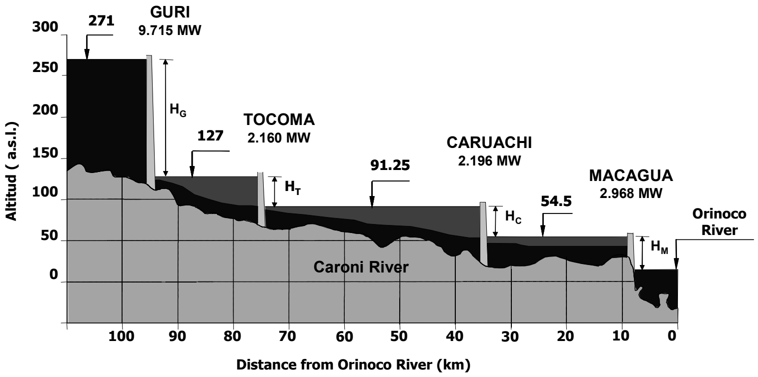

Figure 1. The Lower Caroni River Hydroelectric Development Projects.

Caruachi reservoir reached the normal operating level of 91.25 m (above sea level) on 12 March 2003. The construction of the project was carried out with a two-stage diversion plan, Marcano et al (2004). The first stage diversion was accomplished by construction of cofferdams and the channel width was reduced from 1,200 m to 350 m. The cofferdams allowed building the spillway, powerhouse and right dam on the dewatered river bed. The second stage diversion was accomplished by provision of eighteen 5.5 m x 9 m bottom sluices for construction of the left dam. After completion of the sluice closure and reservoir filling, the first Kaplan unit became operational on 30 April 2003. During and after the reservoir filling, the seepage conditions of dam structures including the left dam were monitored continuously.

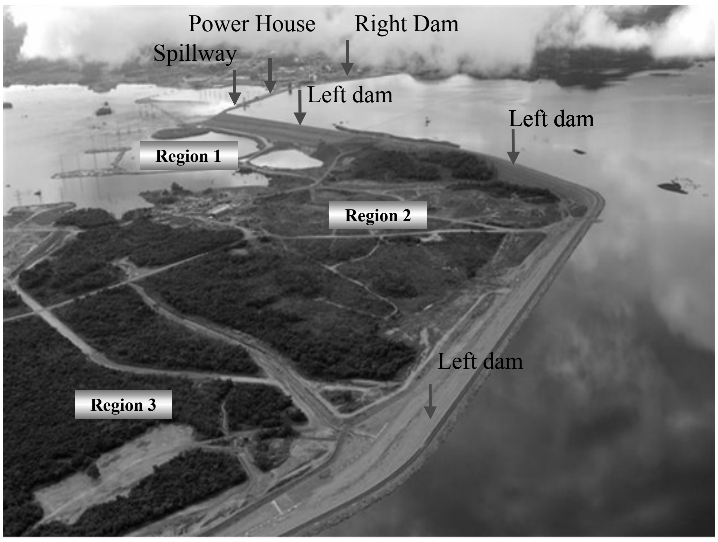

Figure 2. Left dam of the Caruachi project.

2 Objectives

During and after the reservoir filling, the saturation and movement of the phreatic surface inside the left dam and the foundation must be carefully monitored to ensure the integrity and safe operation of the dam. Special attention has been given to the performance of the foundation due to the existence of interbedded pervious and relatively impervious layers in the foundation. A careful analysis of the piezometric and pore pressure data will make it possible to appraise the performance and safety of the left dam in the future. It is our goal to develop seepage simulation models by integrating the models with field and monitoring data including complex geologic information and field conditions at the boundaries of the models. These models will be applied to evaluate the future seepage conditions inside the dam and its foundation for assessing the performance of the dam.

3 Caruachi Left Earth and Rockfill Dam (The Left Dam)

The left dam is situated over three different geologic regions as show in Fig. 2. In Region 1, the dam lies on bedrocks composed of coarse feldspathic gneiss, and the bedrock outcrops along both riverbanks (geologically known as Imataca formation). Over Region 2, the foundation consists of ferrous quartzite and outcropping feldspathic gneiss (Imataca formation). The geology in Region 3 is more complex. It comprises of alluvial sediments from the Quaternary rocks of the Mesa formation, Camacho et al (2001). The dam sections in Region 3 were designed with special consideration given to the control of seepage flow in the foundation. The last 700 m of the left dam is resting on an overburden of up to 75 m in thickness that consists of interbedded layers of alluvium, Kaolin, and discomposed Gneiss (see Fig. 3). Due to the relatively large size of the Mesa formation, several alternative alignments of the dam axis over this formation were investigated. The alignment was finalized by minimizing the volume of the alluvium underneath the dam. As shown in Figure 3, a typical dam cross-section consists of a downstream shell with compacted clay, silt and sand materials, and a upstream shell consists of compacted discompose gneiss. A filter located between the upstream and downstream shells is also provided.

4 Instrumentation

As shown in Figure 4, many monitoring and observation devices were installed in the dam and foundation during construction. Since the last 700 m of the left dam is located in Region 3 with more complex geologic conditions, several pore pressure sensors were installed at three stations such as Section 7 (see Fig. 3). In each section, six vibrating wire piezometers were installed in the foundation to monitor pore pressures. Other devices used to monitor the performance of the dam include 22 Casagrande piezometers for measurement of total pressures, and 52 relief wells for controlling piezometric pressures. A total of 15 observation wells were also installed downstream of the dam for monitoring phreatic surfaces. In addition, seven V-notch type weirs were installed at selected locations to measure the seepage discharges from the dam.

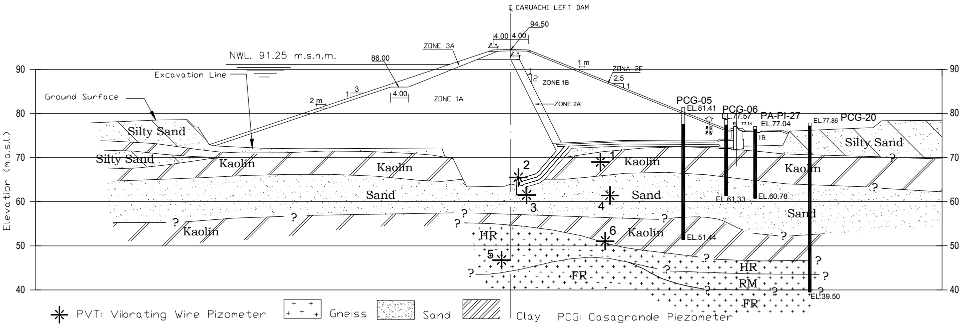

Figure 3. Left dam cross section 7, 3+690.

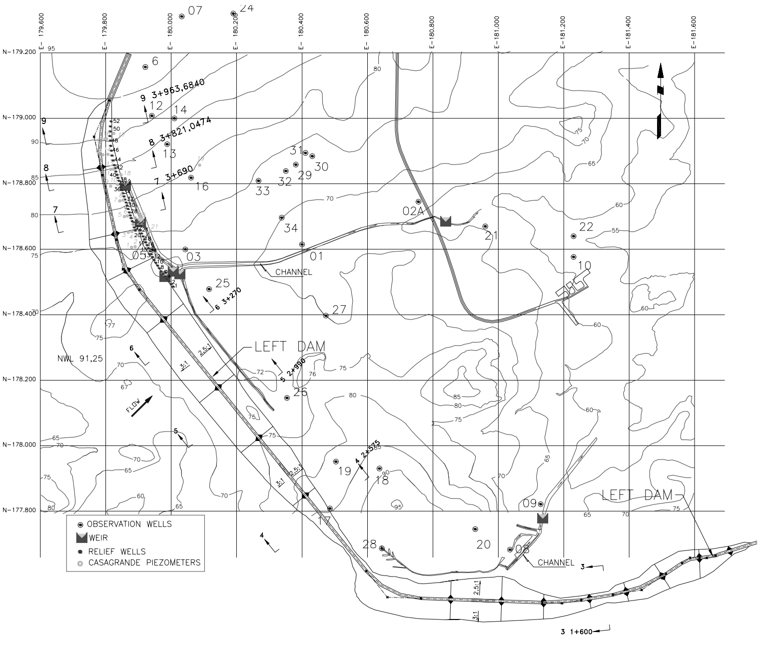

Figure 4. Map showing locations of piezomtric head sensing devices and weirs for flow measurements.

5 Reservoir Filling

During the final stage of construction, all the monitoring devices installed in the left dam had started to function. On December 13, 2002 the closure of the bottom sluices was completed. The reservoir water level had reached elevation 78.12 (16.38 meters below dam crest). On March 12, 2003 the reservoir level reached the normal operating level of elevation 91.25 (3.25 meters below dam crest). During this filling operation, the reservoir was filled at a controlled rate of 0.20 meters per day through adjustments of the spillway gate openings.

5.1 *Observed Piezometric Levels*

A plot of the piezometric level data recorded by the vibrating wire piezometers located in section 7 is shown in Figure 5. Similar plots were also developed for Sections 8 and 9 (not shown).

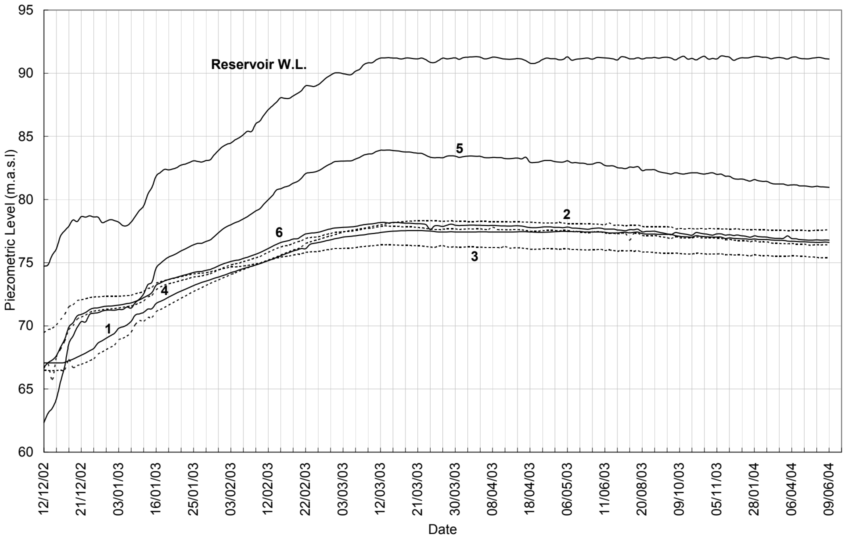

Figure 5. Observed piezometric levels in Section 7 foundation.

these plots show similar trends of the foundation piezometric head responses during reservoir filling. Figure 5 shows that the rising of piezometric level at the bottom of the core trench (Curve 1) followed closely and characteristically in accordance with the rising of the reservoir level. When the reservoir level reached its target level of elevation 91.25 m the recorded piezometric level also reached a relatively stable level. The piezometric level peaked soon after the reservoir reached its target level and started to drop at a relatively slow rate of about 0.1 meters per month. The data obtained from piezometers in the foundation (Curves 2, 3, 4, 5, and 6) indicate that the pore pressures in the foundation responded closely to the filling of the reservoir and became relatively stable after the completion of the reservoir filling. The piezometer readings in the bottom layer (Curve 5) of the foundation was about 6 meters higher than that of other the piezometers at higher elevations in the foundation. This piezometer seemed to have followed the changing reservoir level more closely. The piezometreic head at this bottom layer was dropping at a faster rate of about 0.25 meters per month and appear approaching the levels indicated by other piezometeres at a slower rate. It also appears that this bottom layer may have some degrees of hydraulic connection with the reservoir somewhere upstream. It is also conceivable that the effectiveness of this hydraulic connection was being reduced due to internal migration of fine particles sealing the internal minute passages. The piezometric data recorded by Casagrande type piezometers demonstrated a similar trend as described previously concerning pore pressures recorded by vibrating wire piezometers.

5.2 *Seepage Conditions as Indicated by Relief Wells*

The measured seepage discharge from 11 relief wells located inside the drainage layer between sections 3+619 to 3+760, had decreased by about 40%. In late April 2003, these relief wells were discharging about 7.0 liters per second, and had been steadily decreasing to the recent value of 0.19 liters per second with only one well discharging. As of May 2004, the seepage discharge had become relatively stable. The relief wells placed inside the drainage layer, sections 3+785 to 4+000, also indicated a decreasing discharge. The reduction of well discharge accompanied by a small rate of reduction of the observed piezometric pressure heads (see Fig. 6) is likely attributed to siltation in the reservoir, higher values of permeability used during the design of relief wells, or clogging problems.

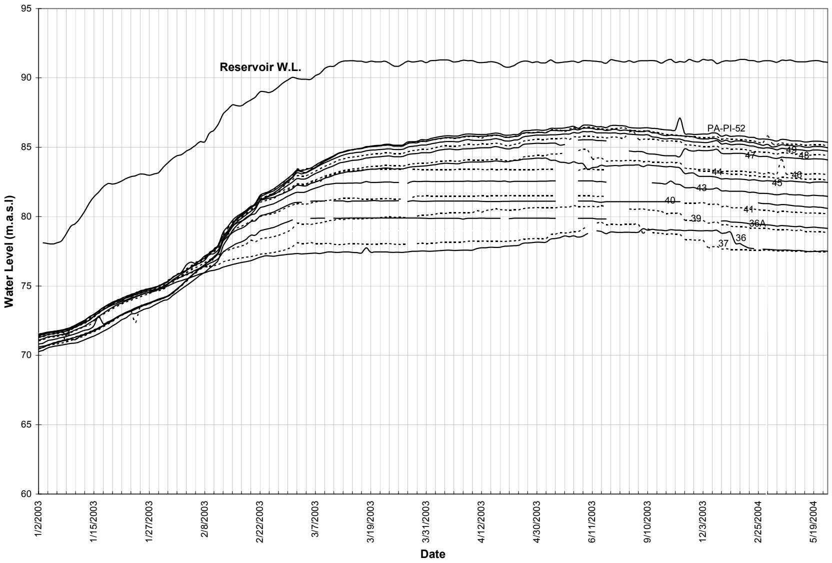

Figure 6. Variation of water levels in the relief wells located in the last 700 m of left dam.

5.3 *Seepage Conditions as Indicated by Observation Wells*

In general, the data obtained from the observation wells show relatively stable phreatic surface in the foundation a year after the completion of the reservoir filling (see Fig. 7). The data also indicate that the water table remains relatively stable in the Mesa formation located about 700 m from the left end of the left dam as well as the Imataca formation.

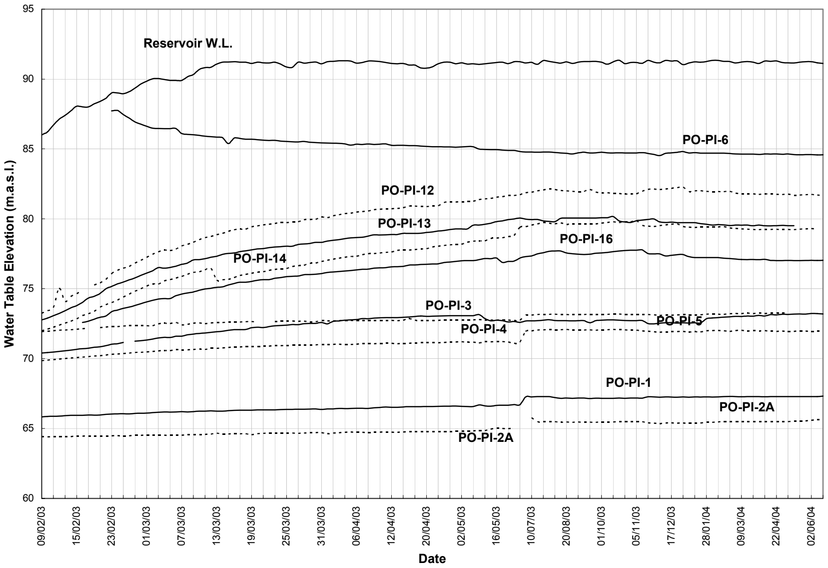

Figure 7. Observed water table elevations in the Mesa Formation.

5.4 *Seepage through Dam Structure*

The measured total seepage discharge through the left dam structure is on the order of 180 liters per second, and it has been estimated that about 91% of the discharge came through the Mesa formation which overlays an impervious layer and a pervious layer in the foundation. The recorded seepage discharges from relief wells and drain outlets for a period of 6 months shown that the seepage flow through the dam foundation is decreasing and becoming relatively stable.

6 Integration of Field Data with Mathematical Seepage Flow Simulation Models – Future Studies

It has been planned to continue the program for monitoring the performance of the dam in the future, and investigations will be focusing on seepage conditions in the foundation in particular the last 700 m of left dam. As a part of this effort, transient seepage simulation models will be developed to supplement the effort. Field data obtained from various pore pressure sensors and piezometers and the test data related to the hydraulic properties of soils and foundation materials will be used to develop the models including development of initial and boundary conditions. Since the original water table of the groundwater at the dam site was located about 10 meters below the base of the dam, the top Kaolin layer of the foundation was partially saturated. The mathematical seepage model of the foundation to be developed will be three-dimensional and capable of simulating the saturation process (wetting) of the partially saturated zones, Wei et al (1978). The foundation will be treated as heterogeneous anisotropic saturated-unsaturated porous media taken into account the complex interbedded layering with different hydraulic properties. The model will be developed to solve the full governing equations for water movement in an anisotropic saturated-unsaturated porous medium, and the finite element method will be applied to obtain solutions. Approximately, the model will cover an area extending about 300 to 500 meters upstream into the reservoir and about 300 to 500 meters downstream from the dam. The right boundary (looking downstream) of the model will follow approximately the longitudinal axes of the approach flow toward the spillway and the exit flow returning to the original channel. The left boundary of the model will be located several hundred meters from the end of the left dam into the left abutment depending on the results of a later investigation of the groundwater regime of the left dam area. The initial conditions will be prescribed based on the field data of the original water table depth and the water contents of unsaturated zones above the water table. Hydrostatic conditions will be imposed at upstream, downstream and right boundaries in accordance with the depth of the water table and the time-dependent reservoir levels. Unsaturated hydraulic conductivities of soils will be determined based on test data, published data of similar soils and database provided by the selected simulation software. The SVFlux-3D seepage simulation software is being considered as the most likely software to be selected for the future development of the Caruachi seepage models. It is an advanced full three-dimensional saturated-unsaturated finite element seepage modeling software. This software includes an extensive database of hydraulic and geotechnical properties of over 6000 soils and greatly reduces the need for performing expensive measurement of soil properties. The software also has a capability of estimating soil properties using one of over 20 published estimation methods.

Summary

The seepage conditions of the Caruachi left dam have been carefully monitored during and after the filling of the reservoir. The collected pore pressure and seepage discharge data have shown that the conditions inside the dam are relatively normal and stable as anticipated. The collected data will be used to develop seepage simulation models for assessment of the present and future seepage conditions with respect to the performance of the dam.

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