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ANALYSIS AND STRUCTURE RESPONSE TO RECENT SLOT CUTTING AT MACTAQUAC GENERATING STATION

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ABSTRACT

Concrete expansion due to ASR at Mactaquac Generating Station in New Brunswick has caused significant deformations in the water retaining and powerhouse structures. Initially, slots were cut in the intake and diversion gravity sections and the analysis and response of the structures to these cuts has been reported previously. Recently, slots have been installed in the powerhouse and in the penstock encasement concrete.

Transverse slots were cut between each unit of the powerhouse with the objective of relieving the effects of the distortions caused by longitudinal movements/thrust. A total of seven longitudinal slots were cut, hence each of the six units had a slot installed on each side. Detailed finite element modeling was used to assess the effects of slot cutting. The finite element program GROW3D was used to perform the analysis. The results of the analysis include the immediate slot closure due to cutting the slot, the immediate rebound of the turbine embedded parts (discharge ring, stay rings, etc), the future rebound of the embedded parts with slots remaining open and displacement rates which are used to estimate the rate of slot closure.

Subsequently, the analysis was updated to assess the effects of concrete expansion upstream-downstream direction. The penstock encasement concrete was found to have a very large axial stress and the restraining effect of the encasement on the powerhouse unit block was causing distortions in the stay rings. The total thrust in the penstock was computed to be almost 500,000 kN. Finite element analysis was used to compute the benefits and response to cutting the penstock encasement. Due to the large forces involved, the sequence of slot cutting was carefully analyzed. The measured response of the unit agreed very well with predictions. The measured and computed response of the powerhouse is presented.

Keywords: AAR, alkali-aggregate reaction, finite element analysis, remedial measures, slot cutting

INTRODUCTION

The Mactaquac Generating Station is the second largest hydroelectric generating facility in the Atlantic provinces of Canada. Since 1985, this project has been in the forefront of the implementation of innovative remedial measures aimed at addressing the continuing effects of concrete growth caused by alkali-aggregate reaction. The GROW3D finite element program has been a valuable tool in evaluating the condition of the structures and their response to proposed remedial measures. This program has been particularly useful in laying out slot cutting plans and estimating the benefit of such slots to the future behavior of the structures.

The objective of this paper is to describe some of the recent slot cutting activities at the Mactaquac Generating station and how the GROW3D program was used to develop these plans. Additional background information on the analysis methods is given in (Curtis 1995, Charlwood et al. 1992, and Thompson et al. 1994).

PROJECT GENERAL ARRANGEMENT

Mactaquac Generating Station, which is owned and operating by New Brunswick Power, is located on the Saint John River, approximately 20 km upstream from the City of Fredericton, New Brunswick, Canada. The 650-MW station was constructed between 1964 and 1968.

The main features of the project consist of an embankment dam, powerhouse and intake structure connected by steel-lined penstocks, and spillway and diversion sluiceway structures, each containing five gated openings.

The main dam is a rock-fill structure, 518 m long, with a maximum height of 46 m.

The power plant comprises a 6-unit installation of 650-MW capacity. The intakes comprise large, formed openings through a concrete gravity dam section. Each is closed by twin intake gates, separated by a central pier. The six steel penstocks are of 8.84-m internal diameter and are completely encased in concrete. The vertical shaft Kaplan turbines have steel plate spiral casings, and drive umbrella type generators.

The spillway and diversion sluiceway structures are essentially identical structures consisting of conventional concrete gravity structures designed to discharge floods up to 15 000 m^3/s.

Construction of the Mactaquac power plant began in 1964, with all water retaining structures and powerhouse Units 1, 2 and 3 being completed in 1968. At that time the powerhouse was constructed with space provided for a further three units. Unit 4 was commissioned in 1972, and Units 5 and 6 were installed by 1979 and 1980, respectively.

BACKGROUND

Evidence of distress in the concrete structures at Mactaquac was first noticed in the mid-1970's by the increasing opening of a longitudinal vertical contraction joint in the powerhouse substructure. By the early 1980's, leakage through horizontal construction joints in the spillway, intake and diversion sluiceway structures was also evident. At that time instrumentation was installed in the foundation rock and within the concrete substructure to monitor the movements.

In 1985, Spillway Gate 10, adjacent to the intake structure, was found to be obstructed by interference between the gate roller boxes and the liner plate at the back of the gate slots. This was caused by differential displacement of the spillway end pier towards the gate opening in excess of 25 mm. Further investigations showed that the end pier was cracked internally.

Slots were cut in the intake in 1988, 1989 and 1992. The slots were cut with a 13-mm diamond wire saw; therefore, as concrete growth continues, periodic recutting of slots is required, although, in the future, a wide slot scheme may be implemented.

The short- and long-term deformation response of the intake are monitored using numerous extensometers, joint meters and inverted pendula. These instruments indicated that the concrete growth rates increased after slot cutting. The increase in the concrete growth rate after cutting the intake slots implied that the growth rate was affected by the stress condition of the structure.

AAR deformations are also affecting the powerhouse where concrete expansion and substructure movements are inducing additional loads on the draft tube piers and superstructure frames. In addition, the generating units are affected by ovalling of the discharge ring, stay ring distortion, and unit alignment. An extensive instrumentation system is installed in the powerhouse in the early 1980s.

In 1992, a detailed assessment of the stress condition of the powerhouse draft tube piers was undertaken. A FE model of the powerhouse was developed and calibrated to both deformation and concrete stress measurements. Overcoring concrete stress measurements in the draft tube piers and substructure concrete were carried out in 1983 and 1989. The initial calibration of the powerhouse FE model also assumed that the concrete growth rate was constant over time. The calibration analyses revealed that measured rates of deformation could be matched reasonably well using the "constant growth rate" assumption. However, stresses were always substantially over predicted by the model. In particular, the computed concrete stresses in the lower portion of the powerhouse were quite large because the constant growth rate of 120 $\mu\epsilon$/yr over 20 years (i.e., a total initial strain of 2400 $\mu\epsilon$) in an area of high restraint can generate concrete stresses well above 15 MPa. Since such stresses seemed unrealistic, an alternative method of analysis appeared necessary and this lead to the development of a stress-dependent concrete growth model. The analysis of the draft tube piers was greatly improved when stress-dependent concrete growth behavior was included in the modeling.

The stress dependent concrete growth model was developed using instrumentation data which included deformations, rebar strain measurements and concrete overcoring stresses. Therefore, the model was developed using prototype data rather than laboratory data.

A variety of concrete growth functions were used in the initial calibration of the model. The best calibration was obtained using a concrete growth function which varied with the logarithm of stress. During the calibration analyses undertaken in 1992, it was also observed that the concrete growth should be determined using the principal stresses and the concrete growth strain should be applied as an initial strain load in the directions of the three principal stresses. It is noted that simulation of enhanced creep in AAR-affected concrete is important.

TRANSVERSE SLOT CUTS

A detailed analysis of the powerhouse was undertaken using the GROW3D finite element program in 1994. A detailed finite element model of several individual powerhouse units was developed for analysis by the calibrated GROW3D program. The objective of the analysis was to investigate the effects of cutting transverse slots between the units of powerhouse. Subsequently, the model would be used to investigate the response of the powerhouse to cutting of the penstock encasement concrete. A detailed description of the finite element model is given in (Curtis 1995).

The finite element analysis was used to establish the layout of the transverse slot in the powerhouse. The initial analyses showed that the slots must extend down to the el 29 ft gallery. The results showed that shallow depth slots could cause severe stressing of the stay vanes and they would provide limited benefit to the discharge ring/turbine blade clearances.

The extent of the transverse slot is shown on a unit cross-section in Fig. 1.

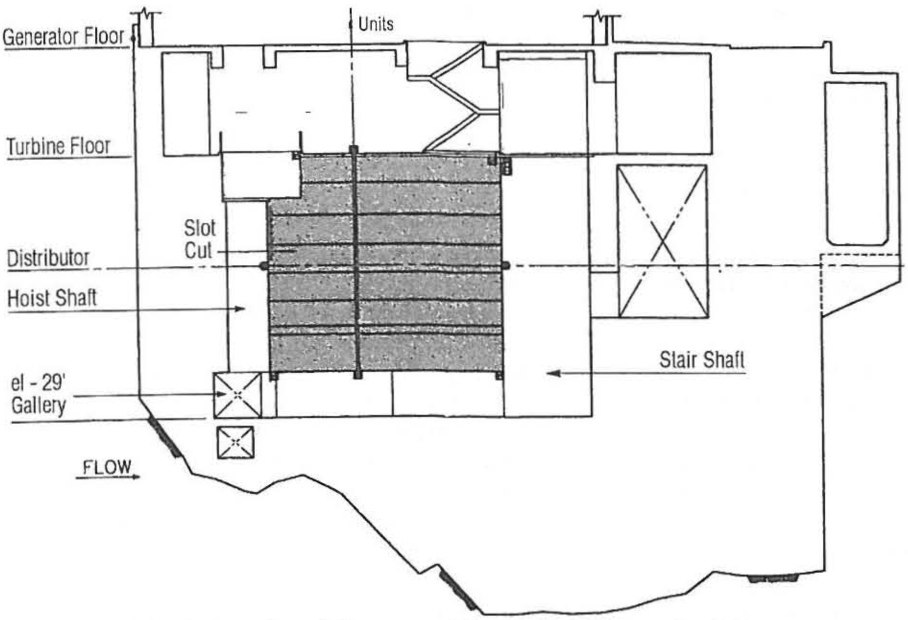

Fig. 1: Location of Transverse Slots at Unit Contraction Joints

The location of the transverse slots along the centerline of units is presented in Fig. 2.

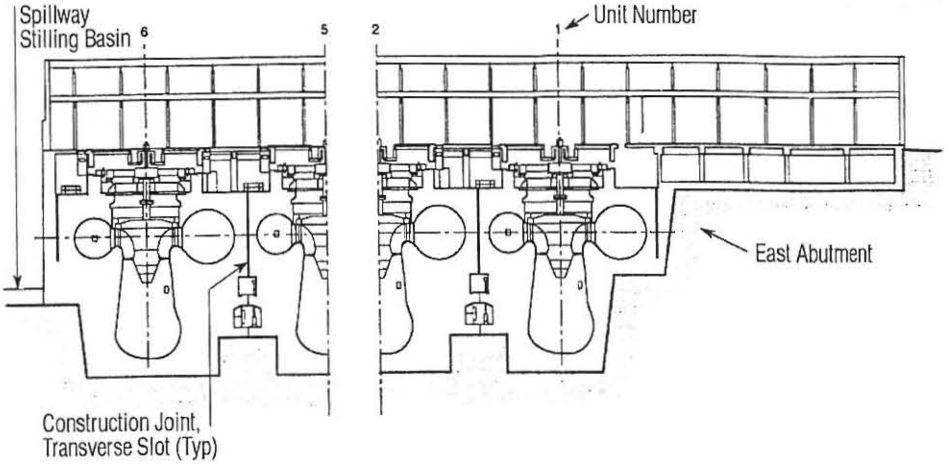

Fig. 2: Transverse Slot Locations on Section Through Centerline of Units

The analysis indicated that the slots immediate slot closure would be about 7 mm after the initial cut. A 15-mm diameter diamond wire was used to cut the slots. The time dependent GROW3D analysis was stepped into the future and the computed rate of slot closure was about 2 mm/yr.

In 1995, seven transverse slots were cut in the powerhouse, i.e., one slot between each unit. The response of the powerhouse to the transverse slots was very close to the predicted values, i.e., the initial rebound at the slot was about 7 mm and the subsequent rate of closure was 2 mm/yr. The slots will be re-cut in 1999 and 2000, to maintain an open slot scheme.

The transverse cuts in the powerhouse met their objectives and with slots maintained open, the turbine blade/discharge ring clearances will continue to improve. The GROW3D finite element analysis was found to be quite effective in developing the slot cutting plan.

PENSTOCK ENCASEMENT CUTTING

As noted in recent papers (Thompson et al. 1995 and Curtis 1995), concrete growth in the powerhouse is causing distortion of the turbine stay rings due to upstream-downstream movements. In addition the draft tube piers are experiencing relatively large shear stresses as the upper portion of powerhouse deforms downstream.

In 1994, the GROW3D program was used estimate the effect of cutting the penstock concrete encasement on the powerhouse turbine components and concrete substructure. The analysis showed that the relatively large concrete encasement was restraining the powerhouse from moving upstream. As a result of this restraint and restrained concrete expansion in the encasement, the computed compressive stress in the encasement concrete was in excess of 7

MPa. Subsequently, overcoring stress measurements in the Unit 2 encasement confirmed this stress magnitude within about five percent.

The GROW3D finite element model included the intake, penstock and powerhouse. The majority of the analysis was undertaken at Unit 2 because it is a typical older unit and it is well instrumented. The location of the penstock cut is given in Fig. 3. The cut is located just upstream of the upstream wall of the powerhouse. An overall view showing the downstream portion of the intake, the penstock and the powerhouse is presented in Fig. 4.

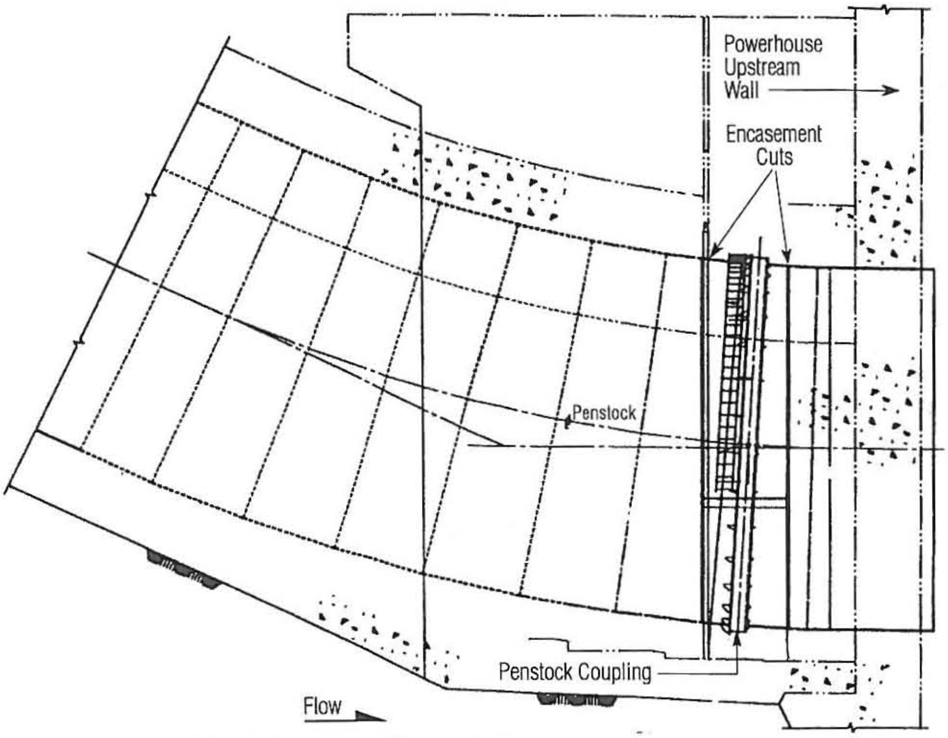

Fig. 3: Location of Penstock Encasement De-stressing Cuts Relative to Upstream Wall of Powerhouse

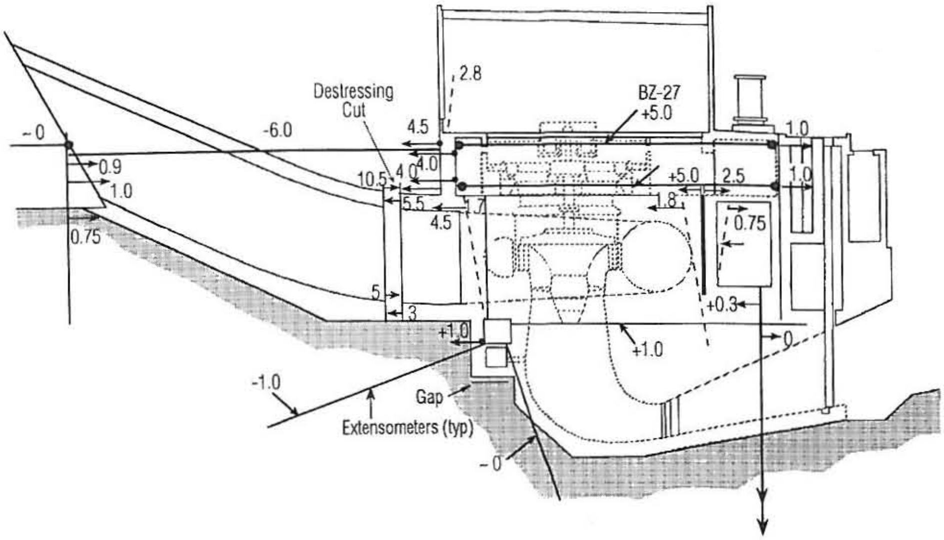

Fig. 4: Immediate Structure Displacement Response to Penstock Encasement Destressing Using Extensometer and Pendula Data (Displacement in mm)

Some key input from the Mactaquac Review Board is acknowledged. Dr G. Lombardi requested that penstock be cut as close to the upstream wall of the powerhouse as possible. A cut close to the upstream wall of the powerhouse would maximize the benefit to the powerhouse stay vane stresses. He also suggested that the gaps under the el -29 ft Gallery be grouted. The gap under the el 39 ft Gallery was caused by expansion of concrete around the draft tube relative to the non-expanding upstream rock. The grouting under the el -29 ft Gallery ensured a controlled shear deformation response to the penstock cuts which was quite beneficial to the stay vane stresses.

It is interesting to note that the total force in the penstock caused by restrained concrete expansion is almost 500,000 kN. This force is greater than the total hydrostatic load acting on one intake unit, hence the intake moves upstream slightly, although it is restrained by rock on its upstream face.

The penstock encasements are cut at a rate of one per year. The Unit 1 penstock was cut in 1996, Unit 2 in 1997 and so on. The results of the Unit 2 penstock cut are presented here, although the Unit 1 response was similar.

The location of the penstock encasement cuts is shown in Fig. 4. The encasement concrete was de-stressed gradually using a 10-mm diameter diamond wire saw. The overall structure response to the de-stressing cuts is presented in Fig. 4. From Fig. 4, the de-stressing cuts caused significant immediate movement in the powerhouse. The upstream shear-type movement caused a substantial reduction in stay vane stresses. A coupling was installed at the penstock cut to allow additional upstream movement as concrete expansion continues.

The predicted and computed closure of the encasement de-stressing cut is presented in Fig. 5. The GROW3D model was provided a good correlation to measurements. It is noted that the slot closure on the west side of the encasement was restrained by the Unit 3 encasement which was cut in the following year (1998).

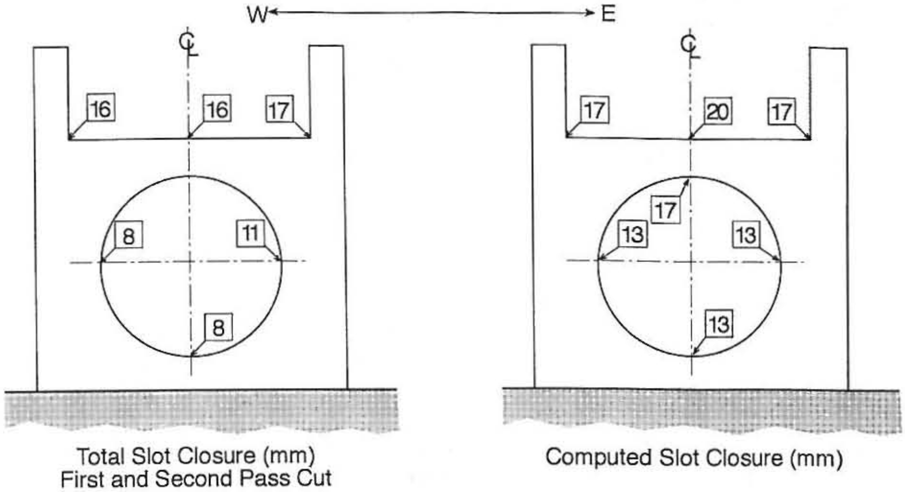

Fig. 5: Measured Total Slot Closure at Penstock Encasement Destressing Cut (Unit 2)

Numerous instruments were monitored during and after the de-stressing cutting of the encasement concrete. Measurements from an invar bar extensometer under the generator floor are presented in Fig. 6. The de-stressing cuts were started on July 8, 1997 and completed on July 31, 1997. It is noted that the thermal-induced movements peak in the winter because the tailrace piers contract in the winter thus causing a downstream movement at that time.

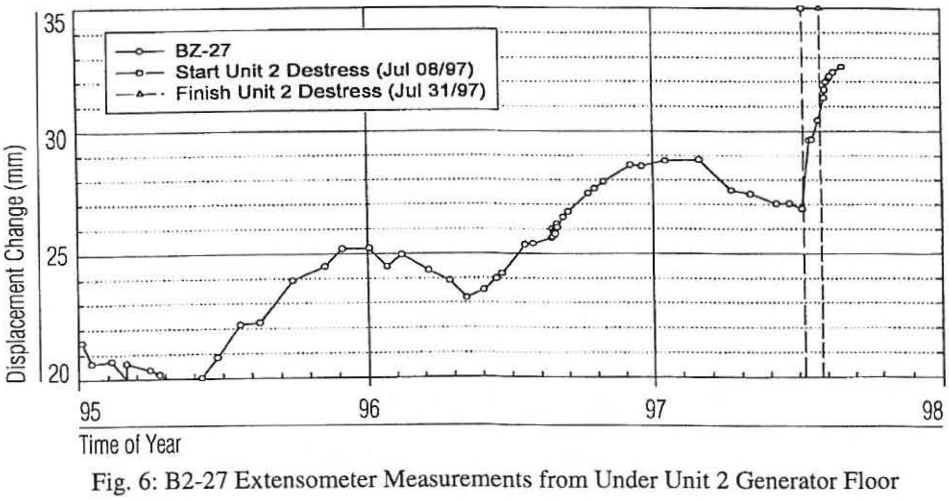

Fig. 6: B2-27 Extensometer Measurements from Under Unit 2 Generator Floor

It is concluded that the powerhouse is responding as anticipated to the penstock cuts. An additional rebound of Unit 2 was obtained when Unit 3 encasement was cut in 1998. The unit block concrete rebounded in a shear deformation mode hence the racking the stay vanes was substantially reduced and future movements will reduce racking.

CONCLUSION

It is concluded that:

- A very large force was released from the penstock encasement and structure responded essentially as predicted by the GROW3D program;

- The response of the powerhouse to transverse slot was also well predicted by the analysis and the initial desired benefits were achieved;

- Further monitoring of both slot cutting remedial actions is required to establish the long-term effects.

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