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Ruskin Dam Spillway Shotcrete Assessed

Study shows that the dam's long service life can be extended by almost 50%

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For more than 4 million residents in British Columbia, Canada, BC Hydro & Power Authority (BC Hydro) is the main producer of electricity. About 90% of the utility's 11,300 megawatt (MW) installed capacity is generated at its 31 hydroelectric facilities. The Ruskin Dam is part of that immense system. Constructed in 1929 and 1930, it is located on the Stave River, about 60 km (37 miles) east of Vancouver, and is the lower facility in the Alouette-Stave-Ruskin Hydroelectric System in the Fraser Valley (Fig. 1).

The dam is a concrete gravity structure composed of eight monoliths situated in a narrow valley and founded predominantly on bedrock. It is 130 m (427 ft) long at the road deck, comprising an 85 m (279 ft) long, seven-bay radial-gated spillway straddled by two 45 m (148 ft) long nonoverflow sections. The dam is 58 m (190 ft) high from its deepest foundation to the road deck on the dam crest.

Fig. 1: Ruskin Dam and 105 MW generating station. The spillway (inset) has undergone two renovations in its 80-year life

Ruskin Dam was built long before the development of air entrainment to protect concrete from frost. As a consequence, the concrete in the spillway suffered some frost damage, as well as erosion/abrasion from water and water-borne debris. Some initial repairs were made on the spillway surface in 1954 using shotcrete. But deterioration continued in the concrete spillway and adjacent stepped structure at the right (looking downstream) abutment.

In 1973, a major program was undertaken to completely resurface the spillway and stepped structure. This was done using dry-mix shotcrete reinforced with 5 mm (0.2 in.) diameter welded-wire reinforcement (WWR). The shotcrete thickness on the spillway varied from about 75 to 200 mm (3 to 8 in.), and the thickness on the stepped structure varied from about 75 to 150 mm (3 to 6 in.).

In 1993, an evaluation of parts of one bay in the spillway and the stepped structure demonstrated that the shotcrete in the spillway bay was in good condition generally and well bonded to the substrate concrete.[1,2] There were, however, some localized areas with layering and sand lenses; these had led to spalling in the outer 50 mm (2 in.) of shotcrete. Also, vertical cracking was evident at about 20 m (66 ft) spacing. These were clearly reflection cracks, as they coincided with the locations of construction joints in the dam. Other visible cracking in the shotcrete totaled about 1 m (3.3 ft) of cracks per 10 m^2 (108 ft^2) of shotcrete. In contrast, the stepped structure was in poor condition. The shotcrete had delaminated from the substrate concrete in many places, and it displayed pronounced scaling, erosion, cracking, and spalling. Further, freezing-and-thawing

Fig. 2: Rolling suspended stage

damage to a depth of about 20 to 30 mm (0.8 to 1.2 in.) was found in the substrate concrete beneath the shotcrete.[1,2]

During 2006 and 2007, the BC Hydro project team made a preliminary design of the dam upgrade. Part of this upgrade program included assessing the condition of the Ogee spillway and the stepped right abutment (Fig. 1).

In 2008, AMEC Earth & Environmental was contracted by BC Hydro to provide a detailed condition survey, estimate the remaining service life of the existing shotcrete, and provide recommendations and cost estimates for remedial alternatives to extend the service life of the dam.

Condition Assessment

Access, safety, and environmental protection

Access to the spillway face was a challenge for the inspection team. A rolling suspended stage equipped with adjustable slope brackets was installed and moved from bay to bay (Fig. 2). In addition, a standby high-angle rescue team, a crane with a personnel basket, and a rescue boat were on site throughout the inspection. An environmental management plan was enforced, requiring sampling and testing of water below the spillway to evaluate pH, conductivity, and turbidity prior to and during coring activities, particularly if coring water drip was observed running down the dam face to the Stave River. The investigation was completed with no safety or environmental incidents.

Condition survey and assessment

The condition survey and assessment included:

- Visual examination and photographic documentation of obvious defects, including cracking, erosion, and signs of construction joint delamination; and
- Nondestructive testing (NDT) using impact echo (IE) (Fig. 3(a)), coupled with sounding for delamination using chain drag (Fig. 3(b)) and appropriately weighted hammers (Fig. 3(c)). While chain drag and hammer testing was conducted for the entire shotcrete surface, IE

Fig. 3: Nondestructive testing: (a) IE; (b) sounding using a chain drag; and (c) sounding using a hammer

testing was conducted at a grid of 2 m (6.6 ft) in accessible areas with no water flow. The shotcrete surface at IE test locations was ground smooth within and beyond the zone between the impactor and transducer.

Cores were extracted at locations that appeared to be either delaminated or sound as indicated by NDT. They were used to evaluate compressive strength as well as boiled absorption and volume of permeable voids. A petrographer also examined the cores.

Results and Discussion

Visual inspection

Visual inspection revealed a number of deficiencies, including cracking; erosion; construction joint delamination at what appeared to be feathered edges; efflorescence and leaching from water seepage; and surface irregularities. Results of visual inspections were recorded in the condition survey maps (Fig. 4).

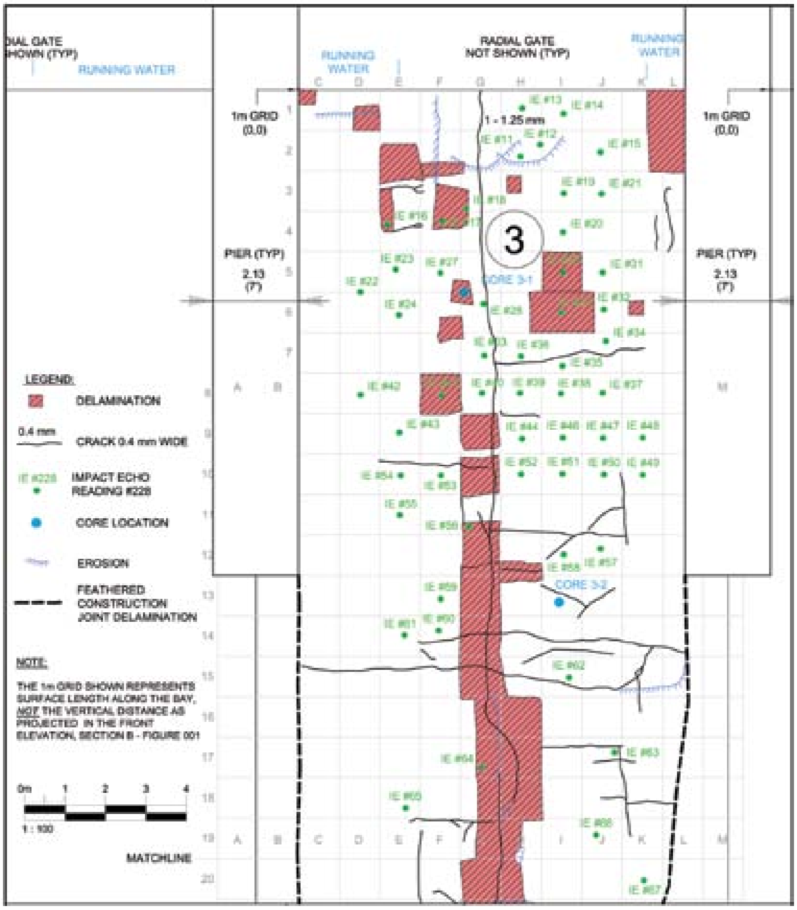

Fig. 4: Example of condition survey map

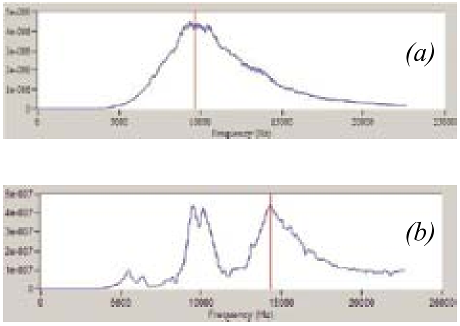

Fig. 5: IE testing results: (a) results indicating sound shotcrete; and (b) results indicating delaminated shotcrete

IE testing and sounding

IE and sounding data were used to categorize the concrete as sound, delaminated, or defective. If IE indicated no defects to a depth of about 300 mm (12 in.), the overlay and substrate were deemed sound (Fig. 5(a)). If a defect was detected using IE and confirmed using sounding, the concrete was deemed delaminated (Fig. 5(b)). If IE indicated a defect that was not confirmed by sounding, the concrete was deemed defective—the defects could be deep delaminations or voids. We also found areas where the IE data could not be interpreted because of poor signals. Although we made attempts to grind rough areas smooth in the majority of test locations, the poor signals could perhaps be attributed to a rough surface.

In total, 217 readings were taken, typically at 2.0 m (6.6 ft) spacing in accessible areas (Fig. 4). Of the total evaluated points, 41% were deemed sound material, about 15% were found to be delaminated, 22% were defective, and 23% of the IE readings provided poor signals that could not be interpreted.

Spillway Bays 1, 2, 3, 5, and 7 were sounded. Table 1 summarizes the total delaminated area detected for each bay.

Bay 3 had the largest percentage of delaminated area (18%), while Bays 5 and 7 had the lowest amount of delamination. The total delaminated area for the entire spillway was calculated to be 99 m^2 (1065 ft^2) or 6%.

Core examination

Cores obtained from the spillway were visually examined prior to preparation for testing and petrographic examination. Detailed information about cores is listed in Table 2.

All cores had delamination planes. Half of the cores had delamination at the shotcrete/concrete interface, and two cores had multiple delamination planes. Cores extracted from locations where delamination was indicated by NDT showed delaminations in the shotcrete layer; cores extracted from locations that appeared sound from the NDT testing showed delaminations in the concrete layer.

The shotcrete thickness was in the 55 to 210 mm (2.2 to 8.3 in.) range in the spillway and 40 to 130 mm (1.6 to 5.1 in.) in the stepped structure. The average depth of delamination below the shotcrete/concrete interface was calculated to be 25 mm (1 in.) in the spillway and 15 mm (0.6 in.) in the stepped structure. Core examination also revealed the presence of porous zones (shadows) in some of the shotcrete cores.

Core testing

Density, absorption, volume of permeable voids, and compressive strength were determined for the spillway shotcrete and concrete (Table 3).

It was determined that the average absorption of the spillway shotcrete was 5.6% and the average volume of permeable voids was 12.7%. These values are well within the limit provided in ACI 506R-05[3]—that is, 6 to 9% typical absorption values and 14 to 17% volume of permeable voids.

Although the average compressive strength of the spillway shotcrete was calculated at 40.0 MPa (5800 psi), the results varied from 20.8 to 69.4 MPa (3016 to 10,063 psi). This is sometimes encountered with dry-mix shotcrete, as the compressive strength is significantly affected by the amount of water added at the nozzle. It should be noted that the specified compressive strength of the shotcrete was 4500 psi (31 MPa).

For the original spillway concrete, the average absorption was 4.6% and the average volume of permeable voids was 11.0%. Much less variation was observed in the concrete compressive strength as compared to the shotcrete compressive strength, although one outlier was excluded from the average based on Chauvenet's criterion. The corrected average strength of the spillway concrete was 28.4 MPa (4118 psi).

Petrographic examination

The petrographic examination indicated that the principal form of distress affecting the concrete is freezing-and-thawing damage. There was evidence of through-core fracturing and cracking,

Table 1: Delamination Summary

Bay no.	Delaminated area, m^2	Total bay area surveyed, m^2	Delaminated area, %
1	11.7	147.5	7.9
2	14.1	316.6	4.5
3	66.3	371.3	17.9
5	3.8	429.3	0.9
7	3.0	336.1	0.9
Total	98.9	1600.8	6.1

Note: 1 m^2 = 10.76 ft^2

Table 2: Shotcrete Thickness and Depth of Delamination in the Spillway Cores

Core no.	Shotcrete thickness, mm	Depth of shotcrete delamination below surface, mm	Depth of concrete delamination below shotcrete/concrete interface, mm	Other observations
1-2	75	10 to 30	110	Delamination is along a large-size aggregate
1-3	200 to 210	140 and 200 (at the interface with base concrete)	No delamination	Porous zones (shadows) in the shotcrete
2-1	190	160 and 190 (at the interface with base concrete)	No delamination	—
2-2	175	175 (at the interface with base concrete)	No delamination	—
3-1	55 to 65	55 (at the interface with base concrete)	0 to 25	—
3-2	130 to 140	No delamination	35	—
5-1	85 to 105	No delamination	350*	—
5-2	170	170 (at the interface with base concrete)	No delamination	—
7-1	85 to 100	No delamination	50 and 305*	—
7-2	85 to 95	No delamination	25 to 45	—
Average	130	—	25	—

*Not included in the average. Only delaminations located near shotcrete/concrete interface are included

Note: 1 mm = 0.03937 in.

both attributable to freezing and thawing. While some minor signs of alkali-silica reaction were observed, the associated expansion would have been insufficient to have caused the observed cracking (Fig. 6).

Assessment

The condition survey established that while the shotcrete-faced spillway appears to be in reasonably good condition overall, there is distress in the forms of cracking, delaminations at construction joints with feathered edges, and more deep-seated delaminations at the shotcrete/concrete interface or in the substrate concrete. There are also localized areas of erosion and seepage through the shotcrete face (Fig. 7).

Based on the findings of the field investigation and subsequent petrographic evaluation and physical testing of shotcrete and concrete components of extracted cores, it is concluded that the prime mechanisms of continuing deterioration of the spillway face and stepped structures were delamination and cracking attributable to ongoing freezing and thawing. This is compounded by the effects of localized seepage and erosion in the shotcrete face and at feathered-edge construction joints.

Therefore, we recommended that the defective and deteriorated areas of the spillway shotcrete be removed and replaced. An overall schematic showing the general areas that have to be removed and replaced is in Fig. 8.

Rehabilitation

For remediation, we recommend the use of wet-mix shotcrete for repairs, as it provides consistent

Table 3: Density, Absorption, Voids, and Compressive Strength of the Spillway Shotcrete and Substrate Concrete

Sample ID	Absorption after immersion and boiling, %	Outlier ID	Bulk density after immersion and boiling, kg/m^3	Outlier ID	Volume of permeable voids, %	Outlier ID	Corrected compressive strength, MPa	Outlier ID
Spillway shotcrete								
1-3-I	7.85	1.27	2.35	–1.22	17.1	1.18	21.7	–1.04
2-2-I	7.04	0.82	2.38	–0.66	15.7	0.80	27.7	–0.70
3-2-I	3.23	–1.33	2.43	0.19	7.6	–1.38	69.4	1.68
5-1-I	4.77	–0.46	2.51	1.48	11.4	–0.35	31.6	–0.48
5-2-I	4.27	–0.74	2.39	–0.54	9.8	–0.80	20.8	0.62
7-1-I	6.37	0.44	2.46	0.75	14.7	0.55	38.7	–0.07
Average	5.59	—	2.42	—	12.7	—	35.0	—
Standard deviation	1.78	—	0.06	—	3.70	—	18.11	—
Critical value for rejection (Chauvenet's criterion)					1.73			
Corrected average	5.59	—	2.42	—	12.7	—	40.0	—
Spillway concrete								
1-3-III	5.34	0.59	2.50	–0.39	12.7	0.62	30.4	0.80
1-2-II	6.59	1.56	2.46	–1.60	15.2	1.52	29.4	0.57
2-1-III	3.27	–1.01	2.56	1.00	8.1	–1.03	27.6	0.18
3-1-II	4.26	–0.25	2.50	–0.40	10.2	–0.27	18.4	–1.77
5-2-II	4.78	0.16	2.53	0.37	11.6	0.22	24.2	–0.54
7-2-II	3.23	–1.05	2.56	1.01	8.0	–1.06	30.2	0.76
Average	4.58	—	2.52	—	11.0	—	26.7	—
Standard deviation	1.29	—	0.04	—	2.78	—	4.69	—
Critical value for rejection (Chauvenet's criterion)					1.73			
Corrected average	4.58	—	2.52	—	11.0	—	28.4	—

Note: 1 kg/m^3 = 1.686 lb/yd^3; 1 MPa = 145 psi performance and will work well to produce the sloped, irregularly shaped patches needed on the spillway. Cast-in-place concrete would be difficult to form, deliver, and consolidate; and it would be difficult to obtain a quality surface finish (air bubbles tend to get trapped under sloped formwork, resulting in numerous voids on the concrete face). With modern wet-mix, steel fiber-reinforced, silica fume modified shotcrete, it's possible to achieve high quality, dense concrete with smooth surface finishes. It is also possible to achieve high compressive strength, excellent resistance to freezing and thawing, and resistance to erosion and abrasion. We recommend removing delaminated zones and placing a full thickness replacement overlay, using mild steel reinforcement to tie the overlay back to the original concrete dam material (Fig. 9).

A complete shotcrete overlay was also proposed as an option. This overlay involves resurfacing approximately 3000 m^2 (32,280 ft^2) of the spillway with a reinforced shotcrete overlay. Although you can use either WWR or steel fibers, we recommend resurfacing the spillway with a steel fiber-reinforced shotcrete overlay to a nominal 150 mm (6 in.) thickness (Fig. 9). This is similar to the approach used in the Littlerock Dam shotcrete overlay seismic retrofit.[4] As in the Littlerock Dam project, it was recommended that a system of shotcrete anchors connected by reinforcing bars be installed to provide mechanical anchorage so that the long-term performance of the bonded overlay is not entirely dependent on bond. Using steel fibers eliminates the complications of installing and achieving good shotcrete

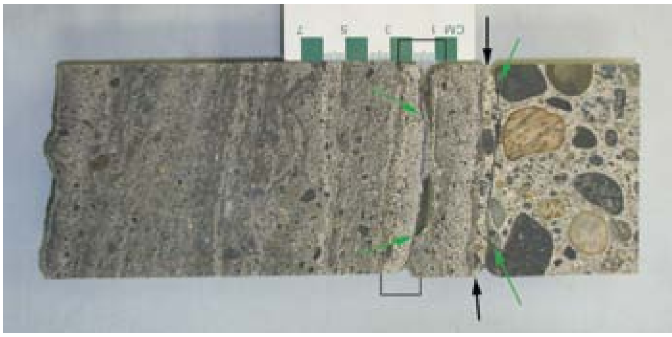

Fig. 6: *Example of petrographic examination photo. Polished core surface of Core B2-1 prepared along the long axis of the core. The black arrows indicate the tight shotcrete (gray) parent concrete (at right) contact. The green arrows indicate through core cracking both in the parent concrete and in the shotcrete layer. The black brackets outline a zone of very weak, highly porous shotcrete*

Fig. 7: *Feathered edge construction joint delamination*

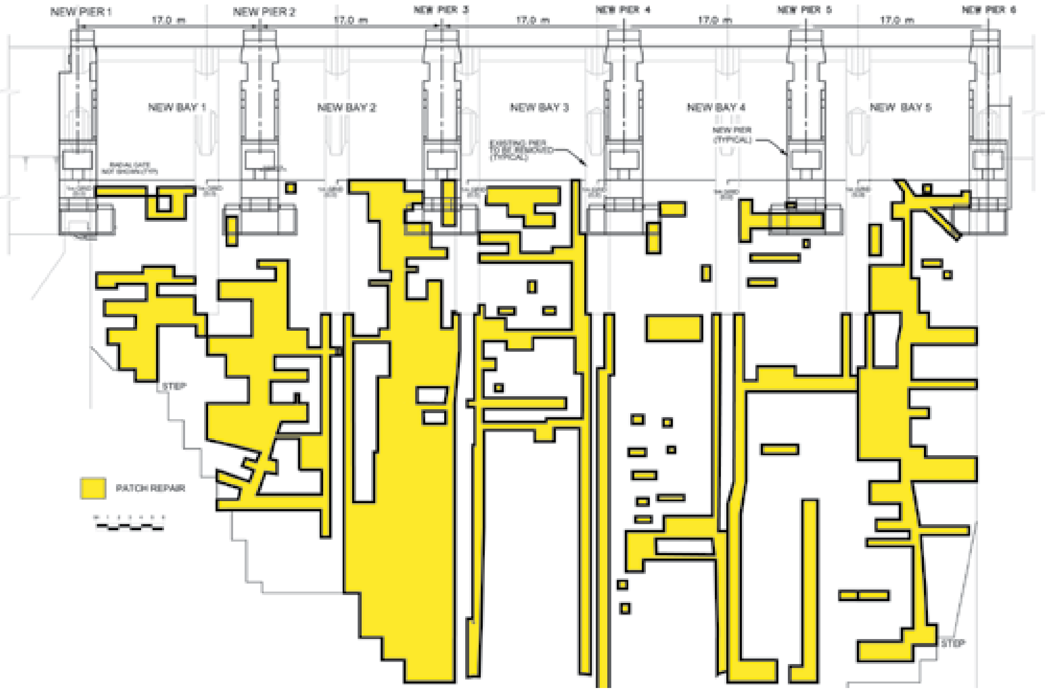

Fig. 8: *Sketch of spillway repair maps (yellow represents area to be removed)*

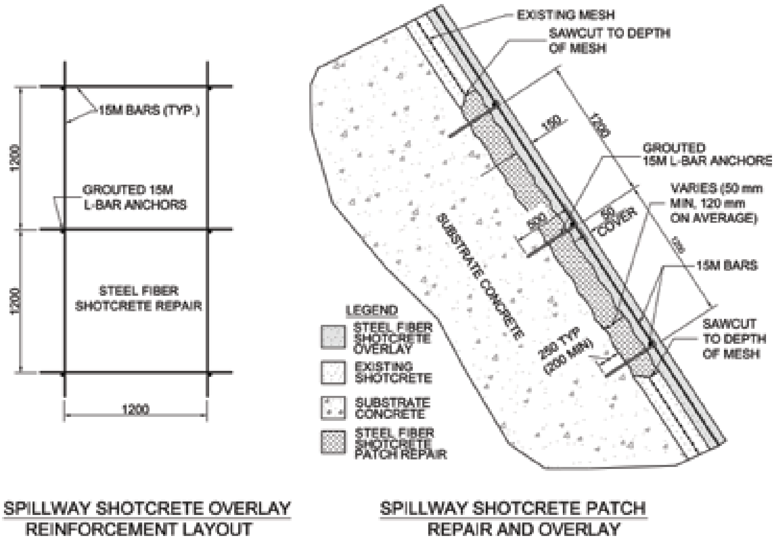

Fig. 9: Steel fiber-reinforced shotcrete repair of spillway surface. All dimensions in mm (1 mm = 0.03937 in.)

consolidation around WWR. When properly cured, steel fiber-reinforced shotcrete has been demonstrated to be very effective in reducing or even eliminating cracking of bonded shotcrete overlays in dams and other hydraulic structures.[4]

Life Extension

The existing WWR reinforced dry-mix shotcrete resurfacing of the Ogee spillway of the Ruskin Dam has extended the serviceability of the dam by nearly 40 years. A major seismic upgrade to the dam is planned, with a view to extending the design life of the dam by at least another 50 years. A detailed condition survey of the shotcrete-faced spillway shows that while the majority of the shotcrete overlay is still in good condition and well bonded to the substrate concrete, there are areas now displaying weathering or deterioration, including cracking, delamination, and erosion. Remedial alternatives involving either patch repair or a full bonded steel fiber-reinforced wet-mix shotcrete to extend the service life of the dam for another 50 years or more have been presented as options.

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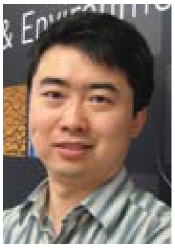

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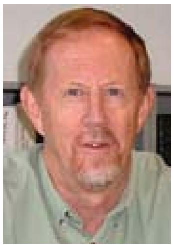

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