Debris Flow Mitigation at the East Gate Landslide

Patrick Zerr, P.Eng.
Project Manager
McElhanney Ltd.

Nick Guaran, P.Eng.
Project Manager
McElhanney Ltd.

Paper prepared for presentation at the "Innovation in Roadway/Embankment Materials and Geotechnical Engineering Session" of the TAC 2023 Conference & Exhibition, Ottawa, ON

ABSTRACT

This case study presents an alternative approach to debris flow mitigation at the East Gate Landslide. The site is in Glacier National Park, three and a half hours west of Calgary along the Trans-Canada Highway. The East Gate Landslide reactivated as a 2,000,000 m3 rock slump in 1997 above the highway and debris flows occur on an annual basis. Parks Canada, subsequently constructed a large berm structure at the base of the gully to protect the highway and store volumes.

The debris flows are self-amplifying, with each year resulting in further erosion of the gully increasing debris flow volumes and costs for removal. Traditional approaches to address this risk, such as increased hardening of infrastructure to withstand flows or avoidance through relocation of the highway were determined to have substantial cost impacts. McElhanney and their partners developed an alternative approach, seeking to address debris flows at their source with a three-component gully erosion mitigation strategy:

1. Diversions to reduce surface flows.
2. Log crib check dams to reduce flow velocity and limit undermining of side slopes.
3. Revegetation of side slopes through live staking.

This paper focuses on the development, implementation, and performance of mitigation measures over the past several years, including the construction of six log dams over the 2020 and 2021 construction seasons. Topics include management of site access and material supply in challenging terrain, dam refinements and lessons learned after multiple years of debris flows, and next steps towards continued gully stabilization.

Key words: resilience, debris flow, adaptation, log crib check dam, erosion

1. INTRODUCTION

1.1. Location

The Trans-Canada Highway (TCH) is the main east-west road connection between Alberta and British Columbia. Between Golden and Revelstoke in BC and within Glacier National Park, the TCH is administered by Parks Canada Agency (PCA) and exposed to numerous geohazards. One of the most significant geohazards is posed by the East Gate Landslide (EGL). Reference locations at EGL are shown in Figure 1.

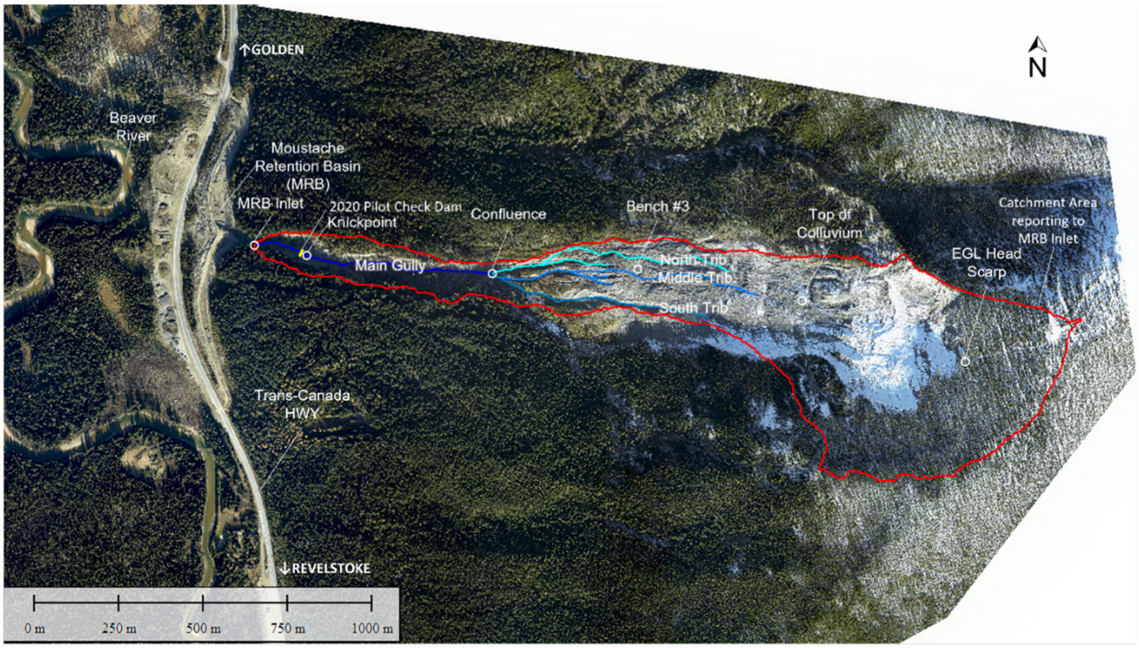

Figure 1 - Reference locations at East Gate Landslide.

1.2. Why this project?

The EGL reactivated as a 2,000,000 m3 rock slump in 1997 and deposited rock colluvium on the western slope of Heather Mountain. Overland flow on the landslide deposit (colluvium) and progressive gully erosion leads to debris flows reaching the TCH located at the toe of the slope*.

The debris is retained by two moustache-shaped retention basins (MRB) located immediately east of the TCH (see Figure 2). The MRB have 80,000 m3 storage capacity and are cleaned out annually. This is associated with significant and increasing costs.

This paper addresses gully erosion mitigation design, construction, and initial performance of the EGL gully erosion intervention.

---

* Approximate coordinates 51° 26.033'N, 117° 28.747'W

Figure 2 - View from Helicopter looking northeast at moustache-shaped retention basins (MRB) protecting the Trans-Canada Highway (TCH). Note: some of the debris excavated from the MRB is deposited between the TCH and the Beaver River (Photo by Tetra Tech EBA, 2014).

2. SITE BACKGROUND

2.1. Geomorphology

Figure 3 is a geologic profile following approximately along the centreline from the EGL headscarp to the TCH (Highway 1). For plan view position of key locations see Figure 1. The geologic profile is an update by BGC Engineering on an earlier landslide process framework by Couture and Evans (2006). The following sections summarize the geomorphology from BGC (2020).

The EGL initiated in January of 1997. The landslide occurs on a slope that has been covered with several landslides of unknown magnitudes and deposit thicknesses in the pre-historic past. It is a complex landslide type and consists of a rock slope failure, a creeping and sliding section resembling an earthflow as well as slumps along gullies.

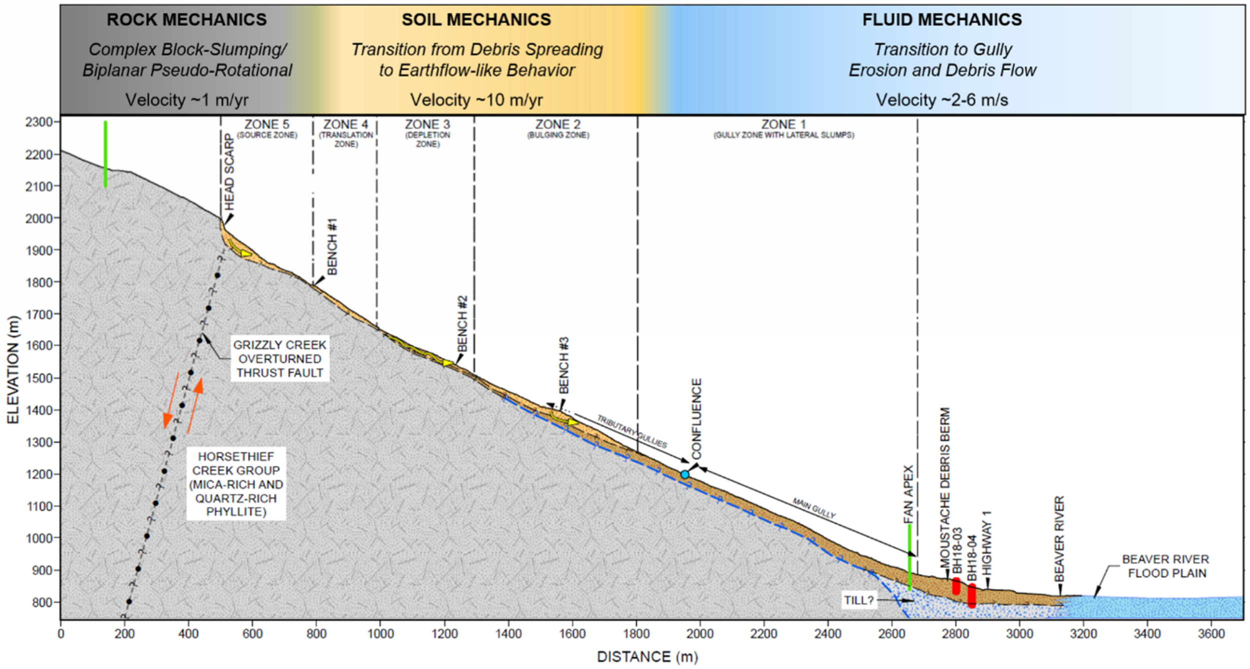

Figure 3 - Geologic profile and process framework of East Gate Landslide.

The deposit of the EGL destroyed the mature forest cover and drastically changed the hydrology of the hillslope. Over time, rilling and gullying occurred on the landslide deposit and a network of surficial drainage channels (small creeks) established itself. These channels coalesce at the confluence at elevation 1200m.

2.2. Debris Flow Characteristics

Debris-flow characteristics are summarized from BGC (2020). While in the initial years following the 1997 event, sediment was primarily recruited from the deposit of the 1997 EGL event (EBA, 2004), it is now primarily recruited through gully erosion.

Change detection analysis of LiDAR and photogrammetric data found that between 2015 and 2018 approximately 70% of the sediment was recruited from the Main Gully. Sediment mobilization from specific areas may vary significantly from year to year.

Most debris-flow events occur during the freshet, however significant events have occurred during fall storms. Debris mobilization is primarily a function of surface water discharge (i.e., higher discharge recruiting and transporting more sediment). Spring peak discharge is governed by snowmelt or rain on snow events, while Fall peak discharge is primarily governed by heavy rainfall.

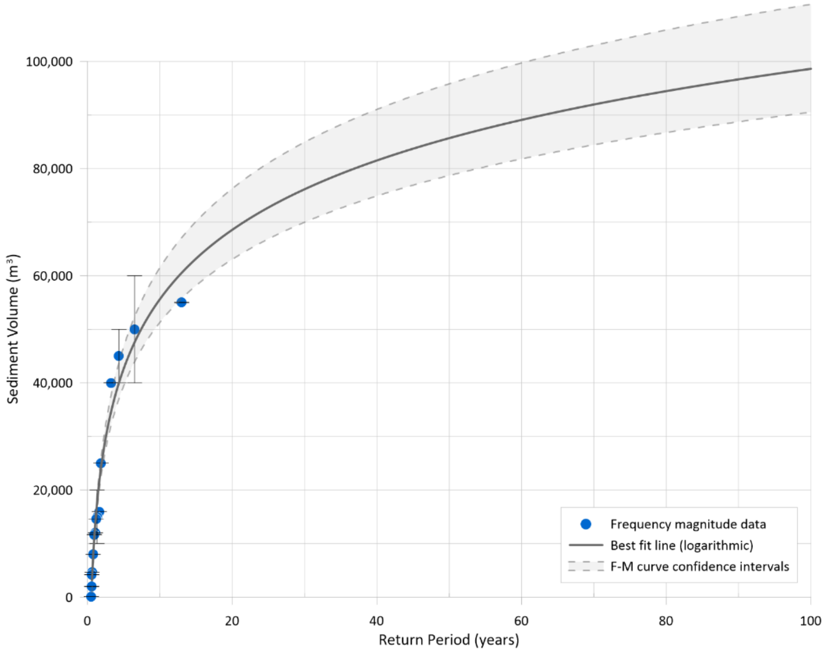

Figure 4 - Magnitude-frequency curve for debris flow events/episodes at EGL. The volumes past the 15-year return period are extrapolated.

Data available from previous reports, notes and surveys were compiled into a database containing 25 recorded debris flow event volumes between 1999 and 2019. The largest recorded single event occurred in 2008 with a volume of approximately 55,000 m3. The median event volume to date is 12,000 m3.

A debris-flow magnitude-frequency curve (Figure 4) was developed for EGL. Although records from 1999 to 2019 were available, only the records from 2007 onwards were used for the magnitude-frequency curve, as air photo reviewed suggest that development of the current Main Gully commenced then.

3. PREVIOUS APPROACHES

Prior to implementation of the works discussed here, approaches for infrastructure resilience at EGL have focused on protection of the highway and resistance of the flows with the MRB. The MRB acts as a storage facility for debris flows transported down the EGL. The MRB can only effectively protect the highway if sufficient storage volume is available to capture flows. Ensuring the continuing functioning of the MRB therefore requires regular operations to clean out and transport debris to an off-site dumping area.

Figure 5 - Excavation of MRB

These cleanout operations create significant expense for PCA, particularly given the remote location of the site and logistics of bulk material transport in the region. More significantly, continued downcutting of the gully has led to increasing year-on-year volumes of debris flows and costs for subsequent cleanout operations.

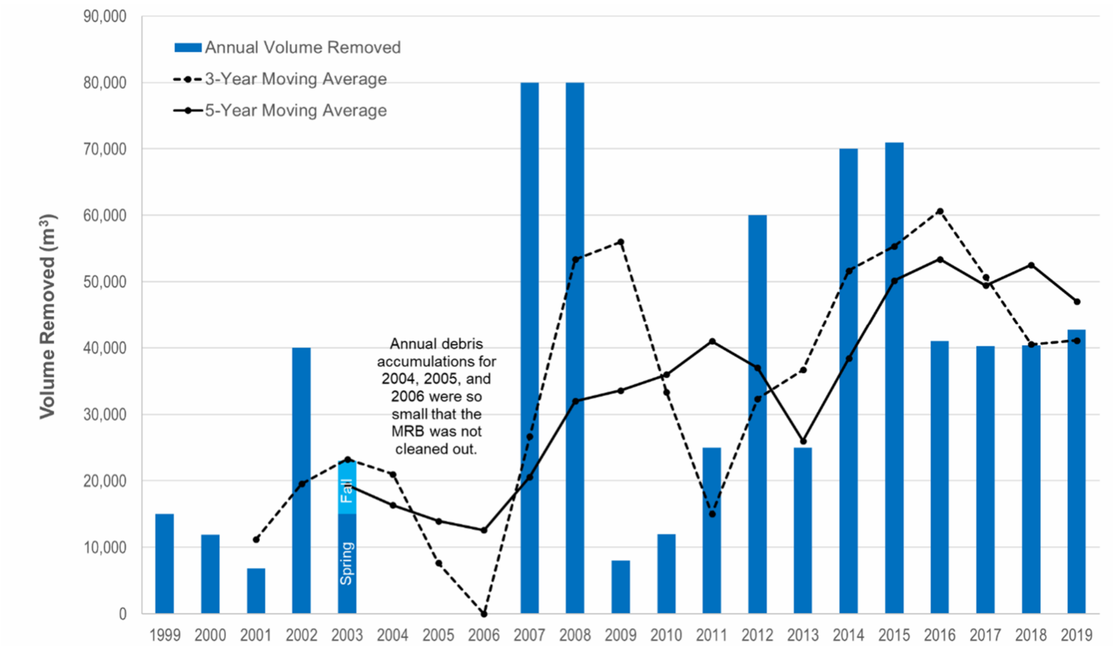

Figure 6 - Debris Cleanout Volumes

Previous work by PCA has included consideration of alternative methods to mitigate the risk debris flows represent to the continued functioning of the TCH. These approaches included consideration of separating the highway from the landslide, potentially by placing it either above the gully with a bridge, or below it, such as with a shed or tunnel structure. Alternatively, the highway could even be realigned entirely, shifted to the other side of the valley for some distance to maximize distance from the gully.

All of these approaches have significant capital costs. Further, all except the last would still require regular inspections to confirm that regular debris flows hadn't struck or damaged the structures they depend on. Finally, the gully is a dynamic geohazard with significant year-on-year variation in its thalweg alignment and profile. Construction of a fixed structure to avoid flows does not preclude the future shifting or enlargement of the gully in a way that once again puts the highway at risk.

4. FRAMEWORK FOR INTERVENTION

4.1. Treat the Source not the Symptoms

Gully erosion has become the primary process for sediment mobilization; between 2015 and 2018, about 70% of the sediment was mobilized from the Main Gully (BGC 2020). Erosion in the gully has formed a sudden increase in slope (the Knickpoint) in the thalweg profile above approximately EL. 940 m (BGC 2020). Headward erosion of the Knickpoint is expected to release significant debris supply in the Main Gully. This will mobilize additional sediment, leading to increased debris flow volume, resulting in further erosion of the knickpoint, as seen in Figure 7.

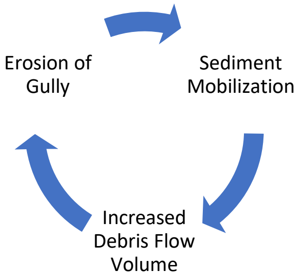

Figure 7 – Gully Erosion and Debris Flow Generation Self-perpetuating Cycle

Given the virtually unlimited sediment sources available, expansion or enhancement of systems such as the existing MRB to protect the highway from debris flows will require continually increasing funding to handle growing volumes, with no timeline for attenuation or cessation of debris flows. Rather, this project developed mitigation solutions which address the issue by controlling and reducing debris flow volumes instead of just withstanding or storing them. Reducing the volume of sediment volumes which arrives at the MRB in turn diminishes maintenance costs.

4.2. Functional Design Requirements

Figure 8 illustrates the functional design requirements for this project (BGC 2020, April 7). The gully erosion mitigation strategy is three-fold:

1. Reduce discharge: Drainage diversion to reduce the amount of water that discharges into the channel system and thus decreasing the total volume of debris that is being entrained through fluvial processes.

2. Grade control: The debris source is directly reduced through series of log crib dams installed in the Main Gully. The weir sill elevation of each check dam provides a fix channel elevation, preventing erosion downcutting. Upstream of the check dam the channel infills with sediment due to the fix elevation provided by the weir sill and therewith sediment supply undermining gully side slopes is significantly reduced.

3. Revegetation for slope and soil stabilization: Revegetation of the bare slopes to trap sediment on the slope, improve surficial stability and reduce surficial erosion.

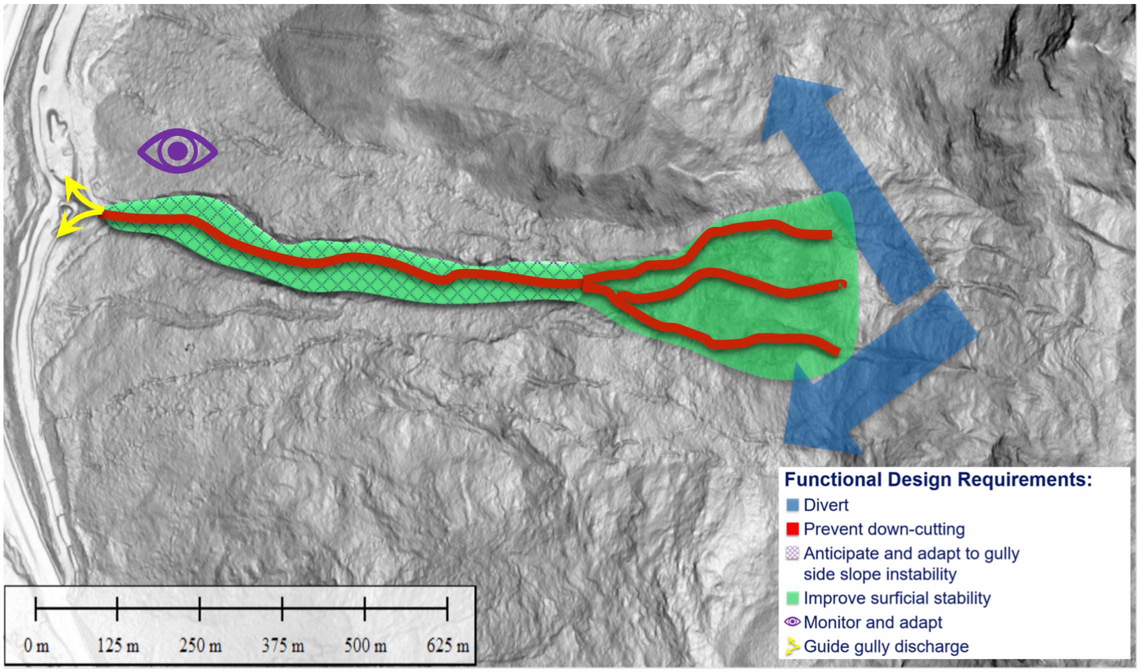

Figure 8 - Functional design requirements for gully erosion mitigation.

Over time, these interventions seek to address the feedback loop in Figure 7, as illustrated in Figure 9. This virtuous cycle will be initiated through the initial implementation of check dams to reduce gully erosion; over time, the aim is for natural revegetation to take the place of human intervention, allowing for continued stabilization of the slope.

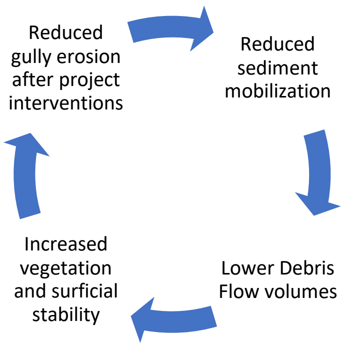

Figure 9 - Debris flow reduction through slope stabilization

4.3. Implementation Approach

Given the extent of this project as well as the considerable uncertainties involved in anticipating and quantifying geomorphological processes, a typical, prescriptive design approach would be cost prohibitive. Instead, an adaptive, phased design approach is applied to facilitate spending where it is most effective. Learnings from previous efforts inform methods and extents of following phases. This includes building pilot structures to assess performance under site conditions and adapt designs as required.

It is expected that significant gully side slope failures will continue to occur until the over-steepened slopes achieve a quasi-stable equilibrium. Costs for stabilizing gully side slopes exceed funding limits. It is therefore accepted that components of the gully erosion mitigation system (e.g., several check dams in series) may be rendered ineffective, while the entire check dam system shall not fail under reasonably expected conditions. Failure tolerance of system components:

5. DETAILED DESIGN OF CHECK DAMS

Check dams form the central element of the debris mitigation approach deployed at EGL and were also the element requiring the greatest degree of engineering design. The design needed to provide for their control of debris velocity, continued integrity as gravity retaining structures, and constructability.

The check dams were developed to be built with the available materials and equipment available at EGL's remote location. Use of in-situ materials was maximized, minimizing transport of resources both to the site as well as within it. Timber logs were the primary construction material, sourced in large part from ongoing clearing works part of adjacent highway works for PCA. Logs were placed in alternating courses, parallel to (header legs) and transverse to (stretcher logs) the direction of the gully. Logs were pinned together with steel rebar, the bottom faces of each element planed on site with a chainsaw to increase contact area with the course below it. Backfilled with gravel sourced on site, the dams functioned as gravity retaining structures. A general arrangement of a dam is seen in Figure 10.

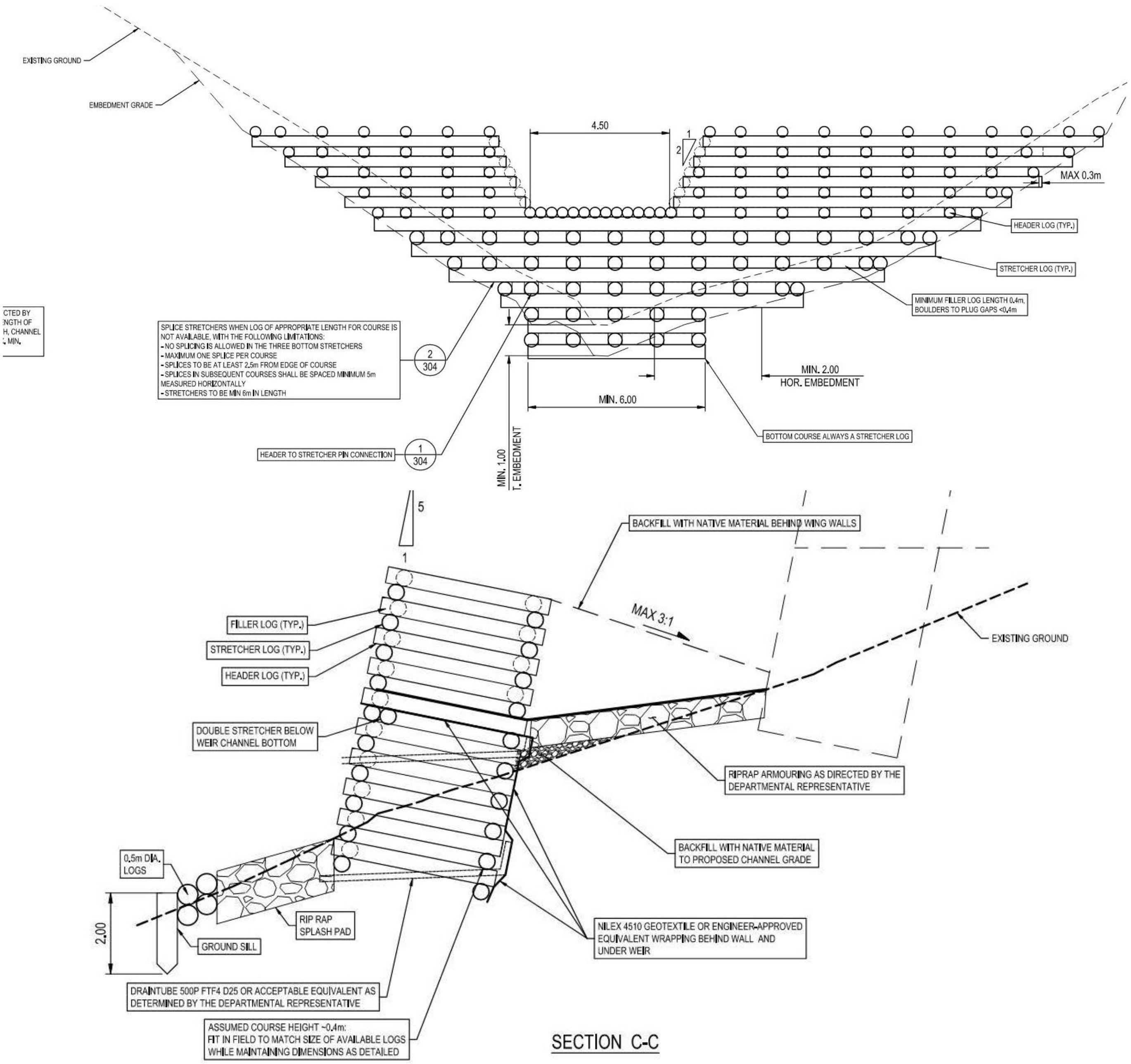

Figure 10 - Check Dam Design Details

Design details for the dams were all developed as typical details, to be adapted to the site-specific context of a given dam. While survey was undertaken prior to construction, the highly dynamic nature of the gully preempted the full design of any dam prior to construction. Dam locations and exact dimensions were determined on-site based on the slope of the surrounding area, presence of boulders or other obstructions, and other details in the terrain not easily communicated through a topographic survey.

The dams are designed to function as a complete system throughout the gully and so effort was also applied to develop the appropriate arrangement of the dams. Each dam represents a considerable investment of labour within a narrow construction season and the tighter the spacing the dams, the more that would be required. Controlling the spacing between each dam was the resultant thalweg of the reprofiled gully in between them – if the dams were spaced too far apart, the thalweg would steepen, increasing velocities and undermining the effect of the dams (Figure 11).

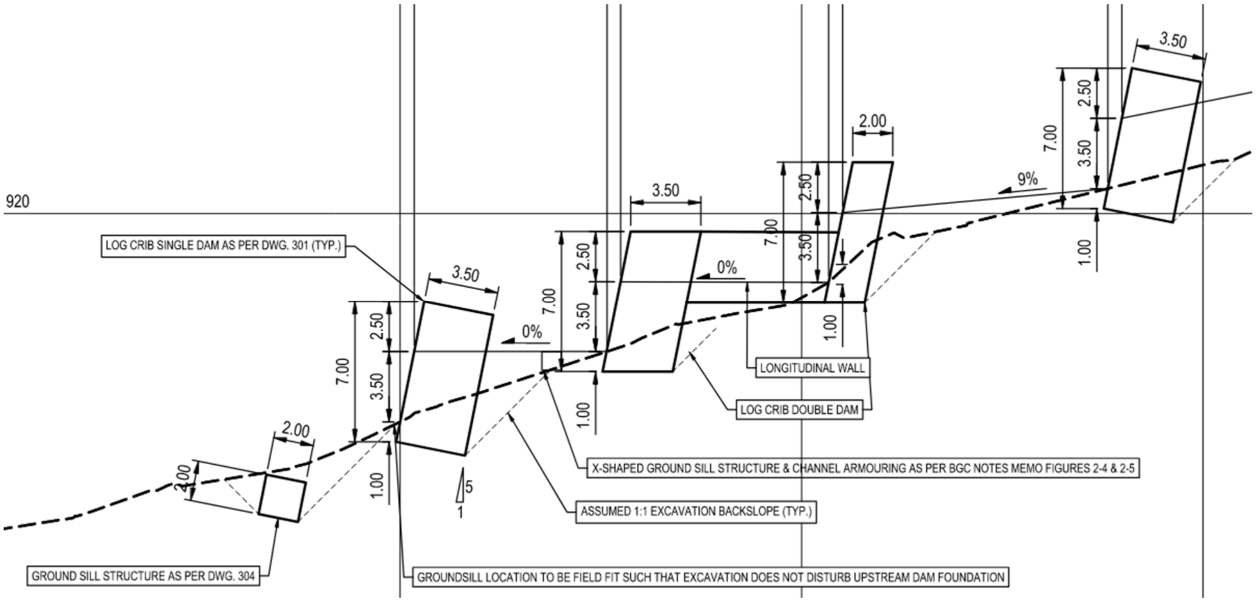

Figure 11 - Dam Spacing

6. 2020 CONSTRUCTION SEASON

A pilot check dam was constructed in 2020 to test several design parameters and performance under site conditions. The steep terrain of the gully also presented unique challenges for site access for both labour and equipment, material supply, and geotechnical safety during construction, as seen in Figure 12, Figure 13, and Figure 14. Time was limited as the high elevation of the project site creates a limited construction time window between early summer snowmelts and early fall snowfall. The construction season for this area ran from the beginning of July to the end of September. Construction of the pilot dam required development of solutions not only suitable for construction of the single dam, but extensible for the continuing construction of additional dams further up the valley, as well as doing so in a manner allowing for the construction of multiple dams per year. The final Pilot Check Dam is shown in Figure 16A. Key challenges contributing to the cost of construction included:

- The site is remote and the availability of contractors to perform the work was limited with a related impact on the competitiveness of pricing.
- Work was also completed using “Spider Excavators” a unique piece of mobile equipment highly capable at traversing steep technical terrain with wheels mounted on individually actuated “legs”. Availability of this equipment in the local area was limited and contributed significantly to the cost of construction.

- While construction of the check dam had some commonalities with the methods used for construction of log homes throughout British Columbia, the structure itself is unique and there was a learning curve for the Contractor which reduced initial efficiency.

Separate from pilot dam construction, a limited program of live staking was also completed, as seen in Figure 15.

Figure 12 - Log supply by tracked vehicle along temporary access road. Photo by McElhanney (July 25, 2020).

Figure 13 - Log placement for dam construction with spider excavator. Photo by McElhanney (July 25, 2020).

Figure 14 - Final placement and connection of logs completed by hand. Photo by McElhanney (August 18, 2020)

Figure 15 - Live-staking of gully side slopes. Photo by Brinkman Restoration. (August 31 – September 2, 2020)

7. INITIAL LEARNINGS FROM PILOT

Valuable experience (summarized from BGC 2021, July 6) was gained from the performance of the 2020 pilot check dam to date. Overall, the check dam performed well under the debris flow loading.

The 2020 Pilot Check Dam experienced its first debris flow on November 5, 2020 without damage; some minor deposition occurred on the right (in flow direction) wing wall. However, a ground sill made from logs across the channel and located several metres downstream to hold riprap in place was destroyed. This was likely due to insufficient lateral embedment.

The check dam survived several debris flow events during the 2021 freshet with a total sediment volume retained in the MRB of about 29,000 m^3. Video camera recordings documented a range of debris flow hydrographs at the 2020 Pilot Check Dam. Some were fairly "smooth" surges, while other surges exhibited highly variable discharge (or velocity) even within a single surge. This is possibly due to large boulders causing temporary blockages until momentum pushed them forward again.

Figure 16 shows the 2020 Pilot Check Dam after construction and late in the 2021 freshet.

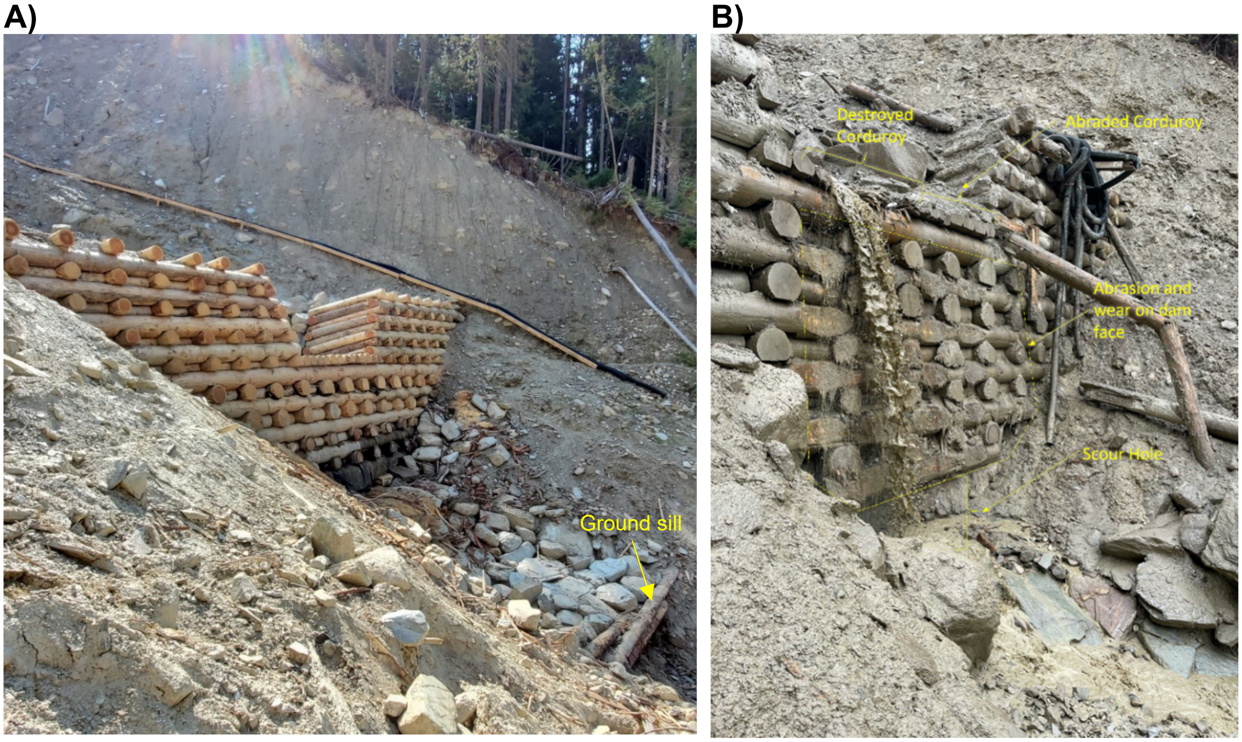

Figure 16 A) 2020 Pilot Check Dam at end of construction (Photo Sept. 5, 2020 by BGC, J. Stratton), note; the downstream log ground sill was destroyed in the Nov. 5, 2020 debris flow event. B) Photo of 2020 Pilot Check Dam taken on June 9, 2021, note; destroyed (sacrificial) corduroy in weir, abrasion and wear on the dam face and scour hole undermining the check dam (Photo by Pierre Friele).

The following performance and key issues on the pilot check dam were noted:

- **Global Stability**: The check dam performed satisfactorily and survived the debris flow loadings. No significant global displacements were noted.

- **Toe Scour**: Figure 16 shows significant toe scour occurred. In addition, the foundation soil was washed out under the front mud sill (i.e., lower most stretcher). This poses a stability concern. Toe scour may have been accelerated by loss of the ground sill during the November 5, 2020 event. However, the scour hole may have formed regardless.

- **Wing wall overtopping**: The pilot weir was intentionally sized relatively small because it was difficult to fit in a larger weir in the deeply incised gully geometry. Mud deposits, a leaning log, and displaced role of flexible pipe are clear evidence of wing wall overtopping by debris flows, indicating that the pilot weir is undersized. Based on review of video recordings, wing wall overtopping is interpreted to be of short duration (a few seconds) and had not resulted in abutment scour.

- **Abrasion**: Significant abrasion and wear is evident (Figure 16): The corduroy lining of the weir bottom was installed with round tops and flat milled bottoms. The round tops of the corduroy logs were abraded and flattened by an estimated 2 to 5 cm. The right half of the weir the corduroy was destroyed. The channel facing sides of the wing walls also show wear and abrasion but still appear to be intact. On the battered downstream check dam face, the debris has abraded concave shapes into the stretchers and worn the front of exposed headers.

- **Other Wear**: A piece of wood was split of the lowermost front stretcher of the left wing wall (Figure 16), presumably from a point load (boulder or log).

- **Grade stabilization**: The channel base above the weir has infilled with sediment as intended at about 3.5H:1V or 16º.

- **Wing wall protection**: Backfilling the wing walls appears to have been a successful strategy to avoid direct, high dynamic loads on the back of the wing walls.

8. REVISED CHECK DAM DESIGN

Based on the learnings outlined in Section 7.1, McElhanney developed a revised check dam design to provide additional protection against the potential failures identified. The improved design included three modifications to protect the check dam from front face abrasion, toe scour, and corduroy abrasion.

8.1. Front face abrasion

The angle to which the check dam is built (5V:1H) allows the water and mud flow to slide along the face of the check dam and also makes the front face an easy target for boulders and other debris transported downstream, which resulted in the significant abrasion shown in Figure 17A. To prevent this from happening in the subsequent check dams, the weir sill logs were cut 0.5 to 1.0m longer, creating an overhang which effectively protects the face of the structure. Figure 17B shows the improved check dam.

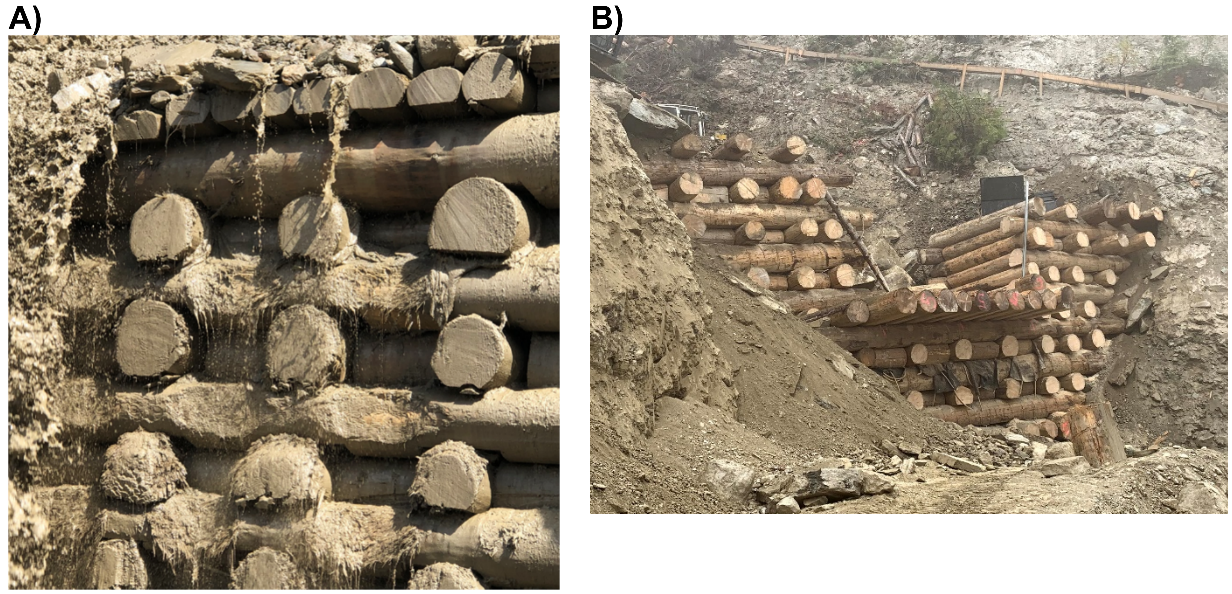

Figure 17 A) Front face abrasion observed after the 2021 freshet (Photo by Pierre Friele). B) New check dam built in 2021 with overhang to protect front face from abrasion (Photo by McElhanney)

8.2. Toe scour

The root cause for the toe scour was identified as the limited integrity of the rip rap splash pad. It is likely that the high energy of the debris flow event was sufficient to dislodge one boulder creating a weakness of the entire splash pad which eventually washed-out. To create a splash pad acting as a single solid element, grouting of the riprap was introduced in the 2021 construction season.

8.3. Corduroy abrasion

This component of the check dam was always considered a sacrificial element, given the extreme exposure to the debris flow, and designed to be easily replaced in due course; what was not anticipated was the fact that it took only one year to damage it to the point that a replacement was already needed. Despite the knowledge that this system, also when fully built, would require regular maintenance until the downcutting is fully stabilized and the side slopes revegetated, the idea of an annual replacement of the corduroy was not acceptable. To strengthen the corduroy a 0.5in thick steel plate was installed and bolted to the check dam.

9. 2021 & 2022 CONSTRUCTION SEASONS

In 2021 the successful bidder of the tender project had engaged the same subcontractor that performed the work on the pilot check dam in 2020. That resulted in an extremely efficient construction season given the experience that the contractor acquired the previous year.

In total four new check dams were built in less than two months, plus a fifth one was left unfinished, without the wingwalls, due to the lack of timber supply at the end of the construction season. This, as it will be described later, resulted in a significant weakness of Check Dam 6.

All new check dams were built following the modified design presented in Section 7; additionally, Check Dam 1 was retrofitted by installing the steel plate and rebuilding the splash pad with grouting to seal the voids. Retrofitting the overhang was considered a task too onerous given the budget and time available and therefore not included in the scope of work.

9.1. Subsequent 2021/2022 Developments

Between 2021 and 2022 significant movements occurred upstream of Check Dam 6, caused by a lateral landslide which pushes material from the left side of the gully towards the thalweg, which shifted over 20 meters since 2015 as shown in Figure 18.

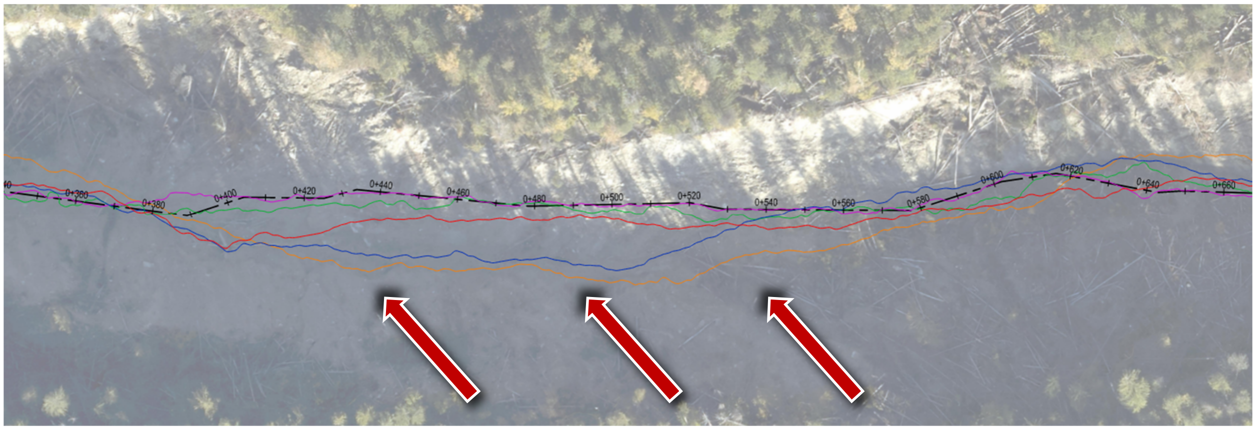

Figure 18 Thalweg migration over the years. In orange, lower in the image, is the thalweg in 2015; in magenta, the thalweg in 2022

Due to this movement, as well as the lack of wing walls, Check Dam 6 has been completely buried by Spring 2022. Check Dam 4 and 5 were subject to significant damage, varying to partial crushing to complete failure and loss of the wing due to the soil pressure and significant displacements (Figure 19A).

Fixing the damaged check dams was a relatively simple task, because of the modular construction of the structures. The contractor had to remove the damaged sections, re-establish a horizontal plane and re-assemble the wing walls.

The shifting thalweg, if not stopped, may have catastrophic consequences if able to move sufficiently to the right and bypass the already built check dams. That will likely result in undermining of the check dams and complete loss of all structures. To prevent this, in 2022 a series of smaller structures were built by assembling 3 or 4 logs pinned together with dowels and a 15mm galvanized aircraft cable. Figure 19B shows a section of thalweg reinforced with these structures. In total approximately 40 sill log structures were built in 2022.

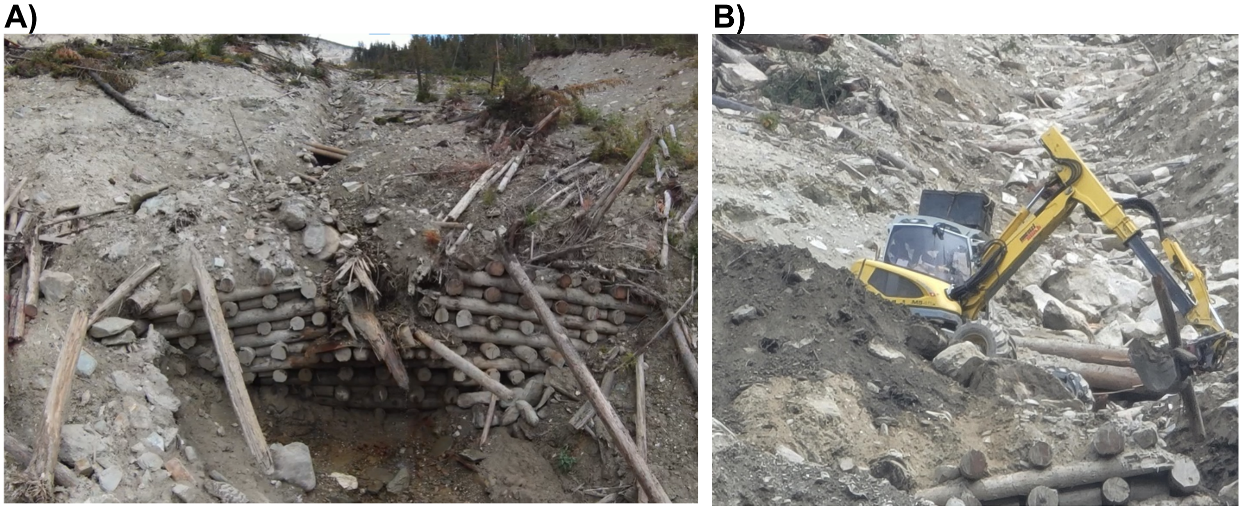

Figure 19 A) Damage to Check Dam 5 caused by the Lateral landslide. B) Construction of sill log structures to stabilize the thalweg.

9.2. Drainage Diversions

The 2021 construction package also included the first drainage diversion in the upstream catchment. As described in Section 4.2, these diversions allow to reduce the catchment area draining into the gully, redirecting the flow into the adjacent streams. The diversions were constructed by excavating a trench intercepting the natural channels that were naturally developed in the upper catchment and reinforcing the trench with rocks and boulders found in the area to prevent erosion. Figure 20 shows a completed drainage diversion.

Figure 20 Drainage diversion in the upper catchment area

Diversions must be done carefully, adding incremental catchment areas over the years, and then monitoring the adjacent gullies on an annual basis to determine if significant alterations are visible that may indicate the potential for secondary landslides in these gullies. In 2022, after a field inspection, there were no signs of negative impacts and additional diversions were completed as part of the 2022 construction season. To date approximately 20% of the EGL catchment has been diverted to the north catchments.

10. NEXT STEPS FOR PROJECT

As part of the multi-year erosion mitigation program in the Main Gully we anticipate construction of roughly 60 log crib check dams and several diversions, as well as re-vegetating a significant portion of the currently 60,000m^2 of disturbed gully side slopes and upper catchment.

The increasing construction difficulties as the work area progresses further upslope introduce another layer of challenges, such as material supply and different terrain conditions, requiring the design team to adjust the scope of work to fit the budget and contractors to modify their construction plans. As an example, in 2022, helicopter long lining was required to bring logs from the laydown area to the assembly area, significantly impacting construction costs and schedule.

11. CONCLUSIONS

This case history demonstrates how debris-flow hazards of very high frequency (i.e., several events per year) are being managed at East Gate Landslide. A detailed geomorphological assessment provided a process understanding that allowed the administrative authority, Parks Canada Agency, to address the debris-flow hazards at its source, rather than treating its symptoms at the highway. This is aimed to eventually stabilize the Main Gully with the goal of ever diminishing need for maintenance and decreasing operation and maintenance costs.

Due to the scale of the project an adaptive approach in hazard management is being implemented. As illustrated by the lessons learned from the 2020, 2021, and 2022 construction seasons, next phases of the project are benefiting from learnings of previous efforts, allowing costs and solutions to be tailored to site specific conditions.

This case study suggests that, in some cases, road authorities challenged with large geohazards may reduce costs and uncertainties by using adaptable designs and a phased construction schedule.

12. ACKNOWLEDGEMENT

The authors would like to acknowledge the support of Parks Canada Agency for this ongoing project, in particular Messrs. Gilles Lussier and Ryan Calder. This manuscript was prepared on the authors own time with support from BGC Engineering Inc. and McElhanney Ltd.

REFERENCES

1. BGC Engineering Inc. (2020, March 27). Geomorphological and Hydrological Site Characterization – East Gate Landslide Gully Erosion Mitigation. Report issued to McElhanney and Parks Canada Agency, File 1572003.

2. BGC Engineering Inc. (2020, April 7). East Gate Landslide: Gully Erosion Mitigation Design Basis – DRAFT. Issued to McElhanney and Parks Canada, Project No. 1572 003.

3. BGC Engineering Inc. (2021, July 6). East Gate Landslide – Pilot Check Dam Lessons Learned from 2021 Freshet DRAFT. Issued to McElhanney and Parks Canada, Project No. 1572 011.

4. Couture, R. & Evans, S. (2006). Slow-Moving Disintegrating Rockslides on Mountain Slopes. In: Evans S.G., Mugnozza G.S., Strom A., Hermanns R.L. (eds) Landslides from Massive Rock Slope Failure. NATO Science Series, vol 49. Springer, Dordrecht

5. Tetra Tech EBA Inc. (2014, June 3). East Gate Slide Site Visit Memo [Technical Memo]. Prepared for Parks Canada Agency.

6. EBA Engineering Consultants Ltd. (2004, January). East Gate Landslide Study, Beaver Valley, Glacier National Park, Report to Public Works and Government Services Canada. Project No. 0807-7825120.