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Verification of the mitigation measures for preventing the concrete face failure of a 210m CFRD

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1 INTRODUCTION

The Nam Ngum 3 Hydropower Project is a 480 MW scheme located in Lao PDR and developed by Electricité du Laos (EDL). The project includes one of the highest Concrete Face Rockfill Dams (CFRD) in the world with a maximum height of about 210m.

The project is under construction since 2015. As per June 2019, about 140m of rockfill has been placed. The full commercial operation of the plant is scheduled on November 2021.

The design and the construction of the rockfill and the concrete face is one of the project major challenges. This is due to the height of the dam, the valley shape and the expected high deformations and stresses of the concrete face. More specifically, past experience shows that the expected deformation modulus combined with the valley shape factor led to cracking failure of the concrete face unless specific construction arrangements were adopted.

Moreover, in the case of this dam, the upstream face is constructed slightly upstream of the narrowest part of the valley. As a consequence, there is a significant stiffness contrast between the sides where the concrete face is almost supported by the bedrock and the central part where it lies on the rockfill. Hence, a diagonal bending of the concrete which is not encountered in common CFRDs needs to be addressed appropriately.

ARTELIA, appointed as Owner's Engineer by EDL is conducting a numerical analysis used to check the design and the construction provisions proposed by the Contractor. They shall actually be efficient and adequate to avoid any extensive cracking of the concrete face. The Contractor is also performing a series of numerical analysis used to justify his design but due to the complex behavior of the dam it is not possible to check the results without the help of another numerical model.

Based on the carried out numerical analysis, some adjustments of the construction provisions are being proposed to the Contractor.

2 CONCRETE FACE FAILURE ISSUES ON CFRD

CFRDs are built based on past experience and the continuous evolution in construction provisions and methods. Still a few numbers of high CFRDs have exhibited high leakage rate (up to 1700 l/s) when being impounded.

The leakages are due to a failure of the concrete face for which the deformation is strictly prescribed by that of the rockfill. Actually, the concrete face, with the unique role to ensure the watertightness of the dam, is not able to withstand the water pressure due to its obvious slenderness.

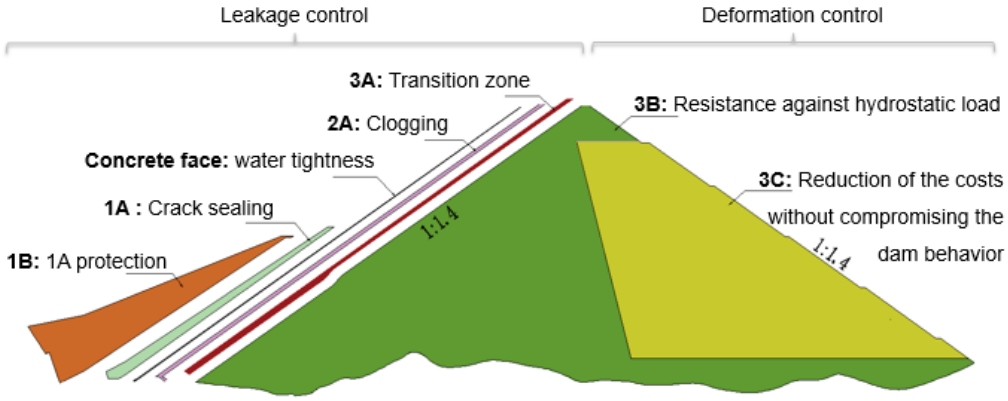

Figure 1. Zoning of the Nam Ngum 3 dam – Central upstream to downstream section.

The stiffness of the rockfill and the valley shape of the dam are the main parameters governing the risks of failure of the concrete face. Several studies show that narrow valleys combined with deformable rockfill increases the concrete face failure risks.

As there is a size effect between the rockfill of the same petrographic nature, the ideal solution would be to use small diameters of rockfill for high CFRD in order to increase their apparent Young's modulus. However, this is not realistic due to the huge increase in construction cost due to the rock crushing. Consequently, it is preferable to apply mitigation measures which allow the deformation of the rockfill to be accommodated by the concrete face without any failure.

Two means of mitigation measures are now state-of-the-art.

The first type concerns the construction schedule which involves the construction of the concrete face after the completion of the rockfill. This avoids the concrete face to be prestressed by the construction settlement of the rockfill. In the case of Nam Ngum 3 dam, two stages of concrete face are planned in order to even avoid any prestress due to the early time-dependent settlement of the rockfill.

The second type involves a series of vertical expansion joints on the concrete face which allows a significant decrease in the stresses due to the impounding. The Nam Ngum 3 dam includes three types of construction joints:

- Tension joints without any initial opening but able to open under normal operating conditions;
- Compression joints with 5cm initial opening and expected to experience partial closure under normal operating conditions;
- Compression joints with 2.4cm which are of intermediate type.

3 MAIN HYPOTHESES OF THE NUMERICAL ANALYSIS

The numerical model performed by ARTELIA by means of *FLAC3D* (Itasca 2019) is rather detailed in order to capture the complex behavior of the dam. It includes:

- A limited extent of the bedrock;
- The main rockfill zones 3B and 3C;
- The concrete face;
- The plinth.

The relative displacements between the members are allowed by means of several interfaces:

- The rockfill/bedrock interface;
- The concrete face/rockfill interface;
- The concrete face/plinth interface (also called peripheral joint);
- The vertical expansion joints of the concrete face with the possible initial opening.

The model includes 100,000 elements most of which are hexahedra. The explicit integration scheme of *FLAC3D* allows the highly non-linear behavior of the dam (initial opening of the vertical joints, HSM law of the rockfill) to be modeled without any numerical issues.

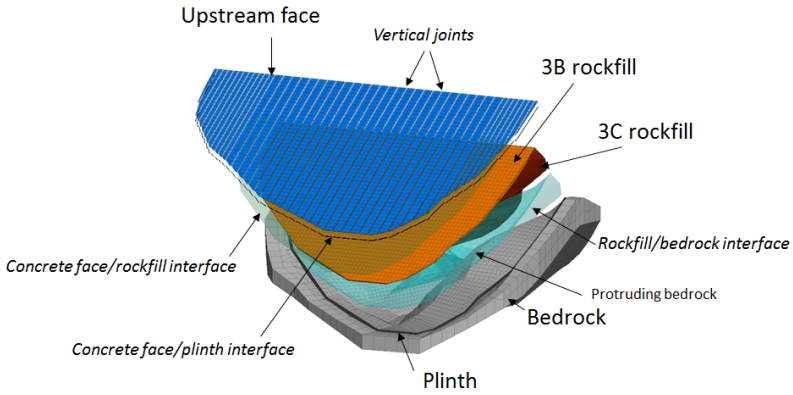

Figure 2. Exploded view of the numerical model of the Nam Ngum 3 dam.

The dam bedrock, the plinth and the concrete face are assigned a linear elastic constitutive law. The rockfill follows the HSM constitutive law for which the parameters are calibrated from large-scale triaxial and oedometer tests. The assessment of the scale effect is based on Frossard's approach and involves:

- The ratio of the diameter of the material used for the construction to that of the samples of the laboratory tests;
- A statistical parameter related to the distribution of the defects in the material.

The scale effect is a factor lower than unity which is applied to the moduli of the material. Based on this approach, the final apparent Young's modulus of the rockfill is about 80MPa.

The monitoring data of existing CFRDs show that a long-term deformation of the rockfill usually occurs after the impounding. Only the long-term deformation during the first 30 years of operation of the dam is significant as stabilization is expected. Prior to any future data given by the monitoring system of the dam, an average value of final long-term settlement given by the literature is chosen for the Nam Ngum 3 dam: 0.3% of the dam height.

Such behavior is included in the numerical model of the Nam Ngum 3 dam where the long-term deformation is generated by a creep formulation following Shen's approach. Practically, incremental stress relaxation is applied to the model until the long-term crest settlement is reached. The stress relaxation applied to each element of the model depends on its stress state as per Shen's approach. The material parameters are calibrated from laboratory tests.

4 RESULTS

The calculated maximum settlement values at the end of construction and after 30 years of operation are respectively 1.9m and 2.4m. They are of the same order as CFRDs of comparable heights.

The beneficial effects of the initial opening of the vertical expansion joints are highlighted by means a sensitivity analysis considering or not this initial opening. A significant decrease in the magnitude (30%) of the compression stress and the area of the region under high compression stress (400%) is noticed. On the other hand, the extruded curb behind the vertical compression joints needs to be sawn in order to avoid compression crushing which may tear the watertight protection of the vertical joints.

The calculations also show that the protruding bedrock generates diagonal tensile stresses in the concrete face which cannot be balanced by rebar cross section designed so far and which needs to be increased.

Finally, the calculations show that despite a delayed construction of the concrete face, a detachment between the concrete face and the rockfill is expected at high elevations. This detachment tends to increase after 30 years of operation. The construction of a horizontal joint (without any crossing rebar) at the bottom of the detachment proves to be efficient in the reduction in their magnitude and in their extent according to the numerical model. Moreover, such construction provision may also avoid any random cracking of the upper part the concrete face under seismic loadings even if the dam is built on a rather low seismicity area (PGA = 0.12g).

5 CONCLUSIONS AND PROSPECTS

The material parameters of the model are continuously updated with the progress of the construction of the rockfill and the available monitoring data (hydraulic and electromagnetic settlement gauges). It appears that the apparent Young's modulus of the rockfill is higher than expected (150 MPa approx.), probably owing to a compaction which is higher than usual. More specifically, the compaction generates grain breakages which reduces the in-situ diameters of rockfill and consequently reduces the scale effect factor to be applied on the material moduli.

The numerical analysis performed confirms that most of the construction provisions should allow the concrete face to avoid a critical failure. A few aspects of design still need to be addressed in order to secure a satisfactory water tightness.

The calibration of the numerical model to the monitored behavior will be continued until the first impounding. It is possible to use the model as a help for the monitoring and maintenance of the dam for its operation.

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