Steep creek hazard mitigation case studies: some lessons learned from past events

Emily Moase, Alex Strouth & Matthias Jakob
BGC Engineering, Vancouver, BC, Canada

ABSTRACT

Steep creek hazards such as debris flows and debris floods pose considerable risks to mountain communities and infrastructure. While substantial steep creek mitigation knowledge exists, particularly in Europe and Japan, there are few published performance case studies available in English. This is a concern given the experience-based nature of steep creek mitigation design. This paper presents several short case studies that document the behaviour of steep creek hazard events, and existing mitigation systems. For each case, we identify lessons learned that can be applied to improve and optimize future designs. The case studies highlight the importance of a phased approach for mitigation design. The approach should include a thorough hazard assessment, and account for steep creek-specific design challenges, such as process variability, avulsion and scour.

RÉSUMÉ

Les aléas liés aux torrents à forte pente tels que les laves torrentielles ou écoulements hyperconcentrés posent un risque considérable pour les communautés et infrastructures de montagne. En dépit des niveaux de connaissance considérable en Europe et au Japon en ce qui a trait au confortement des torrents à forte pente, très peu d'études de cas sont disponible en Anglais. Ce qui est inquiétant si on considère qu'une grande partie de la conception des structures de confortement est basé sur l'expérience. Cet article présente plusieurs courtes études de cas qui documentent le comportement des événements d'aléas liés aux torrents à forte pente. Pour chaque cas, nous identifions les leçons retenues qui peuvent être appliquées pour améliorer et optimiser les conceptions futures. Lorsque considéré dans leur ensemble, les études de cas démontrent l'importance d'une approche par étapes pour la conception de confortement. L'approche devrait aussi inclure une étude approfondie des aléas qui inclue les défis spécifiques aux torrents à forte pente comme la variabilité des processus, les détournements de chenal, et l'affouillement.

1 INTRODUCTION

Engineers are continuously challenged to combine information logically and efficiently to make optimized design decisions, and an engineer aiming to mitigate a debris flow is no exception. First, there is the obvious problem of steep creek processes such as debris flows and debris floods themselves: fast flowing, erosive, entraining, high impact and debris-loaded. There are also more subtle, technical challenges, from the minutiae of foundation and concrete design, to the mid-scale issues of structure and outlet sizing, to the macro-scale of mitigation system assembly – in other words, what type of structure should be built where, why, and for how much?

This paper focuses on the macro, system-scale engineering challenges, through the lens of nine case studies that document the behaviour of steep creek hazard events and existing mitigation systems. Each case carries a message or lesson that can inform future mitigation designs. Through the paper, we aim to show that a phased, iterative design approach is beneficial for achieving a robust and reliable mitigation system.

The authors were not involved in the design or construction of any of the presented case studies. The project descriptions and interpretations are made from the perspective of a distant outside observer, likely with many shortcomings and oversights. Rather than critiquing the specific designs, this paper seeks to act as a catalyst for an open discussion and sharing of lessons learned from performance of existing debris-flow and debris-flood mitigation structures.

2 BACKGROUND

2.1 Mitigation techniques

Reducing the risk from debris flows and debris floods involves reducing either the magnitude, intensity or probability of the hazard, or reducing the severity of the consequences (Hungr et al., 1987; VanDine, 1996). Risk reduction (mitigation) can be achieved with structural or non-structural techniques, which may be implemented in the watershed, in the channel, on the fan, or in the community (Hübl and Fiebiger, 2005). A wide range of techniques can be applied, including source zone stabilization, channel consolidation, channel stabilization, debris retention, debris regulation, energy dissipation, diversion, improved conveyance, local protection, relocation, warning and emergency response (Carladous et al., 2016; Moase et al., 2017).

2.2 International mitigation design experience

International practitioners are more experienced with debris-flow and debris-flood mitigation design than practitioners in Canada (such as these authors). This includes countries such as Austria, Switzerland, France, Hong Kong and Japan, which have government agencies involved in landslide management, in addition to centuries of experience (Hübl et al., 2005; Okamoto, 2010).

International experience has shown that mitigation systems perform best when multiple mitigation measures are combined to create a “functional chain” (Kettl, 1984; Fiebiger, 2008). The utility of this chain is improved by including a range of mitigation techniques, which serve different objectives with respect to debris-flow control (Mazzorana et al., 2015; Piton and Recking, 2016). It is also important to develop an understanding of process-structure interactions; in other words, how the debris flow, debris flood or other hazard will behave when it impacts a structure, and how the structure will respond upon impact (Piton and Recking, 2016; Wendeler, 2016).

2.3 Phased design approach

Practitioners in some countries follow phased design approaches when developing debris-flow mitigation systems. These design approaches are documented in national technical guidelines, such as the National Institute for Land and Infrastructure Management (NILIM) Technical Notes in Japan, the Geotechnical Engineering Office (GEO) reports in Hong Kong, and the Torrent and Avalanche Control Service (WLV) guidelines in Austria (NILIM, 2007a, 2007b; GEO, 2017; WLV, 2017).

A similar phased design approach was developed by Moase (2017) for use in Canada (Figure 1). The authors have found this approach to be useful for several consulting projects.

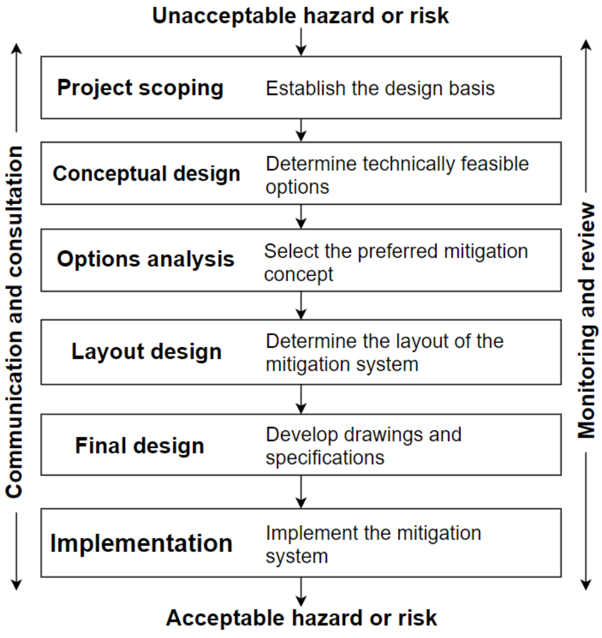

Figure 1. Recommended mitigation design approach (adapted from Moase, 2017).

Design begins with the Project Scoping phase, which seeks to establish the design constraints and objectives. This phase relies heavily on the accuracy and completeness of the hazard assessment, complemented by input from all stakeholders affected by the hazard or mitigation strategy.

Conceptual Design and Options Analysis phases involve identifying and comparing the many possible mitigation strategies, and ultimately selecting a preferred concept for more detailed design. The goal of these phases is to identify a mitigation concept that meets the constraints and objectives established during Project Scoping.

The goal of the Layout Design phase is to select the location, length, width, and height of the structural elements. A detailed understanding of the interaction between debris-flow or debris-flood processes and the different design elements is needed.

Final Design and Implementation phases involve developing final detailed drawings and specifications, and constructing the mitigation elements. Geotechnical and structural (e.g. concrete, steel) stability are evaluated and addressed by the design details. Reviews during construction evaluate if actual field conditions encountered are consistent with the design assumptions and intent.

The case studies presented below highlight lessons learned and demonstrate that each phase of design is important for achieving a well-performing mitigation system.

3 CASE STUDIES

3.1 Hummingbird Creek, BC – Roads modify watershed

On July 11, 1997, a debris flow occurred on Hummingbird Creek near Mara Lake, BC. The event initiated as a debris avalanche in the upper watershed, below a forest road culvert. The drainage area above the culvert had been approximately tripled by logging activities, and there had also been high antecedent precipitation (Jakob et al., 2000). The debris flow mobilized approximately 92,000 m^3 of debris and severely damaged two houses on the fan. There were no direct casualties, but a person suffered a heart-attack allegedly upon seeing the debris flow approach. The Hummingbird Creek debris flow reminds practitioners about the importance of roads and surface water drainage modifications for debris-flow risk management. Roads and culverts can dramatically alter watershed areas, and this alteration isn’t always apparent on maps or lidar. The design team needs to work closely with the geohazard specialists to define credible geohazard scenarios, estimate their probabilities and define the design event magnitude.

3.2 Schallerbach, Austria - Sediment volume estimation

On June 8, 2015, a 100,000 m^3 debris flow filled and over-topped a 1,500 m^3 debris basin on Schallerbach (Schaller Creek) in Tyrol. This event caused extensive damage in the village of See (Figure 2). The existing barrier and basin were not destroyed. However, the storage capacity was undersized by a factor of almost 70.

Figure 2: Debris-flow damage on Schallerbach following the June 2015 event. Photograph by Feuerwehr Landeck.

In 2016, a re-designed barrier was constructed to replace the overtopped structure. The new barrier is 24 m high and can store 50,000 m^3 of debris. It cost approximately $18.5 million CAD (€12.55 million, 2016 dollars). This example highlights the importance of a hazard assessment that estimates the magnitude and frequency of debris flows prior to mitigation design.

3.3 Bow Valley, AB - Sediment recruitment from fans

The debris-flood events that occurred in the upper Bow River Valley, Alberta (including Canmore and Exshaw) in June 2013 are among the best-studied hydrogeomorphic events in Canada. Pre- and post-event LIDAR scans allowed change detection calculations on the alluvial fans, which highlighted zones of erosion and deposition, as well as provided estimates of the net sediment input to the fan.

In the case of Jura Creek, near Exshaw, the change detection suggested that a substantial portion of the sediment in the event was entrained on the fan itself. Of the estimated 45,000 m^3 of debris that was deposited on the lower fan, approximately 19,000 m^3 had been recruited from the upper fan, suggesting that the initial debris flood sediment volume only transported 26,000 m^3 past the fan apex (BGC, 2015). High volumes of sediment entrainment from fan reaches were observed at many alluvial fans in Bow River Valley.

This example challenges the traditional notion of debris-flood fans being entirely depositional landforms. Any mitigation design needs to account for the location of the structures and account for the possibility of fan entrainment upstream or downstream of the structure. Sediment starvation through construction of a sediment basin will invariably lead to downstream channel erosion. This effect will need to be considered, particularly if there is downstream buried infrastructure.

3.4 Neff Creek, BC – Fan scour

Neff Creek drains a 3.3 km^2-sized debris-flow prone watershed located approximately 30 km north of Pemberton, BC. The fan encompasses an area of approximately 0.5 km^2, with an average gradient of 12.5°. For about 1 km upstream of the fan apex, the creek descends through a steep bedrock canyon with an average gradient of 22° (Lau, 2017). On September 19, 2015, a debris-flow on Neff Creek destroyed powerlines, and buried a highway, railroad and two residences on the fan. An assessment of the event by Lau (2017) suggests that up to 12 m depth of scour occurred near the fan apex. The scour may have been a result of the steepness of the fan, the relative looseness of fan materials, the relatively large watershed that allowed a comparatively large volume of water to be discharged, the long duration storm that triggered the event, and potentially other factors. Of the 220,000 to 328,000 m^3 of the total sediment deposited on the fan, about 83,000 m^3 (25-37%) were derived by fan scour. Dramatic scour like this is of particular concern for pipelines, where scour could expose the pipe to boulder and debris impact. An informal survey amongst seasoned expert showed that no one would have been able to predict such behaviour with any confidence and that the topic of extreme fan scour is under-researched. For practitioners, events like that observed on Neff Creek ought to be considered in hazard assessments as well as mitigation design.

3.5 Patterson Creek, BC – Avulsion and overtopping

Patterson Creek flows under the Trans-Canada Highway between the towns of Chilliwack and Hope, BC. The catchment area is 5.7 km^2 with a 10° average fan gradient and a 27° average catchment gradient. A small debris retention basin and outlet structure were constructed on Patterson Creek immediately upstream of the highway. The basin was designed in the 1980s and is operated by the Ministry of Transportation and Infrastructure (MoTI) in BC.

In 2001, a debris flow occurred on Patterson Creek and avulsed from the channel at a sharp bend above the debris basin (Figure 3). The flow bypassed the basin and approximately 17,000 m^3 of debris was deposited on the Trans-Canada highway; fortunately, there were no fatalities.

In November 2017, a rain-on-snow event in the upper watershed triggered debris flows on Patterson and several neighbouring creeks. There was no avulsion in this event, but the debris overwhelmed the basin and overtopped the debris barrier, causing erosion on the downstream face (Figure 4). The upstream face of the barrier is protected with concrete, which likely contributed to preventing erosion of the structure.

These events provide two lessons: Layout of design elements particularly on the lower fan needs to consider the potential for upstream avulsion. Barrier and basins designs, unless they can be dimensioned generously, should include elements that accommodate overtopping; often this would be a protected overflow spillway or an outlet structure.

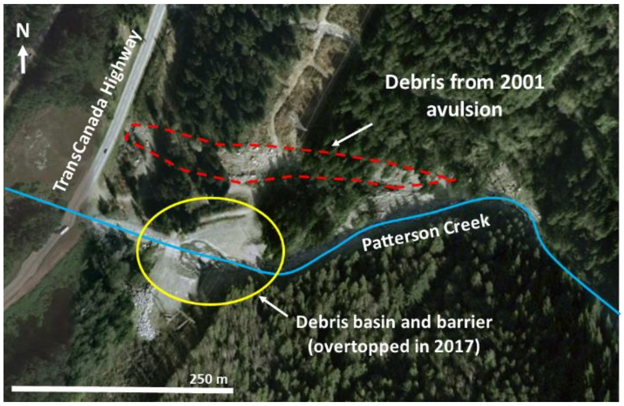

Figure 3: Patterson Creek satellite image showing debris and avulsion path from the 2001 event. Image from Google Earth, dated 2004.

Figure 4: Looking upstream at the partially reconstructed Patterson Creek barrier following overtopping during the November 2017 event. Photo by J. Park, December 2017.

3.6 Hope Creek, BC - Knickpoint erosion

As part of the Coquihalla Highway construction near Hope BC, a debris-flow deflection berm was constructed on Hope Creek in 1985. A debris retention basin was also excavated and, to increase the basin capacity, the inlet slope to the basin was over-steepened (pers. comm. O. Hungr, 2016).

In November 1995, a 50,000 m^3 debris flow occurred on Hope Creek (Jakob et al., 1997). The flow initiated from two side slope failures with a combined volume less than 3,000 m^3; the remainder of the material was entrained during the flow and largely on the fan at a debris entrainment rate of 50 m^3/m. Although a previous hazard assessment had not identified the potential for such a large debris flow, the deflection berm and basin prevented major damage to the town.

Nonetheless, it is possible that the mitigation indirectly contributed to the debris flow size through knickpoint erosion. A knickpoint occurs when a slope abruptly steepens. Knickpoints may pre-date an event as part of the natural or anthropogenic topography, or form naturally during flood and debris flow events (Eaton et al., 2017). In the case of Hope Creek, a knickpoint was created during excavation to increase the capacity of the basin. When the debris flow occurred, the knickpoint may have regressed backwards and significant quantities of fan sediments may have been entrained that would otherwise remained stable (Figure 5).

Knickpoint erosion can be avoided by maintaining shallow basin inlet slopes, by protecting the over-steepened reach from erosion, or by locating the cuts in bedrock.

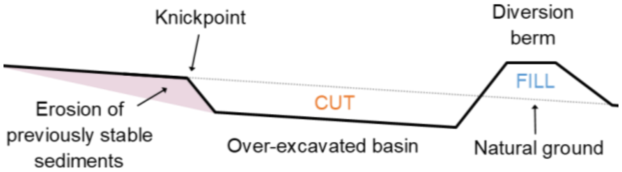

Figure 5: Erosion of a knickpoint formed during debris basin excavation could contribute to the debris-flow volume.

3.7 Schnannerbach, Austria - Hazard characteristics

Schnannerbach flows through Schnann, in Tyrol, Austria. A debris flow in the early 1990s prompted the construction of a barrier in the upper watershed, approximately 400 m above the town. The barrier is a concrete gravity-arch structure with four 3.6 m wide horizontal slots and a graduated crest; construction was completed in 1991 (Figure 6).

Figure 6: Debris-flow barrier on Schnannerbach in Austria. Photograph by E. Moase, May 2016.

The barrier functioned as designed during near-yearly events in the 1990s. However, a subsequent debris flow in 2005 passed through the slots “as if the barrier wasn’t even there”, causing damage in the village below (pers. comm., Christian Weber, 2016). The barrier retained approximately 13,000 m^3 of sediment, but allowed a further 20,000 to 25,000 m^3 to pass (Gems et al., 2014). The 2005 debris flow may have been finer grained than most of the debris flows that occur on Schnannerbach.

Since the 2005 event, several techniques have been tried to decrease the slot size of the Schnannerbach barrier, including installing a steel grid. However, the grain size of debris flows on the torrent continues to be highly variable, and the steel grid caused too much sediment capture during coarse-grained events. In spring 2016, a new experimental system was installed in the barrier. It consists of rubber balloons, installed in the slots, which can be remotely filled with water to block the slot openings in the event of a fine-grained debris flow or debris flood. The system can be remotely activated by the mayor of Schnannerbach, on the advice of the WLV, based on weather data and a real-time video feed from the dam. The balloons were developed using a physical model in collaboration between WLV and Austrian academics, but had not been tested by a full-scale debris flow, as of the time of the primary author's visit in May 2016.

Schnannerbach is an excellent example of the complex nature of debris-flow mitigation design. Even creeks that have behaved as predicted for years may produce anomalous events; this has also been observed on creeks in Canada (Jakob et al., 1997). Professionals should be aware of this potential.

In the authors' opinion, the grain size differences on Schnannerbach may arise from the ability of the watershed to produce both debris flows and debris floods. The watershed area is approximately 6 km^2. At this watershed area and the associated channel gradients, transitions to debris floods at a higher volumetric water content are conceivable. Such flows can be more mobile, hence fitting through constructed openings. This is confirmed by Gems et al. (2014), who state that the main hazard at Schnannerbach comes from fluvial rather than debris-flow processes, although the dam was built to manage debris-flow hazards. Hence, the Schnannerbach example demonstrates the importance of hazard assessment which ought to identify the entire spectrum of events that may occur on a given creek. Multi-process behaviour then needs to be integrated in the resilient design of mitigation structures.

3.8 Ryugamizu, Japan – Domino effect

On August 6, 1993, a debris flow occurred on a small creek above the village of Ryugamizu in southern Japan. The watershed area was only 0.04 km^2, but 90 mm of rain was recorded in one hour. The debris flow impacted a train that was stopped at the station (Takaya, 2003). It was later determined that the two concrete closed check dams on the creek had failed, allowing the debris flow to pass. Takaya (2003) hypothesized the following series of events (Figure 7):

1. A tributary debris flow occurred upstream of the left abutment of the upper dam (Dam 2).
2. Because of the oblique impact angle with the channel, the tributary debris flow super-elevated and outflanked the right abutment of Dam 2.
3. Still moving obliquely to the channel, the debris flow super-elevated and out-flanked the left abutment of the lower dam (Dam 1), approximately 20 m downstream.
4. The out-flanking caused the erosion and failure of Dam 1, and the debris stored behind Dam 1 was released.

The Ryugamizu, Japan case is referred to as "domino effect" failure, in which the performance of one structure contributed to the failure of other structures in the system. In the case of Ryugamizu, literature suggests that the dams should have been located slightly farther downstream, to allow for direct impact from the tributary debris flow (Wendeler, 2016). It also emphasizes the need for three-dimensional modeling that allows for superelevation to examine its potential effects on the location and sizing of debris barriers.

3.9 Quality assurance – Zhouqu, China

Wang (2013) describes lessons learned from a large debris flow that impacted 6 villages in Zhouqu County in northwestern China, destroying 200 buildings and causing approximately 1700 fatalities in August 2010. The potential for large debris flows was recognized in the area, particularly after the 2008 Wenchuan earthquake. Unfortunately, the planned mitigation was only partially completed and poor-quality workmanship contributed to breakage of check dams, which contributed to the severity of the 2010 event (Wang, 2013). Only 9 of the planned 14 dams had been constructed, and the dams that were

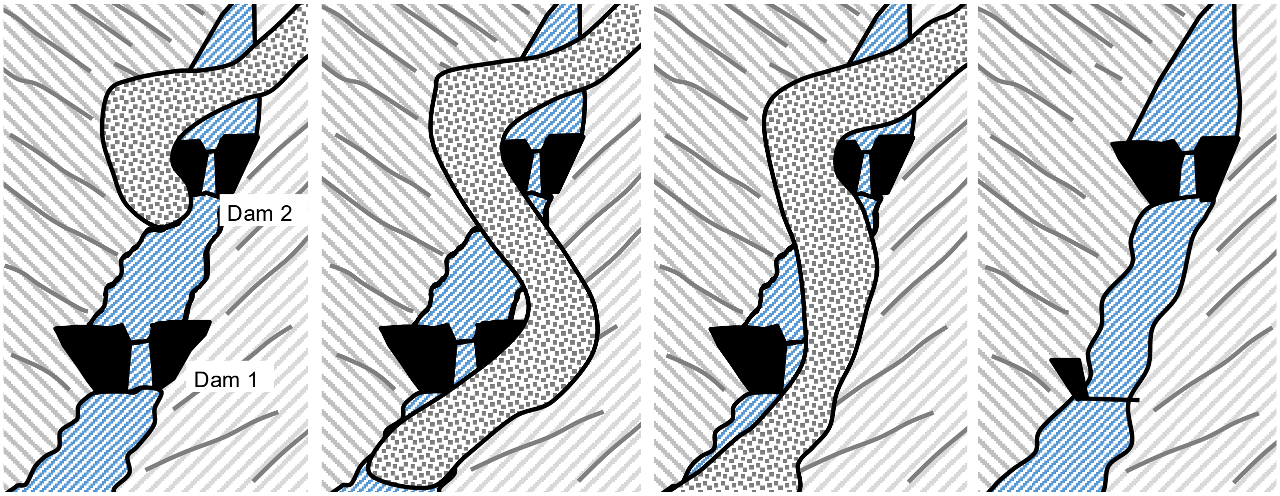

Figure 7: Sequence of events during the Ryugamizu check dam outflanking event, modified from Takaya, 2003.

constructed were not built to resist the impact forces exerted by a debris flow. In this case, failure of the mitigation system was caused by poor quality assurance practices during the construction phase, including a failure to achieve the design intent (Wang, 2013).

4 LESSONS LEARNED

Table 1 summarizes the lessons learned from each case study. While far from a global summary of mitigation issues, the table demonstrates that all mitigation design phases are critical for achieving a well performing mitigation solution. It also emphasizes the need for multi-disciplinary collaboration during mitigation design, including hazard specialists and engineers with specific experience in steep creek hazard management.

5 CONCLUSION

Case studies are fundamental to good engineering and geoscience practice and can be used to demonstrate new techniques, and learn from mistakes or inefficiencies. This paper examined debris-flow and debris-flood case studies to develop “lessons learned” that can be applied to future debris-flow and debris-flood mitigation projects.

When considered together, these case studies highlight the importance of a thorough hazard assessment and a critical evaluation of the possible interaction between the debris-flow or debris-flood event and the proposed structures. Some of the process/structure interactions (e.g. avulsion, out-flanking, over-topping, and erosion) are unique to steep creek environments and require foresight from the geoscience and engineering design team to overcome. Therefore, professionals experienced with debris-flow and debris-flood hazard and mitigation design are needed in all project phases.

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Table 1: Summary of lessons learned from each case study.

	Critical Mitigation Design Phase				
Case study	Hazard recognition & project scoping	Conceptual design & options analysis	Layout design	Final design & construction	Lesson learned for mitigation design
Hummingbird Creek, BC	✓				Roads and culverts can dramatically alter watershed areas. Hazard assessments require physical exploration of watersheds with human modifications.
Schallerbach, Austria	✓				A hazard assessment is needed to select the debris-flow event volume used for mitigation design.
Bow Valley, AB	✓	✓			Large volumes of sediment can be recruited from fans in natural or unprotected channels, which can affect event volume and appropriate types of mitigation measures.
Neff Creek, BC	✓	✓	✓		Debris flows can cause extreme scour on fan surfaces from long duration storms, which can affect appropriate mitigation concept and layout.
Patterson Creek, BC			✓	✓	Layout design should consider potential for upstream avulsion, and design elements should accommodate overtopping by events greater than the design event.
Hope Creek, BC			✓	✓	Knickpoint erosion and sediment recruitment at basin inlets can reduce basin storage capacity. Erosion protection is a critical design detail.
Schnannerbach, Austria	✓	✓	✓	✓	Subsequent debris-flow and debris-flood events on the same creek can have highly variable characteristics. These characteristics can affect final design details. Design elements and layout should consider effects of sediment starvation or sediment influx downstream of barriers.
Ryugamizu, Japan			✓		Location of the upstream structure selected during layout design phase made it susceptible to outflanking. Outflanking of the upper structure contributed to failure of downstream structures.
Zhouqu, China				✓	Inadequate construction and quality assurance practices led to collapse of structures during debris-flow events.

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