Considerations in the design and construction of dike breach repairs

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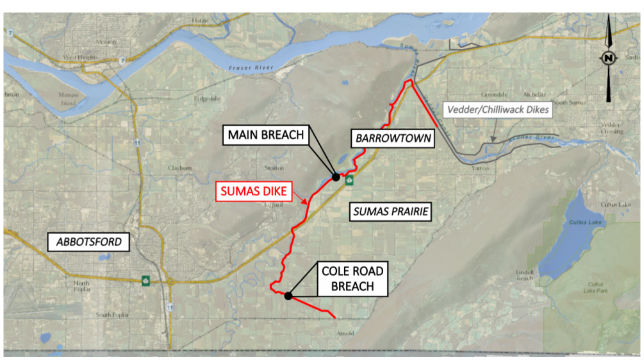
ABSTRACT In recent years, the increased occurrence of unprecedented weather events has resulted in catastrophic failure of key infrastructure including flood control structures such as dikes. Dike breaches, when they occur, require emergency-level efforts to restore flood protection. Decisions made during early stages of the work can impact future remediation where required. In many instances, dike repairs must be completed using a multi-stage approach whereby the initial or emergency stage consists of immediate repairs to close the breached section(s) of dike to stop the flow of water followed later by the remediation stage to reinstate the breached section(s) to function as a dike. This paper discusses the various considerations surrounding the design and construction of dike breach repairs including remediation considering factors that affect decisions including breach location and access, breach size and scour depth, site-specific ground conditions, material delivery, and monitoring of the emergency work. In most instances, emergency repairs address only immediate needs and may not be sufficient as a complete long-term solution. Post-event efforts usually follow, including subsurface geotechnical exploration(s), detailed analysis, design, and construction of remedial works. This paper will also draw on experiences gained from the recent breaches and other flood-related damage of the Sumas River Dike in Abbotsford, BC, with the objective of providing insights for future planning.

Introduction

In recent years, the increased occurrence of unprecedented weather events has resulted in catastrophic failure of key infrastructure including flood control structures such as dikes. In November 2021, a series of atmospheric river events resulted in failure of the Sumas River Dike at two (2) locations; the main breach occurred approximately 4.5 km southwest (upstream) of the Barrowtown Pump Station and second smaller breach occurred at Cole Road, south of the Trans-Canada Highway (Highway 1) as shown on Fig. 1. The events also resulted in erosion and/or partial washing out of the water side slope at several sections of the dike.

Fig 1. Sumas River Dike breach locations.



The breaches occurred because 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 design and construction approaches discussed herein draw on knowledge and experience gained with two recent local dike breaches that occurred due to overtopping and rapid downcutting, as well as erosion damage in other sections of the dike due to high flows; however, these approaches apply equally to dike breaches that could occur because of other failures mechanisms (e.g., internal erosion, seismic loading, external erosion).

Dike Breaches – Sumas River Dike, Abbotsford, BC

An aerial view of the main breach along the Sumas River Dike is shown on Fig. 2 and the Cole Road Breach is shown on Fig. 3. As previously noted, these two breaches occurred because of floodwaters overtopping the dike followed by rapid downcutting of the dike structure.

Fig 2. Aerial image of the main breach looking southwest.

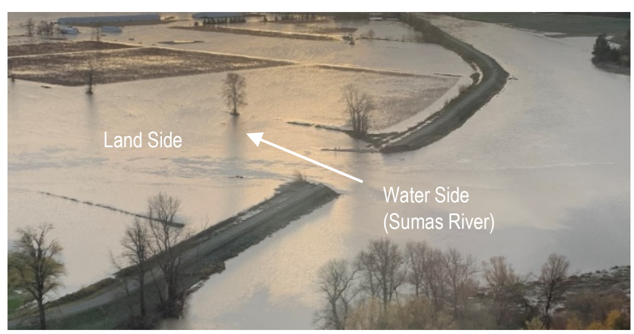
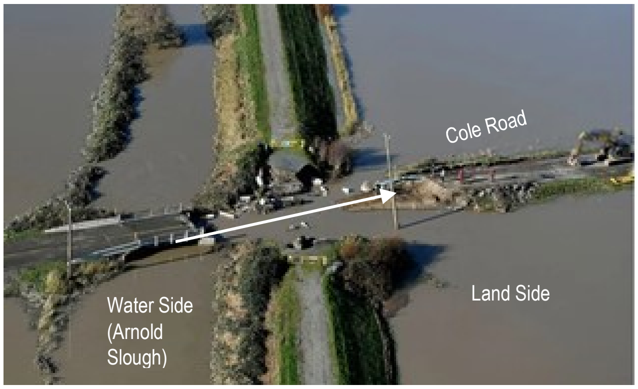


Fig 3. Aerial image of the Cole Road breach looking northwest (Photograph: Vancouver Sun)



The Sumas Breach was video recorded by the farmer who lives immediately east of the breach location which showed overtopping and downcutting of the dike. Other evidence of overtopping and initial formation of other potential breaches was observed as pinnacles of gravel deposited onto farm fields (see Fig. 4) and near vertical scarps eroded into the landside dike slopes as flood water cascaded over top of the dike (see Fig. 5).

Fig 4. Pinnacles of gravel deposited onto farm fields.

Fig 5. Near vertical scarps eroded into landside dike slopes.

Research work has been carried out in the Netherlands to better understand the mechanics of breaches in sand dikes considering both river dikes and lake or sea dikes (Visser P, 1998, T.S. Albers, 2014 and others). Fig. 6 illustrates the geometry that might be typical of a breach that occurs in a sand dike adjacent to a relatively shallow river. Of note, a large scour hole develops extending both on the landside and waterside of the dike.

Fig 6. Dike breach adjacent to a river with no waterside toe protection (Visser 1998).

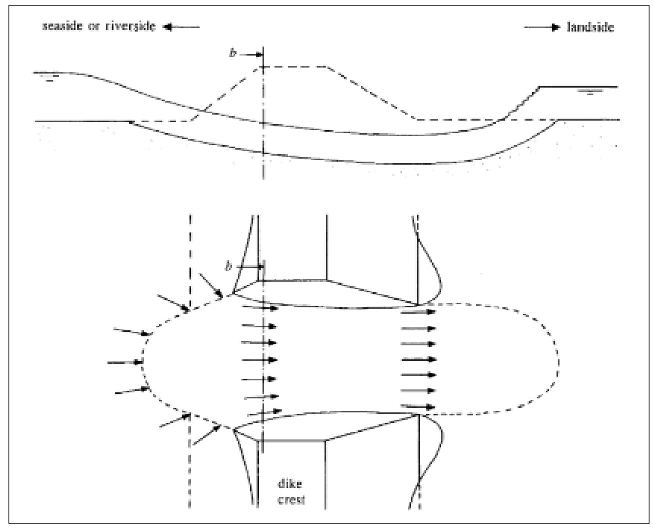
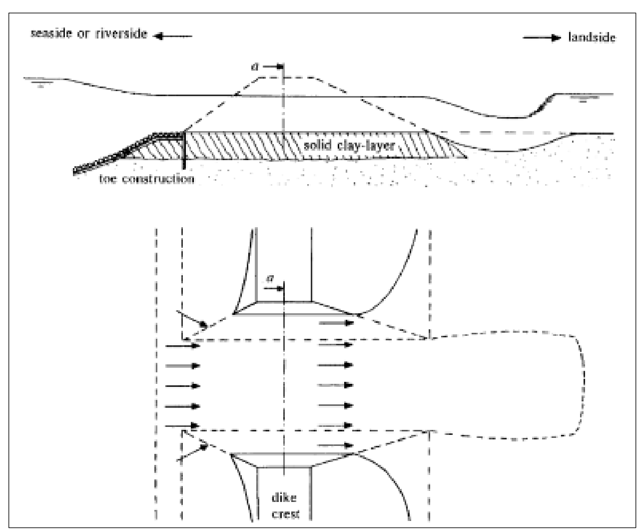


Fig. 7 illustrates a breach geometry that might be typical of a breach that occurs in a sand dike adjacent to a relatively shallow river with base and toe protection. Of note, a scour hole still develops; however, it does not extend as far into the waterside of the dike compared to Fig. 6.

Fig 7. Dike breach adjacent to a river with base and waterside toe protection (Visser 1998).



At the main breach, the Sumas River Dike is constructed primarily of silt and sand that was later upgraded with a drainage zone on the landside that was constructed of sand and gravel. The geometry of the main breach was consistent with that shown in Fig. 7 but by coincidence and with some help from Mother Nature. An aerial photograph of the main breach under repair is shown on Fig. 8. Note the brush that remains in place near the toe of the waterside dike slope following the breach event. In essence, the line of brush and its root system acted as natural toe protection and prevented propagation of the breach scour hole into the Sumas River. In addition, this protected edge would aid in construction of the initial closure of the main beach.

Fig 8. Remaining brush along toe of the waterside dike slope at the main breach (Photograph: Kerr Wood Leidal)

A similar geometry for the dike breach and scour hole was not observed at the Cole Road Breach which is likely due to the existing bridge abutment and Cole Road situated on the water and land sides of the breach, respectively (see Fig. 3).

Emergency dike repair

Once a dike breach has occurred, there are several considerations that need to be addressed in a very timely manner. One of the key considerations is the initial closing of the breach. Access, size of the breach and flow velocities through the breach will factor into decision making. In the past, attempts have been made to close dike breaches using boats or barges, storage containers, construction equipment and other similar large objects (T.S Albers, 2014) but with only very limited success. More often, filling with suitably sized granular fill materials is the most reliable solution.

Another primary consideration is access for construction equipment to the breach site. Water will likely surround all sides of the dike at the breach site. In most instances, the top (travel) surface of the dike will just be wide enough to accommodate travel in one direction (see Fig. 9). A review of existing information including as-built drawings, if available, should be carried out prior to mobilizing to the breach site to assess the construction of the existing dike and whether it can support heavy construction equipment and loading dump trucks. Some of the dikes in the Lower Mainland and Fraser Valley of BC, were originally constructed as agricultural dikes. In several instances these early dikes were constructed using dredged materials from the adjacent waterbody that consisted of fine-grained soils and as such are prone to disturbance and deformation under loading and inclement weather (see Fig. 10).

Many dikes will have some pullouts and/or access ramps along the dike which may need to be improved to accommodate construction equipment. If fill material is hauled to the breach using dump trucks, which would be the most likely scenario, then pullouts can be used to leapfrog loaded trucks to the breach site.

Fig 9. Limited access to the main breach site.

Fig 10. Example of poor-quality, fine grained dike fill material.

If the breach is closed with mineral fill in conditions of flowing or standing water, then it will be impossible and impractical to use fine-grained soils; attempting to do so would likely be disastrous. Larger crushed rock (riprap sized or similar) can be used to construct an initial crossing (closure) to stop open flowing water through the breach (see ① in Fig. 11); however, seepage flow will continue through the initial closure due to the porous nature of the coarse crushed rock. Once the open flow is stopped then smaller sized crushed stone (i.e., 75mm minus) can be used to widen and build up the closure (see ② and ③ in Fig. 11, respectively) while at the same time reducing seepage flows. *It should be recognized that the use of the finer crushed rock (gravel) within the central portion of the dike closure cross-section may be crucial to allowing for installation of a low permeability barrier or core as part of the remedial phase of the work. Failure to do so would likely result in significant challenges for installation of a low permeability barrier, possibly requiring deconstruction of a portion or most of* *original emergency repairs*. Fig. 12 shows construction of the initial crossing of the main breach of the Sumas River Dike and different zones of crushed rock fill sizes are shown in Fig.13 as the dike is being raised.

Fig 11. Schematic of initial closure of breach and construction sequence.

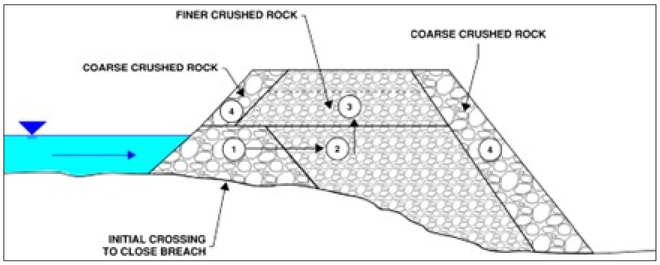


Fig 12. Initial closure of the main breach.

Fig 13. Raising and widening the closure of the main breach.

In the end, what is likely to be achieved is a reinstated dike section that leaks due to the porous nature of the granular fill; however, the seepage flows would be more manageable than the original flows through the open breach.

Design of remedial repairs

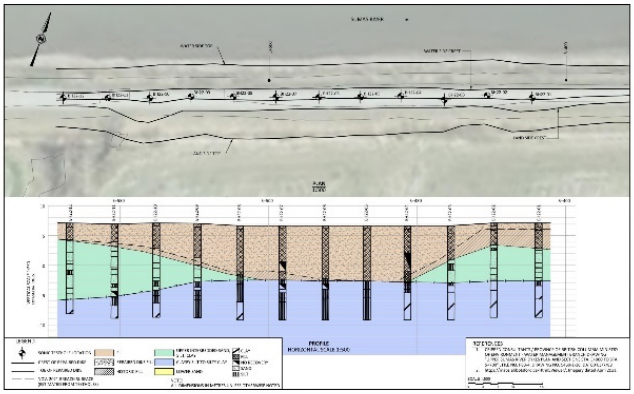
Once the breach is closed, as previously described, then there is a good possibility that remedial repairs will be required to install a barrier (core) so that the repaired section can be reinstated to function as a dike. Design of the remedial measures will, in most instances, require a geotechnical exploration be undertaken to assess the depth and extent of the new fill placed as part of the emergency repairs, the characteristics of the underlying foundation soils and the presence or absence of pieces of larger crushed rock within the central portion of the dike that could influence the choice of technology used to install a low permeability barrier (core). A detailed drilling exploration was carried out at the site of the main breach of the Sumas River Dike (see Fig.14).

Fig 14. Drilling exploration at the main breach.

The results of the field exploration can be used to develop a model of the breach site confirming the depth and extent of the breach, and in turn used to establish the required extent and characteristics of the barrier. The field exploration for the main breach of the Sumas River Dike included continuous sampling of the new fill using sonic drilling methods to confirm the presence or absence of pieces of crushed rock within the central portion of dike section. In addition, electronic Cone Penetration Testing (CPT) probes were extended through the crushed rock fill and down into the foundation soils beneath the breach to obtain data that could be used to assess the hydraulic conductivity and strength of various soils strata encountered.

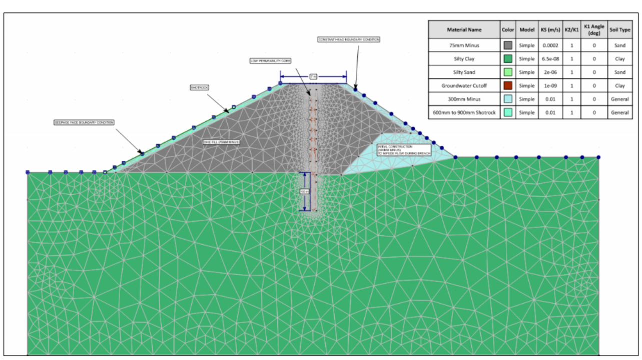
A summary plot, like that prepared for the main breach and shown on Fig.15, is useful to establish the extent (depth and length) as part of design of the barrier and to set up a model(s) for seepage and stability analysis.

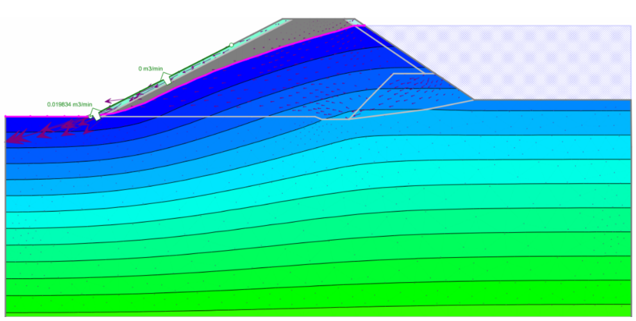
Fig 15. Plot of test holes and interpreted subsurface conditions along the main breach of Sumas Dike.

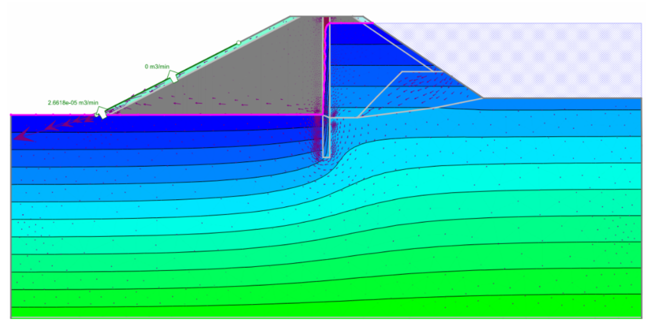


Detailed seepage analyses are typically carried out to assess the potential benefits of installing a low permeability barrier within the closed section of dike. Fig.16 illustrates the results of some detailed seepage analysis that was used to assess the potential benefit of installing low permeability barrier at the main beach in this case by means of Cutter Soil Mixing (CSM) technology. For the main breach, the addition of the low permeability CSM barrier lowered the seepage flows by about two (2) orders of magnitude. In addition, stability analysis should also be carried out to check dike stability if loading from the new dike mass is considerably greater than the pre-existing dike, if the foundations soils are weak and/or if seismic loading needs to be considered. Specific details on the design of the CSM barrier installed for the main breach of the Sumas River Dike are provided in Mylleville et al., 2023.

Fig 16. Seepage analysis plots for the main breach.







Options for remedial repair

Assuming the entirety of the emergency repair is constructed using crushed granular fill of varying sizes, seepage will continue through the body of the dike until a low permeability core or barrier is installed within the central portion of the dike. There are several options for seepage mitigation that can be considered including:

1) re-construction of the dike section with a low permeability core;
2) construction of a low permeability core using soil mixing technology;
3) construction of a steel sheet-pile barrier;
4) construction of a low permeability core using secant piles; and,
5) installation of a low permeability geomembrane liner.

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, bulk fill zone, filter(s) and drainage. This option would be time consuming and likely encounter considerable constructability challenges (e.g., excavation support, dewatering, and the like) associated with earthworks being carried out below the groundwater table and in proximity of a water body (e.g., a temporary cofferdam would most likely be required).

The **deep soil mixing** option involves mechanically mixing the in-situ soil; in this case, smaller sized 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 crushed gravel fill and encountering larger crushed rock sizes while maintaining connection and seal between adjacent sheet piles.

Secant piles can also be used to form a low permeability barrier along the center of the breach by means of installing a series of overlapping reinforced and non-reinforced concrete piles. Again, the primary construction challenge would be associated with encountering larger crushed rock sizes.

For smaller and shallower breaches, it may be possible to install a **low permeability geomembrane liner** within the body of the dike repair to act as a barrier. However, site-specific conditions and construction approach will dictate the feasibility of this option.

The selection of the most appropriate remedial repair option depends on several key factors specific to the breach site, including but not limited to (in no particular order):

1) the geometry, location, and extent of the breach;
2) the size, composition, and design of the dike;
3) anticipated hydrologic/hydraulic conditions at the time of repair;
4) access for construction equipment;
5) characteristics of the underlying natural soils; and,
6) availability of local materials and equipment.

In all cases, a highly experienced contractor should be engaged to provide input at the emergency repair stage and at the concept development stage of the remedial repair design.

For the main breach of the Sumas River Dike, 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. Cutter Soil Mixing (CSM) technology (a type of deep soil mixing) was selected as the preferred option to reinstate a low permeability barrier within the breach closure. CSM is one of several proven and locally available methods for deep soil mixing and has been successfully used in other similar barrier applications (Arnold et al., 2011, Holzman et al., 2019 and others). Fig. 17 shows the CSM rig installing the low permeability barrier at the main breach.

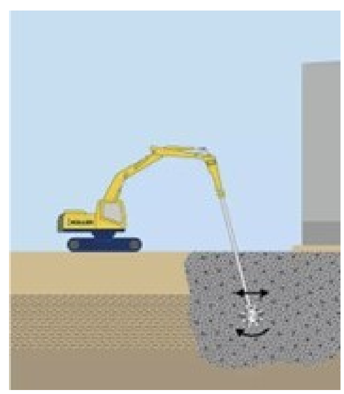
Fig 17. Installing CSM barrier at the main breach.

During construction of the CSM barrier at the main breach, larger pieces of crushed rock were encountered within in the finer crushed rock/gravel zone and posed a significant challenge for the CSM equipment resulting in delays and equipment damage. Despite best efforts during construction of the emergency repair, some larger pieces of crushed rock were present in the zone intended to be constructed of smaller sized crushed rock/gravel. The contractor mobilized appropriate drilling equipment to pre-auger the remaining portion of the barrier alignment and remove larger pieces of crushed rock that were obstructing progress. Further details on the CSM barrier construction and how challenges were overcome at the main breach of the Sumas River Dike are provided in Mylleville et al. 2023. Fig. 18 shows the CSM Rig and pre-augering drill situated on the main breach site.

Fig 18. CSM rig and pre-augering drill at the main breach.

The Cole Road breach is considerably smaller in size and extent. Due to its size and other access constraints (e.g., the presence of existing overhead and buried utilities), the proposed method to reinstate a low permeability barrier is Mass Soil Mixing (MSM), which is better suited to smaller scale projects where the depth of penetration into the underlying soils is also limited. Similar to CSM, MSM uses a rotary mixing tool that spins about a horizontal axis attached to a large excavator to mechanically mix cement and/or bentonite into the in-situ soils progressing in a series of pre-defined panels (see Fig. 19). Similar to CSM, the amount of cement and/or bentonite added is designed by the Contractor to satisfy a defined performance specification.

Fig 19. Schematic of mass soil mixing (Image: Keller Group plc 2023).



Other flood-related damage and recovery

In addition to the aforementioned breaches, the events of November 2021 also resulted in localized damage of the Sumas Dike, which did not result in catastrophic failure of the dike but still require special attention and repair. Much of the flood-induced damage was bank erosion of variable severity and extent along the water side of Sumas Dike. In addition, there were also localized slope failures in which the water side slope was partially washed away but did not cause a complete breach of the dike. In both scenarios, the dike can be reinstated without the need to deconstruct the dike. Rather, a protective layer of appropriately sized rip rap can be placed on the slope to reinstate the dike and protect against potential future erosion. Depending on the gradation of the existing/remaining dike fill material, one or more granular soil filter layers may be required between the existing finer-grained dike fill material and the outer riprap protective layer to mitigate potential internal erosion/piping. It is essential to obtain representative samples of the dike fill along the affected section(s) of the dike from which sieve and hydrometer testing can be completed for use in the analysis and design of the filter layer(s). Sonic drilling methods proved to be successful in obtaining continuous samples of the affected sections of the Sumas Dike in 2022-2023 and inform filter design(s) (Fig. 20).

Fig 20. Sonic drilling to obtain representative samples of dike fill.

The contractor should exercise care when placing materials directly onto the slope to prevent segregation. In many cases, site conditions and regulatory requirements (e.g., fishery window) may necessitate placement of filter layer(s) and rip rap under water. In this scenario, consideration should be given to increasing the thickness of the filter layer(s) and working with an experienced contractor to develop an appropriate placement methodology to ensure the intent of the filter design is met. Reinstatement of sections of the Sumas Dike that were eroded during the November 2021 event are currently underway (Fig. 21).

Fig 21. Reinstatement of eroded section of Sumas Dike.

Closing comments

Increased occurrence of unprecedented weather events, in particular prolonged precipitation, can be expected to challenge our flood control infrastructure into the future. Several decades had passed since a major flooding event has occurred in the Lower Mainland and Fraser Valley of BC but the events of November 2021 and the resulting breaches that occurred along the Sumas River Dike has heightened awareness of our flooding vulnerability.

When a dike breach does occur, there is an initial emergency response that necessitates closing the breach as quickly as possible, the details of which can influence future remedial repairs should they are required (e.g., mitigation of seepage). In most instances, emergency repair entails closing the dike breach using mineral fill; however, careful selection of appropriate fill sizes and construction sequencing can provide a measure of flexibility in selecting and designing remedial measures (e.g., installation of a low permeability barrier) and hopefully eliminate the need to deconstruct the initial emergency repair.

There are several proven construction technologies available to assist with both emergency and remedial repair of dike breaches. Cutter Soil Mixing proved successful in installing a barrier (core) in the main breach repair but there are other construction methods such as sheet-piling and secant piles that could also be applied.

Flood-related erosion that does not result in a catastrophic breach, such as that which occurred in some sections of the Sumas River Dike, can be repaired with careful planning, design, and construction of a protective riprap layer and, if needed, one or more filter layers between the original dike fill and the riprap.

In all cases, an experienced, specialized contractor should be engaged from the early stages of a dike breach event and/or flood-related damage, to provide practical input on potential mitigative measures that can be implemented for emergency and permanent repairs.

It is the intent of the authors to share the experiences gained through the recent breaches of the Sumas River Dike to improve our collective preparedness moving forward.

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