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LOWER CHURCHILL PROJECT

TECHNICAL MEMORANDUM: Comments on the aDB Collapse Investigation Report

1 Purpose

This document provides summary comments based upon a review of aDB's Collapse Investigation Report dated April 20, 2017.

2 Overview

On May 29, 2016 at 11:58pm at the Muskrat Falls Hydroelectric Project near Happy Valley – Goose Bay, Labrador, the wooden formwork and falsework supporting freshly poured concrete in DT 2 failed nearing completion of the 530 m^3 pour, resulting in collapse. On May 30, 2016, NL OH&S issued Stop Work Orders #0671924-01 and #0671924-02 pertaining to all concrete pours in all four draft tubes and any associated works until the formwork and falsework systems were evaluated by a P. Eng. licensed to practice in the province.

ILF was contracted by Astaldi to perform independent review of the incident, to perform a technical review of engineered systems, and to support the contractor in developing corrective actions, as required by the review findings.

aDB Structural Engineering Inc, (aDB) was contracted by Nalcor to perform an independent assessment of the collapse and review engineering analysis performed by Astaldi's third party engineer (ILF).

3 Summary Comments

In general, the conclusions and recommendations made by aDB align with ILF report MFA-AT-SD-331-EN-A99-0031-01 with some exceptions, as stated within this report. ILF concurs with aDB's conclusion that the failure of DT2 falsework lead to the collapse of concrete pour D2ESB-03. ILF concurs with aDB that the failure was due to inadequate design of the falsework/shoring system, degradation of wood quality, and poor fabrication quality. However, ILF indicates in their summary report that the design and fabrication deficiencies were substantial enough that failure was imminent regardless of observed erection deficiencies and wood quality. Additionally, ILF did not observe significant erection errors in DT2 when performing the investigation. Consider that approximately half of the formwork and falsework associated with the roof pour remained standing after the collapse which allowed inspection of the installation and fabrication of nearly half of the members associated with soffit pours in DT2 after the incident.

ILF chooses to abstain from commenting on work culture as it is outside the scope their technical engineering review mandate.

3.1 Review of Executive Summary and General Conclusions

The following subsection headings 3.1.1 through 3.1.5 were extracted from aDB's executive summary and conclusions and are examined against information and calculations that ILF has observed, or performed, respectively.

3.1.1 The shoring system was not designed properly

- ILF concurs with aDB's conclusion. The towers were under designed by a significant margin. Given CEI's improper use of built-up member factors and assumption for dry service conditions, their calculations overestimated tower capacity by a factor of approximately 2.0. Additional oversights including the lack of bearing plates and fabrication errors in bracing, butt joints, and saw kerfs further reduced the allowable capacity of falsework towers. Post-pour observations of falsework in DT1 support these conclusions including several incidents of local crushing, tower buckling, and shearing of tower legs at top of towers. Although the falsework in DT1 supported the full liquid head of pour D1ESB-03 and did not collapse, it clearly failed by accepted engineering standards. Collapse was avoided only by the smallest of margins.

3.1.2 Wood integrity of the formwork was compromised

- ILF observed ice, water, mold, rot, and saturated wood upon arriving on site June 2, 2016. ILF generally concurs with aDB's comments on the impact of moisture to wood strength and quality and the need to preserve materials from degradation. ILF obtained wood samples for strength testing and submitted samples to the University of Toronto in fall 2016. Results indicated that portions of the wood were not testable due to decay and therefore a lower bound wood strength was not obtained for analysis.

3.1.3 The shoring system was not installed correctly

- Observed deficiencies in DT2 were limited to:
  - Improper shimming at the top of tower legs. Shims are not structural members but serve as a way to fill a gap and to provide even bearing on a surface. Although Astaldi did not properly shim between load bearing beams to the falsework tower legs, which could cause stress concentrations in the tower legs, this has minimal impact when compared to the lack of a bearing plate at top of tower. If a bearing plate were specified by the fabricator (as is required by code), improper shimming would have minimal impact on tower performance and would only result in minor additional deflection of overlying formwork (in the order of millimeters).
  - Localized instances of inadequate nailing of bracing splice plates to tower legs were observed by ILF. Observed deficiencies were minor in nature and included slightly less than specified nail counts or nailing patterns that did not match specified layout. These deviations are expected to have little impact on tower performance, especially when compared to the impact of design errors.
  - In addition to aDB's comments, ILF observed instances where Astaldi modified tower bearing pad designs in the field. The modification involved removing specified anchorage bolts and supplementing with additional lateral bracing. ILF does not believe this modification governed tower performance.

ILF has recommended Astaldi modify their management of change process to better monitor temporary structures. Astaldi implemented these changes in summer 2016.

- aDB makes note that DT4 had substantial erection deficiencies and infers that erection deficiencies may have been present in DT2 prior to failure. ILF can understand this thought process but it should be considered that DT4 was not yet released for pouring concrete. Astaldi had the opportunity to inspect and self-correct deficiencies prior to pouring. To conclude that the significant deficiencies observed in DT4 were present in DT2 is not substantiated by observations in formwork and falsework remaining in DT2 after the incident.
- DT3 was in an early state of construction and erection deficiencies were not observed in members associated with supporting concrete pour D3ESB-03.
- DT1 was more advanced than DT2 and erection deficiencies were similar to those observed in DT2. Deficiencies noted in DT1 were more applicable to the DT2 incident as DT1 was in a more advanced state of construction and had been released by pre-pour inspections.

3.1.4 The fabrication of CEI formwork and falsework system was inadequate

In addition to the noted calculation errors, ILF and aDB have both identified fabrication errors in all of the draft tubes, some being significant in nature and negatively impacting tower capacity. It is difficult to quantify the impact of fabrication deficiencies without full scale testing, and even then results would be difficult to rely upon due to the nature of natural materials used and combinations of deficiencies observed. A list of fabrication deficiencies observed by ILF are as follows:

- Saw kerfs on structural members
- Butt joints improperly staggered
- Improper bracing details within tower leg members
- Improper joining (nailing) of built-up members
- Gaps between butt joints in structural members
- Improper lumber grades –SP #2 observed
- Improper splice plate material (OSB vs ply)
- Non-conforming splice plate size and nailing pattern
- Missing members
- Mis-oriented members
- Lack of steel bearing plate at top of column
- Uneven tower leg bearing surfaces

3.1.5 A combination of these aforementioned factors

Although multiple deficiencies were noted, the under designed falsework towers and fabrication errors governed, and calculations indicate that failure was imminent without accounting for impacts of erection deficiencies observed in DT2 or material quality.

3.2 Additional comments to aDB's report

The following sections discuss select comments within aDB's report. This is not an exhaustive review but rather highlights key agreements or differences in opinion when compared to ILF's analysis and observations.

3.2.1 Unit 2 Downstream Anchors (Section 6.2.2)

aDB comments on the anchors being present at time of failure but could not determine if installed as designed. ILF concurs with this conclusion however does not see the merit in making this statement. Based on field observations, the anchors provided adequate resistance up to the failure as the majority of ties sheared off during collapse of the pour. ILF did observe an instance where a tie coupler failed and pulled out of the concrete but no instances where the anchorage failed. If anchorage was a governing condition, it would be evident by anchorages pulling out before the coil rod failed. This was not observed.

3.2.2 Doka Formwork Loads on Tailrace Soffit (Section 9.6)

aDB comments on tailrace soffit formwork loads on CEI formwork and falsework being a concern of overstressing CEI formwork and falsework. ILF and Doka have performed independent analysis of the scenario to determine the loads and stresses and found the loads and resulting stresses to be at acceptable levels. The load aDB suggests is applied to the draft tube soffit (2,000 pounds per lineal foot) is not observed in the field due to the placement methods, formwork geometry/load transfer, and hardening of concrete during the pour. These circumstances work together to produce reduced vertical reaction loads at the bottom of the form. There was no evidence in the field of overstressing of soffit formwork. Additionally, there was no evidence of observed rotation of soffit formwork about the top of tower, as shown in Figure 12 of aDB's report. The formwork tolerances and smoothness criteria for the project are extremely tight and any movement would have been observed in pre-pour survey.

ILF took note that aDB concludes in the first paragraph of Section 8 in their report stating *"soffit panels did not indicate signs of overloading"* and therefore focused their analysis on falsework towers. This is contradictory to aDB's statements in Section 9.6 where they speculate other activities may have affected the integrity of the formwork and falsework. ILF did not find evidence of overstressing of CEI soffit formwork in the completed pours subject to discussion in DT1, DT2, or DT4 (DT3 was poured using a different support system) due to loads imposed by pouring the draft tube outlet bulkhead. ILF agrees with their statements made in the first paragraph of Section 8. However, we disagree with their statements in 9.6 regarding other construction activities impacting formwork and falsework integrity as there was no evidence supporting this.

3.2.3 Grade of Lumber (Section 6.6.2)

aDB comments on grade of lumber required by CEI's design being No. 1 southern pine and concluded that the lumber found on site appears to be in compliance with the specifications. During field inspections of CEI formwork at the Muskrat Falls site, ILF observed multiple instances where No. 2 southern pine was utilized in fabrication, as indicated by the lumber grade stamps visible during inspection, and numerous occasions where oriented strand board (OSB) was utilized for splice plates instead of the specified plywood. Although ILF does not believe these deviations lead to the failure in DT2, it indicates the fabricator did not conform to their own specifications and provided materials that were weaker than utilized within their design.

3.2.4 Lack of maintenance (Section 9.1)

ILF concurs with aDB's general comments on care and preservation of materials not meeting a reasonable standard on site. However, aDB concluded that the lumber used in fabrication of the formwork was exposed to the elements in between the transportation, storage, and/or utilization process. aDB did not comment on storage conditions at CEI's fabrication facility where formwork was exposed to sun and precipitation for 15 months before shipment to Labrador. Although a casual

observer would likely not appreciate the impacts of southern pine being exposed to the elements over 15 months, Figure 1 through Figure 5 provide visual indication of the weathering that occurred in this period of time. The weathering is observed as darkened and grey wood surfaces. In short, weathering of formwork and falsework started prior to Astaldi receiving the materials.

Figure 1: May 15, 2014. Formwork and falsework at CEI facility. Note fresh, unweathered wood.

Figure 2: July 23, 2014. Formwork and falsework at CEI facility. Note onset of weathering of wood compared to same material in Figure 1.

Figure 3: June 16, 2015 at CEI yard (more than one year after fabrication). Right hand view of falsework towers believed to have been installed in DT2.

Figure 4: June 16, 2015 at CEI yard (more than one year after fabrication). Left hand view of falsework towers believed to be installed in DT2

Figure 5: June 16, 2015 DT1 formwork and falsework at CEI yard in Kansas. Note weathering of tower legs relative to formwork module A26.

3.2.5 Inspection (Section 9.5)

ILF generally concurs with aDB's assessment of the documented inspection process. Improvements to the method and inspection forms were implemented by Astaldi following the incident.

3.2.6 Risk Management of Temporary Structures (Section 10.1)

ILF concurs with aDB's recommendation for a temporary structures policy and advised Astaldi during their development and implementation of the policy that is now in place.

Prepared by:

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This Permit Allows
ILF CONSULTANTS INC.
To practice Professional Engineering in Newfoundland and Labrador.
Permit No. as issued by PEGNL 796
which is valid for the year 2017

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