SPILLWAYS AFFECTED BY ALKALI-AGGREGATE REACTION : TWO CASE STUDIES FROM HYDRO-QUEBEC

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Abstract

Canadian Standards began to warn as to the effects of the presence of Alkali-Aggregate Reaction (AAR) in conventional constructions no sooner than in the 1960’s. Soon thereafter, dam owners recommended test specifications for new constructions until such tests became mandatory requirements. By this time, Hydro-Quebec had already built more than half of its spillways and outlet works. Today, several constructions have reached their useful life expectancy despite being affected by AAR. Nevertheless, these structures can be safely operated notwithstanding their age and distress conditions.

This article presents two case studies on innovative rehabilitations that extend the useful life of these constructions and ensure the reliability and operability of their mechanical systems. In both cases, the observed signs of deterioration were deformed and tilted spillway piers narrowing the gates’ sluices, fractures and deformation of mechanical equipment components eventually causing gates to be damaged, jammed and inoperable.

The instrumental measurements validated the observed deficiencies and provided design guidance to complete the required modifications to the structures. At Rapide-des-Îles, adaptive gates were made-to-measure and installed in the secondary spillway whereas at La Tuque, the overhead hoist supporting structure was made adjustable.

Keywords: Alkali-Aggregate Reaction, Adjustable spillway Overhead Structure, Adaptive spillway gate

1 INTRODUCTION

Hydro-Quebec is one of the biggest dam owners and producers of hydro power in the world, with a hydroelectric fleet including over six hundred dams and almost one hundred control structures built over the last century and using different material technologies. These achievements and ensuing diversity have also built a capital of experience and knowledge at Hydro-Quebec but it remains a challenge to ensure the safety and longevity of its dams. Dam safety is legislated at a provincial and/or territorial responsibility in Canada. In the province of Quebec, the applicable legislation is the Quebec Dam Safety Act [1]. Hydro-Quebec implements a rigorous program that includes monitoring and surveillance of its facilities to comply with this legislation and thereby protect persons and property against the risks associated with the presence of dams.

The condition of a given dam structure is determined by periodic or continuous monitoring and surveillance according to the characteristics of the structure. The result of a rigorous surveillance program in combination with acquired knowledge and experience has exposed damage or structural distress caused by alkali-aggregate reaction (AAR) in some concrete structures. This is especially common for some of the first generation dam structures, in Quebec, that were built before the 1940’s. Damage to concrete caused by AAR reaction includes expansion causing cracking of the surface but it could also lead to potential problems of operability if not treated correctly and efficiently.

The following chapters present how the implemented monitoring management program (MMP) is crucial in diagnosing the root cause of a problem and developing an adequate solution. Two case studies are presented and they include innovative solutions that ensure the reliability and operability of the structures while extending their useful lives. The first case study is the rehabilitation of the secondary spillway at Rapide-des-Îles, where jamming of the gates was observed. The second case study is at La Tuque where the monitoring system detected crest deflections causing partial

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jamming of one of the 7 gates. The selected rehabilitation measures varied with the severity of the deficiencies observed, as described in the case histories.

2 SURVEILLANCE

Once the presence of AAR is confirmed, the Monitoring Management Program (MMP) is implemented and adapted according to the intensity of the swelling and induced disorders. The aim is to ensure appropriate functional and structural behavior. Among other tools, the MMP includes instrumentation, visual inspection and investigation (FIGURE 1).

Moreover, Potential Failure Modes (PFM) analysis is now more frequently performed. The objective is to identify and prioritize the failure modes according to their probability and severity. The focus then moves to PFM's deemed critical to early identification of any developments.

Beyond detection, the analysis of data collected over months or years from instrumentation, visual inspections and investigations, allow description of the behavior over time of a dam affected by AAR or a specific area thereof. Also, structural analyses by finite element analysis in particular, are tools being used as part of the MMP. These analyses provide information about current concrete deformations and stresses and also predict future behavior.

The data provided by PFM analyses, instrumentation, visual inspections, investigations and structural analyses yield to a more complete picture of the functionality and safety issues. This allows optimization of the MMP.

Instrumentation is used to track disorders by measuring deformations, opening cracks, uplift pressure levels in internal cracks and infiltrations.

The first disorders attributable to concrete swelling are functional such as the jamming of spillways' gates and deformation of concrete around generating units. Monitoring is carried out by measuring deformation of piers from either side of spillway gates (FIGURE 2(a)) and around generating units.

Verticality and flatness of spillway piers' grooves can also be measured in order to check if gates are stuck, or to predict the time remaining before that will occur (FIGURE 2(b)). These measures may also be performed on permanent hoist supporting structures (FIGURE 3(a)).

If the intensity of the AAR is important, structural cracking can occur. The surface cracks on downstream faces are easily observable. However, this is not the case whether they are internal or immersed at the upstream side. Hidden cracks may be deduced by visual observation of a new downstream infiltration, the growth of existing infiltration measured by weirs or displacement measured along a pendulum wire (FIGURE 3(b)). It is also possible to identify upstream cracks with divers or underwater robots (FIGURE 4). In addition to that, internal cracks can be characterized using vertical drilling from the crest. If necessary, strain gauges can be set up to monitor the opening of these structural cracks. Structural analyses may then be performed using investigation and instrumentation data, in order to determine if performance criteria are met and to recommend rehabilitation.

3 RAPIDE-DES-ÎLES

The hydropower facility of Rapide-des-Îles is located on the Ottawa River at about 500km of the city of Montreal, Quebec, Canada. The secondary spillway, as shown in FIGURE 5, is on the left side of the intake structure. It was built in 1967 with three vertical lift gates operated by a gantry crane.

3.1 Equipments affected by the AAR

Original embedded parts of gates

The embedded parts of the gates have been the subject of many studies. The verticality of the piers groove was measured. The results for gate #5 are showed in FIGURE 6 and are summarized in TABLE 1. The most critical measurement is a lateral inward vertical displacement of 35mm. Over the 40 years of life of this structure this is an average displacement of about 0,875 mm per year.

Original gates

Studies mentioned the presence of broken wheels, deformations of the skin plate and end girders (with wheels assemblies), and damaged to the sealing system (distorted and corroded parts). In 2007, the measured deformation of the end girder beams of gate #5 was 7mm. The maximum deformation of the skin plate was 16mm. Such disorders are closely linked to poor straightness of the gate's roller path.

3.2 Description of the solution

The effect of the AAR on embedded parts of the gates is multiple. As mentioned above, this reaction occurring in massive volumes of concrete on each bank of the structure affects the verticality in the left/right plan of the piers. Wedging (jamming) and guiding problems of gates should be overcome with the use of new embedded parts adapted to this particular situation.

To a lesser extent, the AAR also affects the straightness of the roller path on which the gates' wheels are traveling. These straightness defects cause significant overloads to the structures, compromising their durability, reliability and safety. It results in broken wheels, distorted beams and cracked concrete.

The new gates must be adaptive and designed to operate despite the presence of such straightness defects. The main design criteria seek to:

- Restore spillway's discharge capacity;
- Consider the effects of AAR in the future by the linear extrapolation of current displacements;
- Insure at least a 60 years life;
- Achieve a design with minimal maintenance.

The existing vertical gates were replaced by isostatic gates. These gates consist of several sections that are fastened together by mechanisms allowing free rotation and displacements in the upstream/downstream direction. Each section is mounted on only four wheels, thereby forming an isostatic system, unlike rigid gates which are statically indeterminate. All four wheels of an isostatic gate stay in contact with the roller path, providing a predictable and controlled load distribution to the wheels gates girders, as well as to the embedded parts, roller path and supporting concrete, as shown in FIGURE 7.

The new lateral embedded parts are designed based on future movements of the piers (lateral average displacement of 0.875 mm/year per pier toward center of the sluice. In order to assess those displacements, each embedded part includes:

- A wider roller path (+50 mm);
- A wider or double web in order to control the flexural moments developed in the beam under an excentric wheel load on embedded girder;
- An adjustable lateral guide;
- A wider sealing face;
- A non-critical depth of gates' gaines.

The interest for this type of vertical gate for a structure affected by the AAR resides in its flexibility. Considering the four supports (the wheels) of each section of the gate and neglecting the torsional effect caused by misaligned planes of the two roller path of a gate, each individual section of the gate is therefore an isostatic system, contrary to that, traditional gate is statically indeterminate since rigid end girders have no possible rotation. Considering the roller path's poor straightness caused by AAR, the main consequence of hyperstatism is that some wheels do not transmit the load as designed, while others are overloaded. With broken wheels and deformations on end girders, the case of Rapide-des-Îles is a good representation of this phenomenon. In contrast, all the wheels of an isostatic gate remain in contact with the rolling path, thus ensuring a predictable load distribution to wheels, end girders and embedded parts.

The work of replacement of mechanical equipment was successfully completed in 2013, providing the complete use of the spillway's gates and thus restoring its full discharge capacity.

4 LA TUQUE

The hydropower facility of La Tuque, built in 1940, is located near the town of La Tuque on the St-Maurice River about 300km north of the city of Montreal, Quebec, Canada, as shown in FIGURE **8**.

It consist, as shown in FIGURE 8, of a retaining wall, a right bank gravity dam, a spillway, a log chute (disused), an intake and a power house, and a left bank gravity dam. The facility is approximately 420m long and founded on rock.

The concrete structure is suffering from alkali-aggregate reaction (AAR). The various site observations and petrographic analysis demonstrate it without any doubt. The AAR is qualified as late and slow. The free swelling average rate is 28µm/m/year. Irreversible displacements measured since 1979 are in the order of 1mm/year in some locations, such as the crest of spillway's piers.

The spillway's equipment was not designed to accommodate displacement of the concrete piers: the lifting device is a screw winch. This system does not tolerate misalignments.

In fact, embedded parts, due to concrete swelling underwent displacements resulting in an increase in friction with the gate's roller. The lifting forces required to operate the gates consequently increased. Overtime, it became impossible to lift the left side gate (VE5) without damage to the lifting device or to the hoist supporting structure. The concrete expansion also created an upstream-downstream misalignment between the hoist and the gate. This impacted the hoist and the interaction between lifting screw and nuts resulting in a loss of efficiency and in a premature aging.

Several mitigation measures have been done on the spillway since construction. Nevertheless, The MMP indicated that major interventions needed to take place to ensure the functionality and security of the spillway for at least the next 25 years.

The rehabilitation of the overhead hoist supporting structure is presented here because the solution is targeted and innovative. In making the design shown in FIGURE 9, a comprehensive and interdisciplinary approach was adopted. The decision to rehabilitate the superstructure arises from various feasibility studies, and mainly for the following reasons:

- The lifting system in place, unlike other spillways of the same generation, has redundancy. Each pass has its lifting system;
- The gates and the hoist supporting structure are in good condition, despite few signs of corrosion and the few local deformations;
- Hydro-Quebec has a large machine shop in Shawinigan where parts of the lifting system can be manufactured;
- Changing screw system by a cable system to modernize the equipment would require replacing the hoist supporting structure because the load distribution of the two systems is different;
- Laboratory results indicate that the structural steel meets the ASTM-A7 standards and is a weldable steel.

After structural analyses were performed, considering the deformed state, it was possible to determine the main effects of the evolving situation of displacement of the spillway's piers due to the AAR on the hoist supporting structure and target mitigation measures. Overall, the main effects are:

- An accumulation of stresses at the base of the towers;
- A change in the structural scheme at the support tower/bridge (loss of a degree of freedom);
- A misalignment of the screw winch.

The interventions are localized and are:

- At the base of the towers RG1, RG2, T5 and T6. After the temporary support, the columns of these towers are cut. When the tension is released, the adjustable base is assembled. The device is removed after the adjustment and stored (FIGURE 10);
- In the lower chords of towers T4, T3, T2 and T1, the same procedure as for the fixed end column is performed except that the adjustable device is different and permanent. (FIGURE 11);
- At the supports of the bridge over the gate VE-3: mobile support and fixed support rehabilitated according to the RAG (FIGURE 12);
- At the hoist's support: adjustable bases (FIGURE 13)
- In a few places: Strengthening or replacing elements that are distorted or highly stressed according to structural analysis.

The various structural works have been completed in 2013. Since then, the displacements measured with auscultation benchmarks are not considered sufficient to initiate a campaign of geometrical measurements over the hoist supporting structure (verticality of columns, alignment mechanisms, etc.), so obviously no adjustment has been made.

Although about 75% of Hydro-Quebec spillways have a hoist supporting structure the La Tuque spillway rehabilitation approach cannot be applied at large because every site and structure is unique for many reasons such as redundancy, environment, height, stiffness among others.

5 CONCLUSIONS

Damage to concrete caused by AAR includes expansion causing map-cracking of the surface but it could also lead to potential problems of operability if not treated correctly and efficiently. Since a spillway is the key element in dam safety, its functionality is essential. Since 2002, this is legislated in Quebec.

This paper presented the case of Rapide-des-Iles where adaptive gates were made-to-measure and installed in the secondary spillway and the case of La Tuque where the overhead hoist supporting structure of the spillway was made adjustable.

No generic solution can be given since each site calls for its innovative, safe and economic rehabilitation, except for the implementation of monitoring management program (MMP).

The way to live safely with spillways affected by AAR is to understand the behaviour of the structure and adopt appropriate repairs to avoid that cracking due to AAR leads to other failure mechanism.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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[1] Gouvernement du Québec, Dam Safety Act - Chapter S-3.1.01, Québec, Updated to November 1st 2015.

[2] CSA A864, Guide to the Evaluation and Management of Concrete Structures Affected by Alkali Aggregate Reaction, 2000 (Reaffirmed 2005).

TABLE 1: Rapides-des-Îles secondary spillway – surveys vs standard tolerances.

Measurement description	Surveys	Standard tolerances
Relative displacements of piers (left-right axis)	From 23 to 45 mm (crest)	3 mm
Inclination of piers (towards upstream direction)	From 20 to 28 mm (crest)	3 mm
Bearing guides flatness defect	From 2 to 8 mm over 0,5 m in height	0,4 mm over 2 m in height

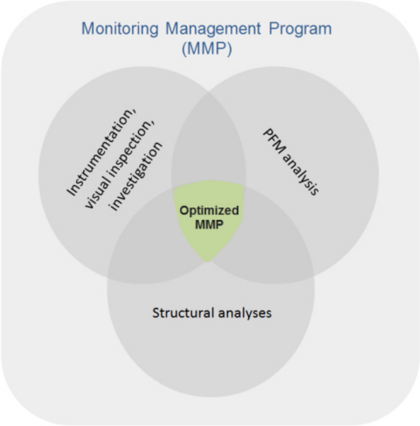
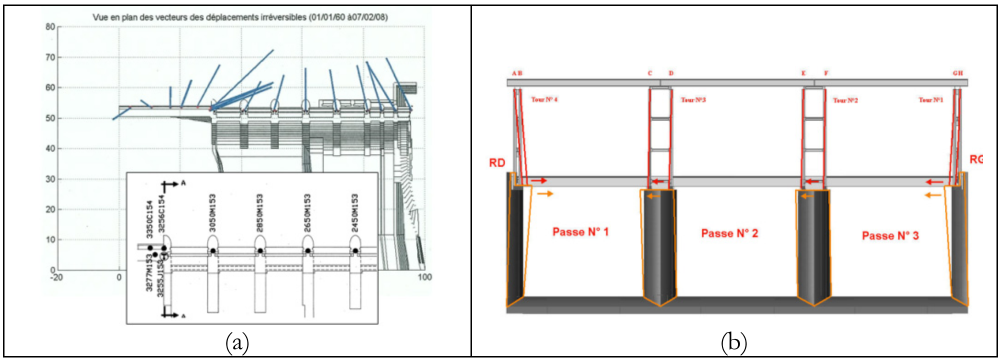
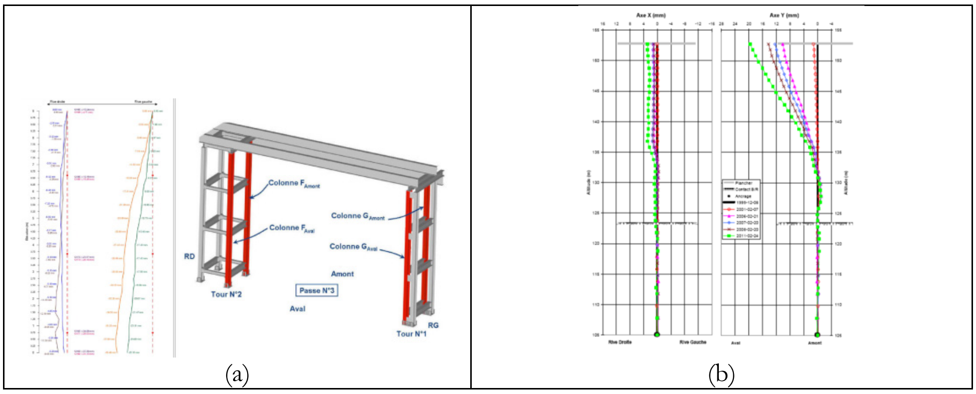


FIGURE 1: Monitoring Management Program (MMP).



(a) (b)

FIGURE 2: Displacement and deformation measurements:
(a) deformation of piers from top (b) verticality and flatness of spillway piers' grooves.



(a) (b)

FIGURE 3 : Displacement and deformation measurements:
(a) deformation of permanent hoist supporting structures (b) displacement along a pendulum wire.

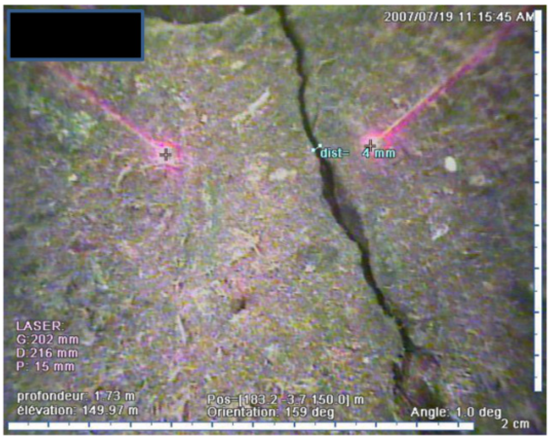

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FIGURE 4 : Inspection using underwater robots.

FIGURE 5: Downstream aerial view of Rapide-des-Iles.

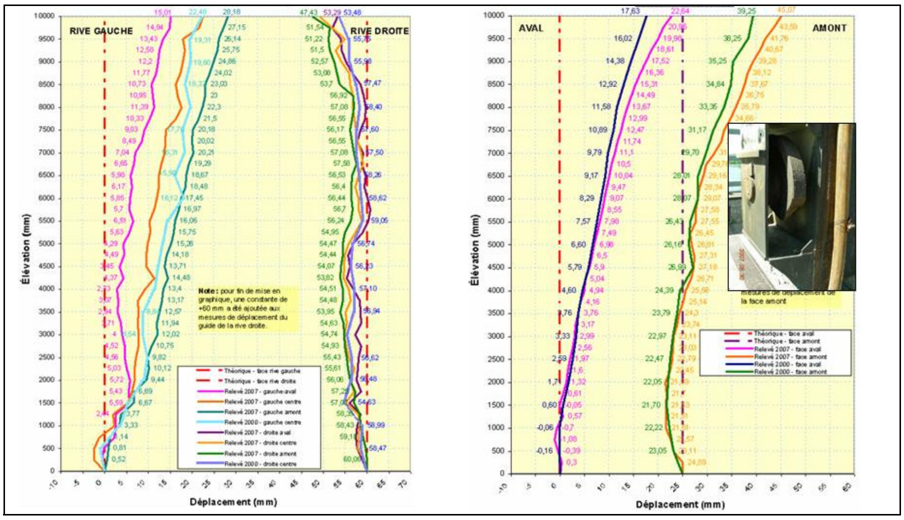

FIGURE 6: Rapide-des-Iles secondary spillway – Surveys.

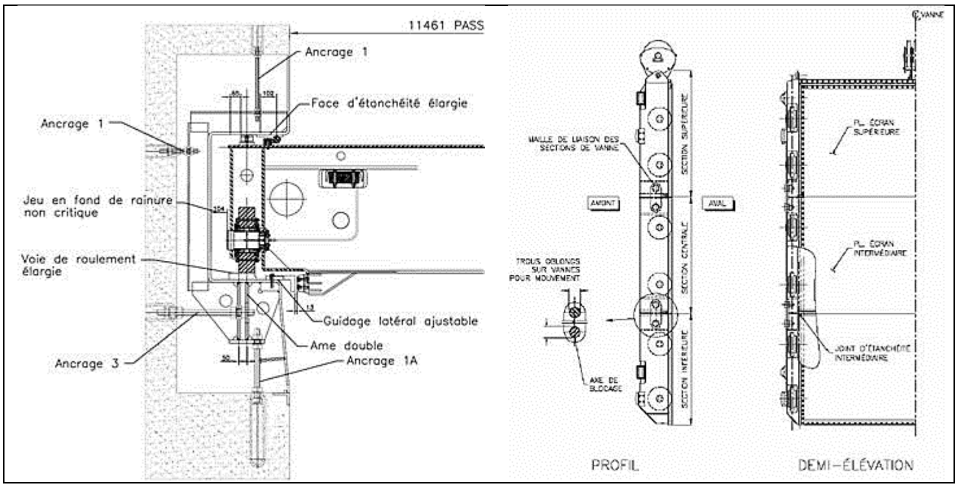

FIGURE 7: Rapide-des-Iles secondary spillway – Gates design.

FIGURE 8: Downstream aerial view of La Tuque.

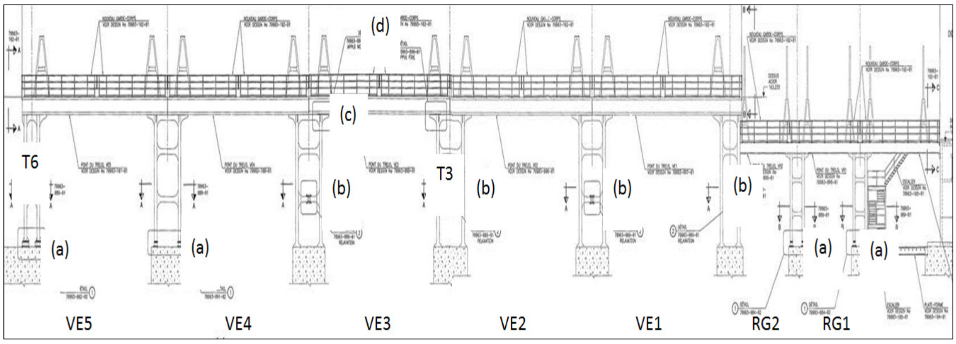

FIGURE 9: La Tuque hoist supporting structure: rehabilitation design:
(a) adjustable fixed end (b) adjustable lower member
(c) bridge or beam supports (d) hoists adjustable supports.

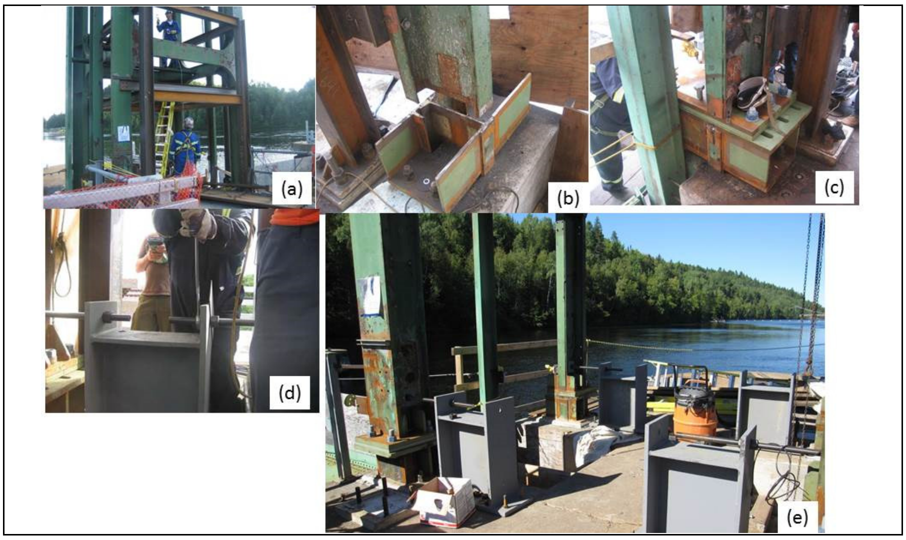

FIGURE 10: La Tuque hoist supporting structure: adjustable fixed end
(a) temporary structure (b) cut (c) adjustable fixed end (d) adjustments device (removable)
(e) 4 columns/tower.

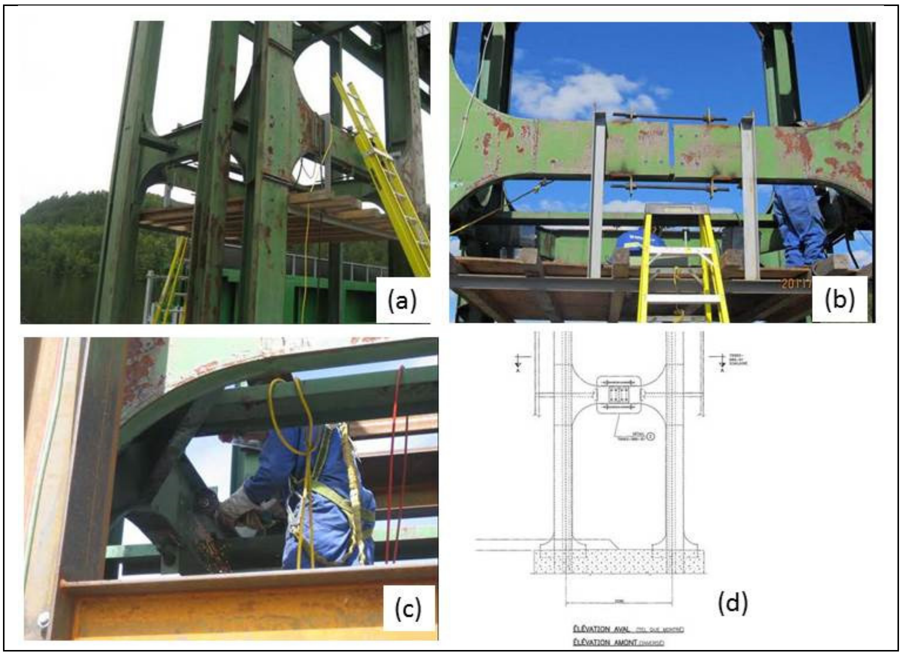

FIGURE 11: La Tuque hoist supporting structure: adjustable lower member
(a) and (b) temporary structure and cut (c) adjustments device (d) design.

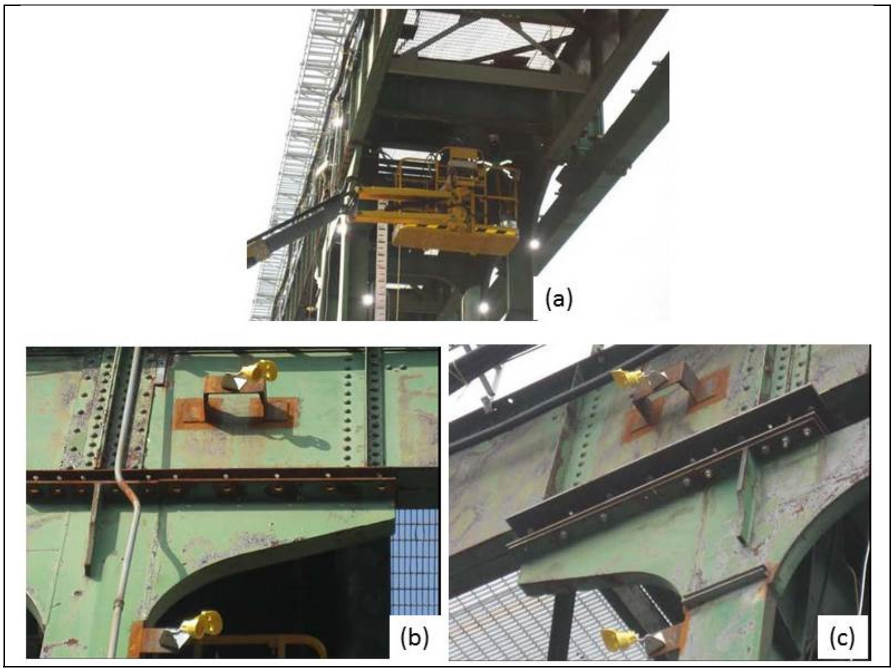

FIGURE 12: La Tuque hoist supporting structure: bridge or beam supports
(a) uplift of bridge (b) rehabilitation of mobile support (c) rehabilitation of support.

FIGURE 13: La Tuque hoist supporting structure: adjustable hoist's support
(a) general view (b) support.