Repair of the Sumas River Dike Breach: A Case History

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ABSTRACT In November 2021, during an unprecedented atmospheric river event, the Sumas River Dike was breached resulting in flooding of a large area of the Sumas Prairie in Abbotsford, BC. The site of the Sumas River Dike breach is approximately 4.5 km southwest (upstream) of the Barrowtown Pump Station along the base of Sumas Mountain. This paper describes the main breach that occurred including the failure mechanism and the key geotechnical engineering considerations related to design and construction of the breach repair. A two-staged strategy was adopted for repair of the dike breach that included the initial emergency repair to close the breach followed by the additional remedial work required to restore the temporarily repaired dike section back to a dike with a low permeability core . Details of the two-stage repair strategy are described including the various options considered, as well as the challenges faced during construction. The flood event also created significant challenges during construction in terms of the supply of the materials required to repair the breach, access to these materials, and maintenance of access between the work site and material supply. These challenges are presented with the intent of providing some insights for future emergency preparedness planning.

Introduction

On November 16, 2021, during a series of unprecedented atmospheric river events, the Sumas River Dike (also referred to as the Upper Sumas River Dike) was breached resulting in flooding of a large area of the Sumas Prairie in Abbotsford, BC. Emergency response focused on closing the breach to stop flowing water from the Sumas River entering Sumas Prairie. The widespread flood event created significant challenges in terms of site access and material supply during the emergency response.

This paper describes the main breach that occurred including the failure mechanism and the key geotechnical engineering considerations related to design and construction of the breach repair. A two-staged strategy was adopted for repair of the dike breach that included the initial emergency works to close the breach followed by the additional remedial work required to re-establish a low permeability core within the temporarily repaired dike section. Details of the two-staged repair strategy including the options considered for the low permeability core are discussed in this paper. Several challenges that had to be overcome during construction are described with the intent of providing some insights for consideration on similar projects as well as for future emergency preparedness planning.

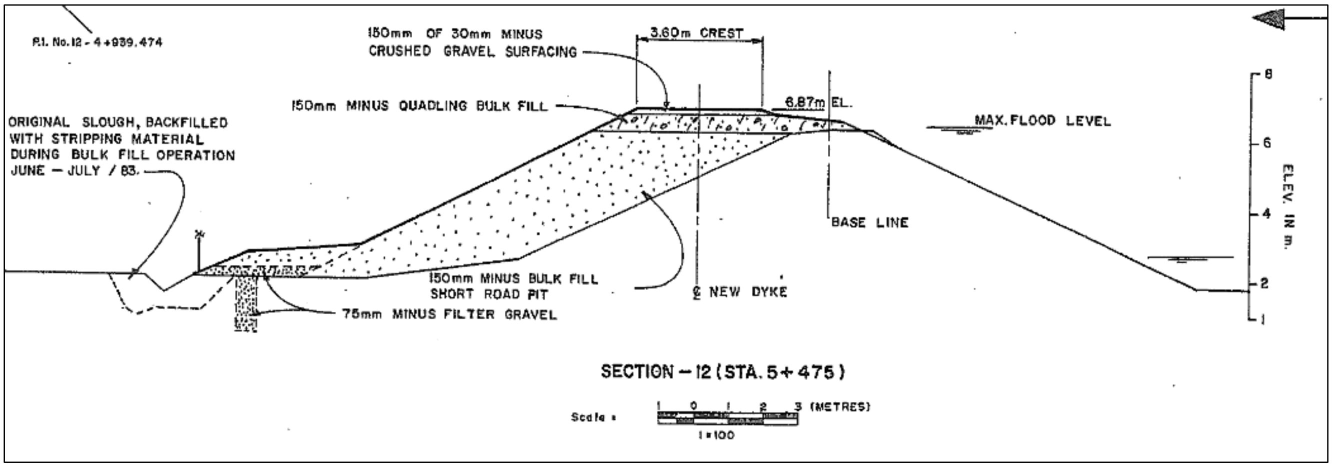
Site Location and Description

The reach of the Sumas River that flows north of the Trans-Canada Highway (Highway 1), along the southeast base of Sumas Mountain, between Highway 11 and Yale Road, was once the approximate shoreline of the former Sumas Lake. Between 1920 and 1924, Sumas Lake was drained for flood control and agricultural purposes after which the first flood protection dikes were constructed. The site of the main breach of the Sumas River Dike is approximately 4.5 km southwest (upstream) of the Barrowtown Pump Station (see Fig. 1) between about Chainage 5+400 and 5+550.

Fig 1. Sumas River Dike breach location.

The most recent upgrade occurred in the late 1980's as part of the Abbotsford Flood Control Program and included adding a granular filter layer to the land side slope of the dike. The dike bulk fill was sourced locally from the nearby quarries including the Short Road Pit and the Quadling Quarry, located adjacent to Barrowtown Pump Station. The land side and water side slopes of the original dike section vary from 2 Horizontal to 1 Vertical (2H:1V) to 3H:1V, with toe to crest height between about 4m to 5m and a crest width of about 4m. A typical section of the original dike section for the reach of dike that was breached (taken from the "As-Constructed" Drawing Set No. 5460-1-10, Rev. A, Sheets 7 to 15, dated 1988 and prepared by Crippen Consultants) is shown on Fig. 2.

Fig 2. Original Dike Section.

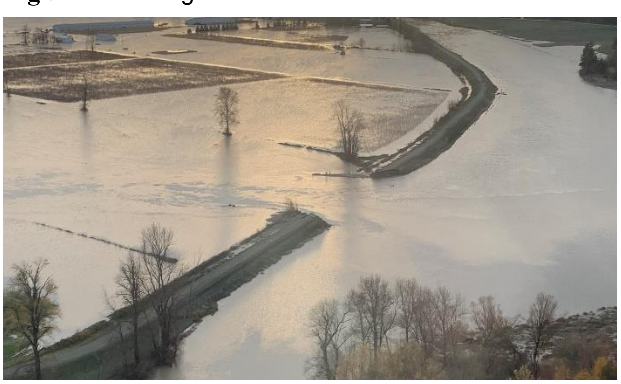


The dike is underlain by a surficial layer of lacustrine deposits (silt to clay), normally less than 5m thick, which is underlain in some areas by Fraser River Sediments, comprising fine sand to clayey silt. These conditions were checked by a site-specific geotechnical exploration carried out following completion of the initial emergency repair and prior to design for the remedial phase of the work to re-establish a low permeability core.

The Breach

The Sumas River Dike Breach occurred on November 16, 2021, during a series of unprecedented atmospheric river events. The breach occurred as a result of floodwaters from the Sumas River overtopping the dike followed by rapid downcutting of the dike structure allowing floodwaters from the Sumas River to flow into Sumas Prairie. The length of the dike breach was about 150m with scour that extended about 4m below the original ground surface (base of dike) and extended about 150m south into the farm field adjacent to the dike. Google Earth Imagery dated July 29, 2022, clearly shows the extent of the initial emergency repair of the dike breach and scour hole in the adjacent farm field. An aerial photograph of the breach taken on November 17, 2021 (day after the breach), is shown on Fig. 3.

Fig 3. Aerial image of the dike breach.



Visual observations of the dike near the breach clearly showed evidence of significant erosion and downcutting of the landside slopes of the dike with several sections of the dike slope eroded to near-vertical configuration near the landside crest of the slope. The exposed near-vertical sand and gravel fill was the material that was added to the landside of the dike in the 1988 upgrade with clear evidence of the well-compacted layers developed during the previous upgrade construction. Deposits (pinnacles) of gravel and cobble sizes extended far into the adjacent farm fields at several locations. Fig. 4 illustrates erosion that occurred along the landside slopes of the dike as a result of overtopping.

Fig 4. Erosion on landside slope of the dike.

Closing the Breach

At the breach, most if not all of the dike structure was lost over a length of about 150m, and in addition, a large scour hole was eroded well below the toe of the dike and beyond, extending some 150m into a farm field to the southeast. The scour hole was about 3m to 4m below the base (bottom) of the existing dike. Ideally, a dike should have a low permeability core constructed of silty and/or clayey soils. However, emergency repair work was carried out during periods of intense precipitation, working initially under conditions of flowing floodwaters and partially underwater, making it impossible and impractical to use fine-grained soils. To attempt to do so would likely have been disastrous. The plan put forward for closure of the breach was to construct an initial crossing (closure) to stop flow from Sumas River, then continue to widen and build up the closure once the open flowing water was stopped. Fig. 5 shows the initial construction of the dike breach closure.

Fig 5. Initial Breach Closure.

The entire closure of the breach was constructed using crushed granular fill of varying sizes, with coarser 600mm minus crushed rock specified for the outside (along the side slopes) and finer 75mm minus crushed rock specified within the central portion of the dike. The initial closure was widened to the south and raised using the finer 75mm minus crushed rock to allow for future installation of a low permeability barrier or core. The widening and raising of the breach closure continued using the smaller crushed rock (see Fig. 6). This material was placed in lifts and compacted using a large vibratory compactor. Specifying the use of finer 75mm minus crushed rock to construct the central portion of cross-section for the dike closure was essential in order provide some degree of flexibility in terms of considering options to reinstate a low permeability barrier, without which, the dike would leak.

Fig 6. Construction of the breach closure.

As the dike breach repair widening and raising was nearing completion, the Sumas River was again reaching near flood stage levels during the second series of Atmospheric Rivers. It was observed that some of the finer, loose and unconfined material within 75mm minus crushed rock fill material was starting to mobilize (move) in localized zones where seepage was greatest on the landside slope of the dike. Subsequently, a layer of larger 600mm minus crushed rock was placed on the landside of the dike as ballast and support. It was recognized from the onset, that seepage through the body of the dike closure would occur and continue until such time that a suitable low permeability barrier or core was installed to mitigate seepage.

Fortunately, the source of fill material was relatively close to the site, being the Jamieson Quarry on the south side of Sumas Mountain. Even though the material source was close to the site, there was only one open haul route available during one period of the initial operations due to widespread flooding. A section of that haul route adjacent to the Sumas River, which was experiencing overland flooding from upslope, was continually monitored and maintained to keep it open to truck traffic.

During initial construction of the dike breach closure, spatial constraints at the breach site did not allow for more than one excavator and one dump truck at a time with just sufficient space for the dump truck to turn around and leave once it was emptied. With the dike only being wide enough for one standard dump truck, trucks were continually being advanced forward to the breach moving from pullout to pullout along the dike between the empty trucks returning from the breach site. Loaded dump trucks were lined up waiting to access the dike at times that extended over one kilometre in length (see Fig. 7).

Fig 7. Loaded trucks waiting to access the dike.

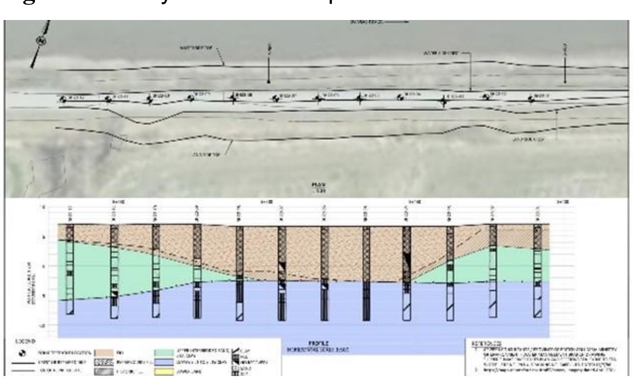
Once the initial breach closure was completed (cutting off open flow through the breach) and had sufficient width, trucks could then follow a haul route on the dike without the need to turn around at the breach site. Fig. 8 shows the landside slope of the completed dike breach closure with adjacent water-filled scour hole which is on the land side of the dike.

Fig 8. Landside slope of the completed dike breach closure.

Geotechnical Exploration

After the emergency repairs to close the breach were completed, a geotechnical exploration was completed to check the extent (depth) of the recently-placed crushed rock fill zone, the characteristics of the underlying foundation soils and to confirm the presence or absence of larger rock sizes within the central portion of the repair (constructed of the finer 75mm minus crushed rock) that would present as obstructions to the proposed core construction activities. This information was also used to establish the required extent of the low permeability barrier and to assess suitable options to construct a low permeability barrier required to mitigate seepage through the breach closure. Twelve (12) test holes were drilled using sonic drilling methods to just over 15m depths within the central portion of the breach closure spaced out along the length of the repaired section. A summary plot of the test hole results is shown on Fig. 9. Of note, the geotechnical exploration did detect some larger pieces of crushed rock in that zone that was intended to be 75mm minus crushed rock.

Fig 9. Summary of test hole exploration.



Options for Seepage Mitigation

As previously discussed, the entirety of the dike breach repair was constructed using crushed granular fill of varying sizes and therefore seepage would continue through the body of the dike until a low permeability core or barrier was installed within the central portion of the dike. Three options for seepage mitigation that were considered included: 1) re-construction of the dike section with a low permeability core; 2) construction of a low permeability core using deep soil mixing technology; and 3) construction of a steel sheet-pile barrier.

The re-construction option would require removal of a large portion or most of the repaired section of dike breach and replace it with new engineered fill including a low permeability soil core, filter(s), drainage, and bulk fill zones. This option would be time consuming and encounter considerable constructability challenges (e.g., excavation support, dewatering, and the like) associated with earthworks being carried out as much as 4m or more below the groundwater table and in proximity of the flowing Sumas River. (e.g., a temporary cofferdam would most likely be required during construction).

The deep soil mixing option involves mechanically mixing the in-situ soil, in this case 75mm minus crushed rock/gravel dike fill, with a bentonite/cement slurry mixture to form a low-permeability barrier (core) along the center of the breach closure (with permeability consistent with the in-situ silty and clay soils). The barrier is constructed by building a series of overlapping rectangular panels along the centreline of the breach closure to form a barrier to mitigate seepage. The primary construction challenge would be associated with encountering larger crushed rock sizes resulting in cutter teeth breakage and possible cutter head damage.

The steel sheet-pile wall option would involve installing (driving) a continuous line of interlocking sections of steel sheet-piles along the centre of breach closure to act as a low-permeability barrier to mitigate seepage through the dike fill. However, there could be constructability challenges associated with driving sheet piles through well-compacted 75mm crushed gravel fill and encountering larger crushed rock sizes while maintaining connection between adjacent sheet piles.

One of the key considerations in selecting the preferred option to reinstate a low permeability barrier in the breach closure was that, as much as possible and practical, the preferred option should minimize the need for de-construction.

The option selected for construction of the low permeability core was Cutter Soil Mixing (CSM), which is one of several proven and locally available methods for deep soil mixing and successfully used in other similar barrier applications (Arnold et al., Holzman et al. and others (2011)).

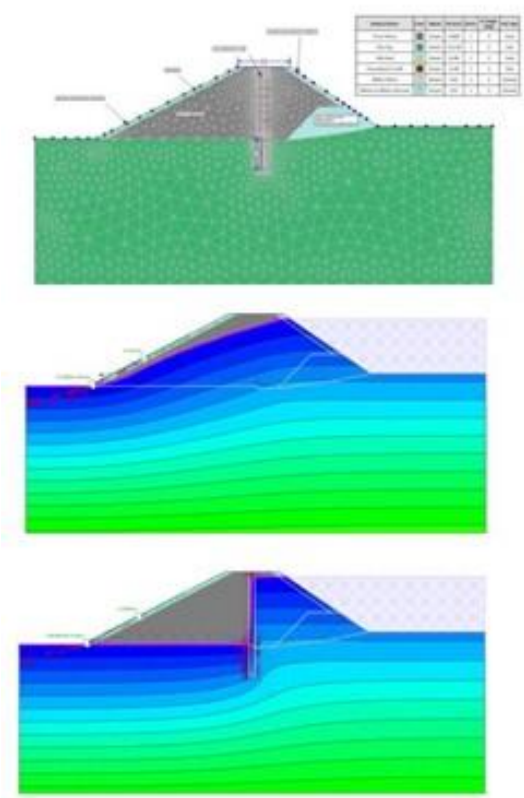
Design of the Barrier

The overall objective was to construct a barrier within the closed breach section that was flexible and with low permeability thereby creating a structure that would once again function as a dike.

Steady state seepage analyses were carried out using commercially available computer software Slide (RocScience 2018, ver. 8.032) to confirm the benefit of installing a barrier with low permeability ($1x10^{-9}$ m/s) to mitigate seepage flows through the breach closure which was constructed entirely of crushed rock of varying sizes (75mm minus material in the central portion and larger, 300mm to 600mm minus on the outside slopes). The findings of the seepage analysis indicated that for the breach closure without a low permeability barrier, the estimated seepage through the closure would likely range in the order of between about 5 and 20 litres/min per metre length of dike closure. This considers conditions in the Sumas River that vary from "normal" to flood level. Installing a low permeability barrier that is 600mm thick and extends 4m into the underlying foundations soils reduces seepage by about two (2) orders of magnitude, or to between about $1x10^{-2}$ and $5x10^{-2}$ litres/min per metre length of the dike closure. Fig. 10 illustrates the seepage analysis model and plots of findings under flood conditions.

To maintain flexibility in the barrier, an Unconfined Compressive Strength (UCS) of 1 MPa was specified for the constructed barrier.

Fig 10. Seepage analysis plots.



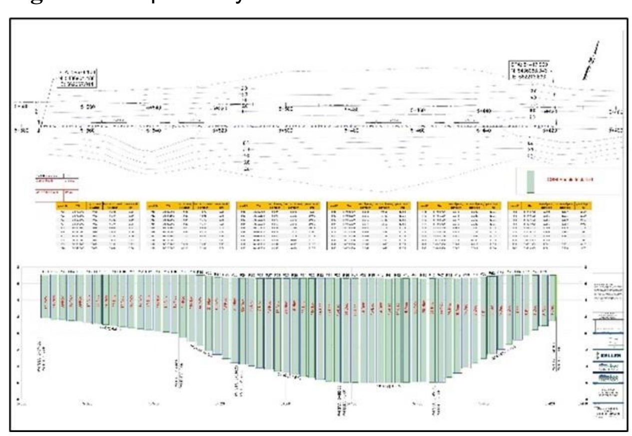
Construction of the Barrier

As previously noted, the barrier was constructed by means of Cutter Soil Mixing ("CSM") technology. CSM is one of several deep soil mixing methods used locally in construction of cut-off barriers and in ground improvement applications. The CSM equipment (RTG RG 27-S rig) consists of a large drill rig, similar to a pile driving rig, that is equipped with a mast that supports a rigid kelly-bar to which the cutting tool is attached. The cutting tool is comprised of counter-rotating drums that are fitted with cutting teeth with a configuration that is specifically designed for cutting and mixing in-situ soils with bentonite and Portland cement slurries. The CSM rig is supported by an excavator, loader, and a batch plant that produces the bentonite and Portland cement slurries. The bentonite slurry and Portland cement slurry are prepared in the batch plant (set up and located adjacent to the work site) and pumped though hoses to the CSM rig. Fig. 11 shows the CSM rig used for construction of the barrier.

Fig 11. CSM Rig.

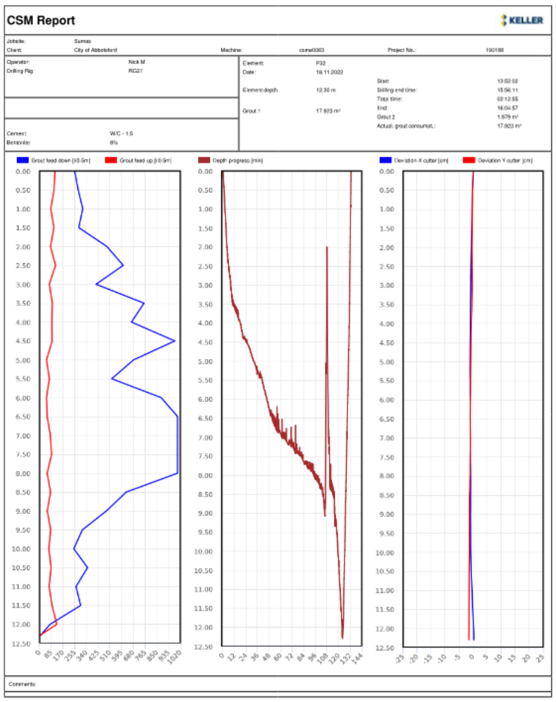
The CSM process involves constructing rectangular panels that are 2.8m long by 640mm wide and extend to the target depth. As the cutting tool advances or cuts its way down into the ground, bentonite slurry is continually added to aid as a cutting fluid and to lower the permeability of the mixed soil-slurry mass. When the cutting tool reaches the target depth, Portland cement slurry (required for strength) is then introduced as the cutting tool is slowly retrieved from the ground. Once the Portland cement is introduced into the process, the contractor's experience and time become a factor as any missteps by the crew or equipment issues could lead to the cutting tool getting stuck in the ground. The contractor tailors the bentonite slurry and Portland cement slurry application to achieve the performance requirements set out in the contract specifications. A total of sixty (60) CSM panels were required to construct the barrier with depths varying between 5.25m and 12.75m. The CSM panel layout is shown on Fig. 12.

Fig 12. CSM panel layout.



During the CSM panel construction process, an onboard monitoring system collects real-time data for each panel construction including progress (cutting tool depth vs. time), bentonite slurry application, Portland cement slurry application and deviation of the cutting tool/kelly-bar from the barrier alignment. A CSM report, or also commonly referred to as "B-Report", is prepared for each panel that is constructed (see Fig. 13).

Fig 13. Typical CSM report.



The left plot in the CSM report in Fig. 13 is a record of bentonite slurry consumption represented by the right (blue) line as the cutting advances down into the ground and then Portland cement slurry consumption represented by left (red) line as the cutting tool is withdrawn upward. The central plot records the progress of the cutting tool for both advance into the ground and withdrawal (from left to right). It is noted that there is greater time and "noise" on the progress plot between about 6.5m and 9m; this is due to difficulties advancing the cutting tool beyond some pieces of larger crushed rock in that zone within the crushed dike fill that was used to close the breach. For Panel No. 32, shown on Fig. 13, it took about 2 hours, 12 minutes to construct the panel which is considerably longer than might be expected.

Some of the larger pieces of crushed rock being present in what is supposed to be mostly 75mm minus crushed rock is most likely due to some larger material being used on the water side during construction of the initial closure ramp into the breach, some larger pieces mixed in with fill delivered to the site and possibly also due to this material having been placed in flowing water. As much as possible and practical, the operator tried to keep the water side slope of the initial closure as steep as possible to keep the outside larger pieces of crushed rock away from the central portion of the dike closure. A total of about 300 sets of teeth were broken on the CSM cutter tool bouncing and grinding on pieces of larger crushed rock that were encountered.

After a period of breakage and delays, a decision was made to pre-drill the panel locations to try to retrieve some of the larger pieces of crushed rock or possibly loosen them with the hopes that they could be "kicked" aside by the cutting tool. Initial attempts at pre-drilling were carried out with uncased holes; however, due to caving in some of the hole, particularly below the water table, this approach had limited success and was eventually abandoned.

The second approach at pre-drilling with cased holes proved to be far more successful. The contractor developed an efficient method for pre-drilling using two adjacent cased holes where the lead (first) cased hole was being drilled (and casing advanced into the ground) with material retrieved dumped onto the ground. After sorting through the fill material and removing the larger pieces of crushed rock, the remaining finer crushed gravel fill was then replaced into the trailing (second) cased hole (and that casing gradually withdrawn). In the end, about half of the sixty (60) CSM panels required pre-drilling. Fig. 14 shows the predrilling arrangement with cased holes.

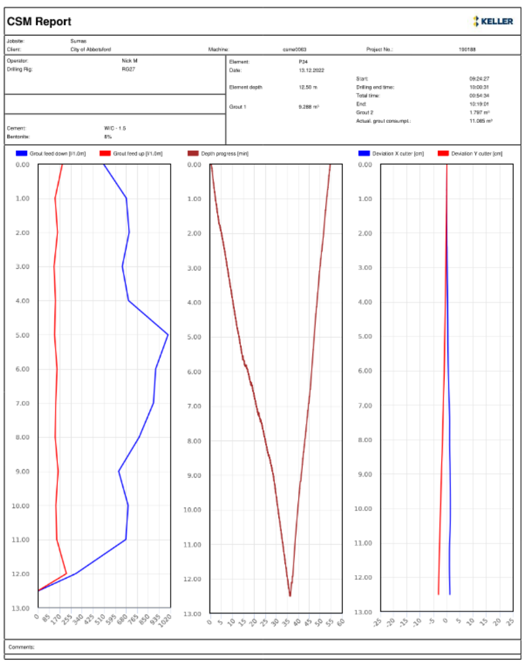
Fig 14. Pre-drilling with casing.

Pre-drilling, particularly with cased holes, proved to be beneficial in getting the remaining CSM panels completed in a much shorter time, and of course, with considerably less risk of damaging equipment as the effort to construct the panel is reduced. Panel Nos. 33 to 43 were pre-drilled using the cased hole approach. Fig. 15 shows both the CSM and pre-drilling equipment on top of the dike breach closure (the water filled scour hole is in the foreground and Sumas River and Sumas Mountain in the background).

Fig 15. CSM and pre-drilling equipment.

The benefit of pre-drilling with a cased hole can be illustrated looking at the CSM Report for Panel No. 34 (see Fig. 16), which is the panel that was installed two (2) panels east of Panel No. 32 (results of which are previously shown above). The time to complete the panel was considerably less, about 54 minutes in this case. As can be seen in the progress (middle) plot on Fig. 16, the cutting tool progress now shows a relatively uniform up and down of the cutting tool without the "noise" associated with bouncing and grinding on larger pieces of crushed rock.

Fig 16. CSM Report for Panel No. 34.



In addition to the challenge of dealing with obstructions, cold weather played havoc with CSM equipment in the latter part of November and early December 2022 resulting in freezing of hoses and lines that feed bentonite and Portland cement grout to the cutting tool.

Samples obtained from completed panels were collected on a prescribed sampling schedule set out in the contract specifications for Unconfined Compressive Strength (UCS) testing to confirm the CSM panels achieve the specified UCS. Samples were also obtained for hydraulic conductivity testing and results of this testing confirmed that the hydraulic conductivity of the constructed panels satisfied the contract specification.

Final Review and Fish Salvage

After completion of the CSM barrier, a final field review of the landside slope was completed looking for visible seepage (point sources of flow) but could only be completed after the water filled scour hole was drained.

Following about a one month delay due to unseasonably cold weather and the Christmas break, the contractor was able to drain (by pumping) the water-filled scour hole on the landside of the breach repair. During the pumping process, and as water levels were lowered in the scour hole, a fish salvage was undertaken to recover fish trapped in the scour hole because of the dike breach. Fish species recovered included several sturgeon some up to 2.1m long, a pair of coho salmon, and numerous other fish. These fish were flushed through the breach when it occurred and then were effectively trapped in the water-filled scour hole for a period in excess of one year. Fig. 17 shows one of several sturgeon that were recovered.

Fig 17. Sturgeon recovered from the scour hole.

Once the water was pumped down, and with fish salvage work still underway, a visual review was carried out along the exposed water side slope of the dike breach repair. At the time of the field review, the head difference between the Sumas River and the scour hole was about 3m. No point sources of flow were observed along the exposed water side slope of the dike breach repair, but several areas of seepage flow were observed along the perimeter of the scour hole with this seepage being groundwater draining from the surrounding farm field. Discussions with the farmer, whose property was directly impacted by the breach, confirmed that the area of the field occupied by the scour hole was always considered a localized wet area. Fig. 18 shows the drained scour hole with fish salvage still underway.

With no observed point sources of flow along the water side slope of the dike breach repair satisfying the final performance criteria, the repair was considered complete.

Fig 18. Drained scour hole and exposed water side slope of dike breach repair.

Challenges

As with any major emergency work, challenges will test the collective experience and innovation of the team with the repair of the Sumas River Dike breach being no different. The key challenges faced during repair of the breach included:

- Weather – during the initial stages of the emergency works, heavy precipitation made for difficult working conditions including continued flooding of some crucial access roads requiring continual monitoring and maintenance. During initial emergency repair of the breach, and during the second series of atmospheric rivers, rising flood waters did threaten continued work at the breach site. Trigger points (levels) had to be established in terms of the minimum freeboard required to allow work to continue.
- Materials – securing fill materials of suitable quality and quantity can be challenging. Fortunately, the large quantity of material required to initially close the open breach and then raise the dike could be produced at the Jamieson Quarry situated on the southeast side of Sumas Mountain. One of Mainland's operations had to be reserved to the Sumas Dike emergency repair only, as there was, as one would expect, other demands competing for material and resources as a result of the widespread flooding. At times, materials delivered to site had to be sorted either because the material was not appropriate or large pieces of crushed rock were intermittently mixed in with finer material or it was just the wrong material which had to be dealt with after it was dumped, in turn slowing down progress.
- Access – much of Sumas Prairie was flooded, access and haul routes had to be planned and carefully staged and coordinated as many of the local roads including stretches of the Trans-Canada Highway were closed. Fortunately, the source of fill was nearby; however, there was only one open route during initial operations which had to be constantly monitored and maintained because of overland flooding; failure to do so would have resulted in losing part of the road. Police and other emergency authorities were controlling access to remaining open roads including accessible local sections of the Trans-Canada Highway for public safety. Hauling on top of a narrow dike required a well-coordinated staging plan and concerted effort to ensure timely, continual, and safe delivery of fill material to the breach site.
- Subsurface obstructions – during construction of the low permeability barrier in the closed breach section, larger pieces of crushed rock were encountered and posed a significant challenge for the CSM equipment resulting in delays and equipment damage. A highly experienced contractor was able to overcome those challenges.

Lessons Learned

Several lessons were learned from this (hopefully) once in a lifetime experience:

- An experienced and motivated team was crucial to the successful completion of the initial emergency works in a safe and timely manner.
- Some foresight in terms of specifying appropriate materials for the initial dike closure (the finer 75mm minus crushed gravel for the central portion of the closure) proved invaluable to the successful construction of a low permeability barrier using CSM technology without the need to deconstruct the initial works.
- Pre-drilling with casing proved to be a successful approach to removing obstructions (larger crushed rock) within the dike fill and contributed to successful construction of the low permeability barrier.

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References

Arnold, M., Beckhaus, K. and Wiedenmann, U. 2011. Cut-off wall construction using Cutter Soil Mixing: a case study, GmbH & Co., Geotechnik 34 (2011), Heft 1.

Holzmann, B., MacKay, Siddle, D. and Olivera, R., 2019. Site Characterization for Cutter Soil Mixing of a Vertical Barrier Wall, 26th Vancouver Geotechnical Society Symposium (2019).