Behavior of the Rock Foundation of a Concrete Dam Affected by Alkali-Aggregate Reactivity

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ABSTRACT: The Beauharnois dam is located near the city of Montreal (Quebec, Canada). The water intake and the powerhouse are founded directly on a quarzitic sandstone rock mass. The coarse aggregate used in the concrete to build the dam originates from these rocks and has a high reactivity to cement alkalis. This reactivity called alkali-aggregate reaction (AAR) is a slow reaction that causes the concrete to swell. Regarding the foundation, swelling of the concrete led to the transfer of stresses to the rock foundation. The intact rock is of high resistance and the rock mass of good quality. The dam foundation is stable to sliding despite the sub-horizontal bedding of the sandstone and the transferred stresses. However, it is shown that, locally, depending on the intensity and orientation of the stresses, they can contribute to the vertical opening of discontinuities near the concrete-rock interface.

Keywords: Dam, Foundation, Alkali-Aggregate Reaction, Discontinuities, Stresses.

1 BEAUHARNOIS DAM

The Beauharnois dam turbines a large part of the waters of the St. Lawrence River (see Figure 1). This large run-of-river power station is 1,397 m long, houses 36 turbine-generator units and is backed by a water intake with 74 passes. The particularity of Beauharnois generating station lies in its construction in three phases. Work for phases 1, 2 and 3 began in 1928, 1948 and 1956 respectively with the commissioning of each phase in 1948, 1953 and 1961.

The concrete aggregates from the Beauharnois power station were obtained by crushing excavation products from the Potsdam sandstone on the development site. The cement used for the construction of the three phases was of the ordinary Portland type. The first signs of concern about the swelling of concrete came in 1940 following the observation of cracks in the concrete of phase 1 of the construction. Several investigation campaigns were carried out to conclude that the swelling was caused by a reaction between the cement alkalis and the aggregates (Bérubé et al. 2000). Nowadays, this type of reaction, called alkali-aggregate reaction (AAR), is well known (Sims & Poole 2020).

Figure 1. Left: Photograph of the Beauharnois Dam. Right: Plan view of the dam with approximate location of selected investigations boreholes (red dots).

2 GEOLOGICAL SETTING

The foundation of the Beauharnois development is composed of quartzitic sandstone belonging to the Cairnside Formation of the Potsdam Group. Figure 2 shows a typical section of the dam as well as a photograph of the foundation rocks taken during construction. The sandstone of the Cairnside Formation consists of 92-99% rounded quartz bound by calcareous cement. The top of the formation may consist of sandstone with a carbonate cement. The feldspar content is low and there are very few accessory minerals. As for joint families, the geological maps of Clark (1952) and Globensky (1986) show some measurements of bedding which is sub-horizontal. The precise orientation of the layers is difficult to determine given the very low dip of the layers which varies from 1° to 6°.

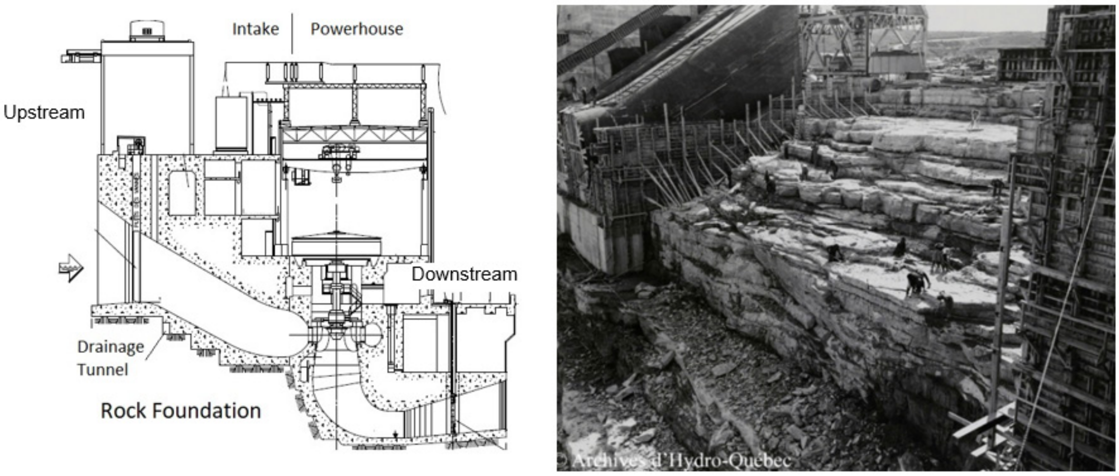

Figure 2. Typical profile of the intake and the powerhouse (left) and the bedded sandstone of the rock foundation (right).

3 FOUNDATION GEOMECHANICAL PROPERTIES AND CLASSSIFICATION

Various investigation campaigns to characterize the concrete at the Beauharnois dam included the drilling of boreholes which, in some cases, were extended into the rock foundation to obtain information on the concrete-rock contact and on the rock foundation. Location of investigation boreholes is shown on Figure 1 (right). Drill core descriptions as well as borehole televiewer surveys were used to determine the quality of the rock mass. Rock specimens taken from drill cores were used to determine the mechanical properties of the intact rock. Classification of the rock mass of the foundation requires linking the resistance of the intact rock, the presence of joints sets (fractures) in the rock with data on the spacing, roughness and filling of these joints. The presence and circulation of water in the rock mass are important inputs in this classification. Quality of the rock mass is assessed using Rock Mass Rating (RMR) and Geological Strength Index (GSI).

3.1 Intact Rock Properties

Values of uniaxial compressive strength, indirect tension, elastic modulus and Poisson's ratio were determined in the laboratory following applicable standards (see Figure 3). It is important to emphasize that this table shows statistical data to assess the intact rock strength. Figure 3 makes it possible to classify the intact rock of the foundation of Beauharnois in a category of high resistance and high stiffness. The density of intact rock was measured in the laboratory, and, for 12 tests, the average value is 2627 kg/m^3 with respective minimum and maximum values of 2592 and 2695 kg/m^3.

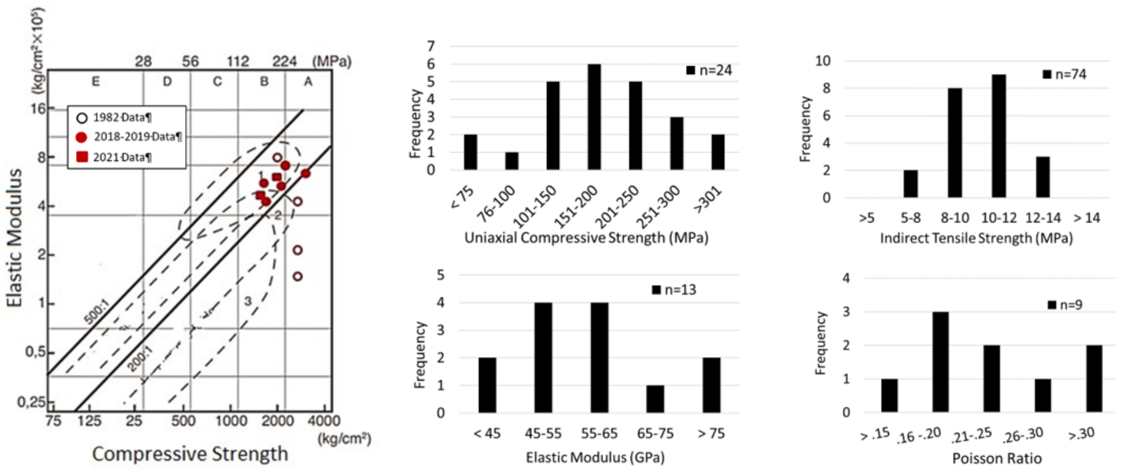

Figure 3. Intact rock classification and geomechanical properties.

3.2 RQD, Joint opening, Spacing and Roughness

RQD values from the 1991, 2018, 2019 and 2021 core descriptions were compiled with the corresponding percentage of cores belonging to each of the RQD classes: 68% of runs (1.5m length) are in the good and excellent quality class, about 16% in the fair class and 16% in the poor and extremely poor quality. The same was done with joint spacing and joint opening data. Spacing classes are chosen to match that of the RMR classification method. A joint spacing of 60 mm and less has the highest total frequency. The distribution decreases linearly up to the class > 2 m for which only one datum is recorded. Joint opening is less than 1 mm in general and the measured values for roughness (Jr) are 1, 1.5 and 3 for a percentage of 40%, 35% and 25% respectively. It is important to consider that the data comes from six boreholes distributed at different locations in the structure.

3.3 Water and drainage holes

No drainage holes are drilled in the rock foundation for the Beauharnois structure. Water collection is made through a drainage tunnel located at the concrete-rock contact and at 9.75 m from the upstream face of the structure. Its purpose is to collect the water coming from the rock and the concrete-rock contact. A series of "box drains", distributed under the structure, are connected to this gallery and they channel the waters to direct them downstream. However, flow rates (estimated visually) are generally low, often referred to as “drops” or less. The compilation of all the data shows that 63% of the observations are less than or equal to the “drops” category, 23% equal to “small flows” and 14% in the “medium” and “high” flow classes.

The previous paragraphs have dealt with the different characteristics of the bedrock foundation. From the ranges of values obtained, the value of the RMR index used to classify rock masses was determined. For the foundation rock mass, a rating of 73 is obtained and corresponds to a rock mass of good quality. For comparison, the GSI (Geological Strength Index) value is also determined with the well-known chart by Hoek & Brown. The GSI value considered is around 70. This corresponds quite well to the accepted equivalence of GSI = RMR – 5 (Ceballos & al. 2014).

4 DAM AND FOUNDATION BEHAVIOUR UNDER AAR STRESSES

4.1 Numerical Model for alkali-aggregate reaction simulation

A numerical model of Beauharnois dam was developed consisting of the right-wing dam, the 37 units (water intake and powerhouse), the spillway, the left-wing dam, and the rock foundation. Each unit has a total height of approximately 38 m and a crest length of approximately 20 m. The rock foundation has approximately a length of 1090 m, a width of 309 m and a variable height ranging from 90 m to 105 m. The finite element mesh is constructed using a total of 21,831,271 elements and 19,537,465 nodes (ANSYS®). The concrete dam body is meshed using ANSYS's USER300 hexahedral elements while the rock foundation is meshed with linear tetrahedral elements. The mesh size is more refined for the concrete dam body elements and is coarser for the rock foundation elements. Finally, the mesh of the rock foundation is constructed so that the nodes at concrete-rock foundation interface coincides and are merged. The numerical model is in constant evolution. However, many details can be found in Roth and Miquel (2021).

4.2 Deformation of the structure

The presence of the AAR inevitably affects the behaviour of the different sections of the dam. One of the first effects of this concrete swelling reaction is the appearance of cracks in various places in the concrete as well as the overall deformation of the structure. Figure 4 shows an image of this deformation (amplified 50 times) as well as an example of concrete cracking. In the vertical direction Z, the swelling creates an elevation. The water intake section deforms upstream and the powerhouse section downstream. The axis of inertia of the lateral swelling (Y direction) is located slightly upstream of the joint separating the water intake from the powerhouse. In the longitudinal direction (X), globally the deformations are negligible.

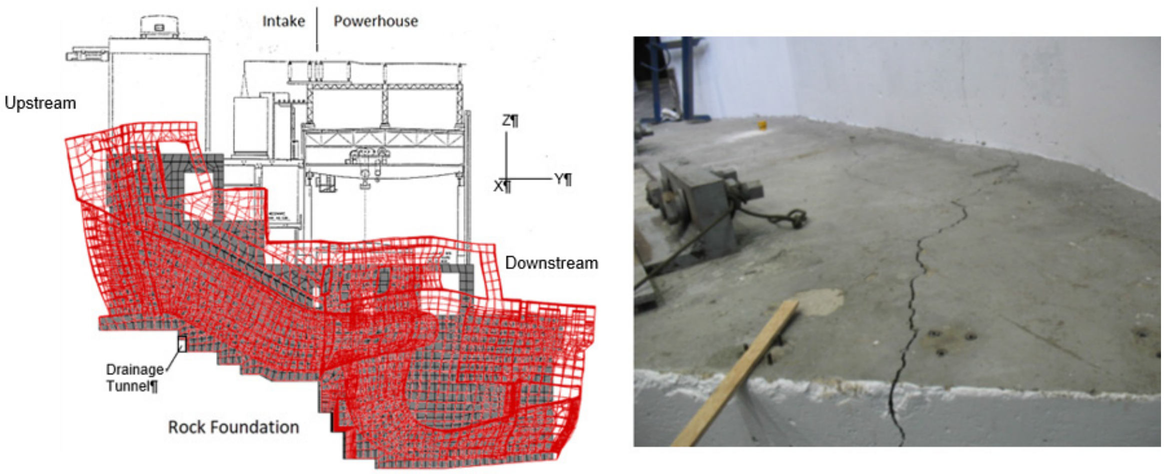

Figure 4. Left: Global deformation of the intake and powerhouse. Right: Example of cracks generated by AAR in the stator's concrete base.

From figure 4, a global movement in the upward (Z) and upstream direction in the vicinity of the drainage gallery is calculated. This deformation of the concrete could contribute to a local movement in the first meters of the rock foundation as explained below.

4.3 Stresses in the shallow foundation

Numerical analyzes of the water intake and the power station show that with the development of the alkali-aggregate reaction, the deformation of the dam (water intake and power station) generates a change in the state of stress down to the first meters from the foundation. Figure 5 shows stress distribution in a transverse section of the structure, parallel to the water intake (upstream-downstream), at the junction of Unit A/B and Unit 1. A tensile stress of about 12 MPa, whose direction is vertical, develops in the rock of the upstream wall of the drainage tunnel. As for the horizontal stresses (shear), they are around 3 MPa on the upstream wall of the drainage tunnel.

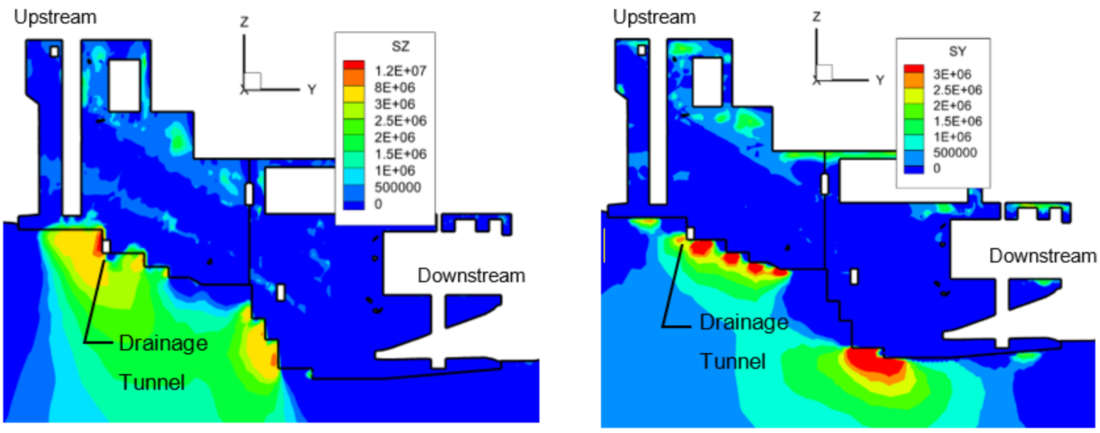

Figure 5. Stresses in the structure and in the shallow depth foundation. Left image shows vertical stresses and the right image the horizontal stresses (Legend scale is in Pa).

By considering the stress values around the drainage tunnel and the nature of the bedded sedimentary rock mass, the presence of some open joints visible in a portion of the drainage tunnel (see Figure 6) are highly suspected to be caused by the stresses applied to the rock foundation. Also, Figure 7 shows pictures of two recent mortar patches on rock mass fracture that contribute to suspect movement related to AAR. It is important to add that a downstream slip in the foundation is discarded from the measurement results of displacement monitoring. Inclinometer probe in inverted pendulum boreholes do not show any upstream-downstream movements. To support that slipping on a rock joint and the failure of the rock mass are excluded as potential failure modes, a failure criterion was established for the intact rock and the rock mass. The stresses generated by the presence of AAR are below the Hoek & Brown failure curves.

Figure 6. Subhorizontal open joints visible in the drainage tunnel at the concrete-rock contact.

Figure 7. Recent mortar patches, emphasized in white boxes, on one of the fractures Left: Broken mortar patch (white arrow) that may indicate a movement. Right: Mortar patch still intact and visually monitored.

However, in a portion of the rock mass that could have been damaged by blasting operations or if it is of less quality, the stresses generated by AAR could lead to local tensile displacement in the shallow foundation. It is important to note that the numerical model considers that the rock has a linear elastic behaviour and therefore does not consider the relaxation of stresses due to cracking. The monitoring of this crack is planned and will make it possible to verify its behaviour in the coming years.

CONCLUSION

This study allows concluding that, overall, the foundation of the Beauharnois dam is of good quality. More specifically, the sandstone, making up the rock mass, is of high resistance. By its nature, the foundation rock mass has many discontinuities for which spacing are variable, but the fact remains that these discontinuities are closed, or with a small opening, which makes it a rock mass all the same quite rigid and relatively tight. Regarding the state of stresses in the rock, overall, the magnitude and orientation of the stresses do not raise concerns about a slip (downstream) in the foundation. However, it has been shown that locally, the stresses contribute to the opening of some joints at the rock-concrete interface.

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