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HAZARD ASSESSMENT OF DEBRIS FLOWS INITIATED BY BREACH OF SMALL EARTH DAMS IN BRITISH COLUMBIA

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ABSTRACT

Small earth dams perched high above the main valley floor pose a potential risk for destructive debris flow generation if they breach. A small outburst can trigger a large debris flow. The Testalinden dam failure in BC demonstrates the destructive power of a debris flow triggered by the water released by a breach through a small, poorly maintained dam. The debris flow destroyed homes and damaged properties. This paper presents a methodology for preliminary assessment of debris flow potential caused by the breaching of small earth dams. The predicted peak breach outflow, the creek gradient, and the estimated height of the water, or outflow per unit width in the creek channel are used as criteria to delineate possible locations along a creek where a debris flow may initiate. Dam failure consequence classification should incorporate assessment of breach-induced debris flows.

RÉSUMÉ

Les petits barrages en terre perchées au-dessus du fond de la vallée principale présentent un risque potentiel de génération de flux de débris destructeurs s'ils se brisent. Une petite explosion peut déclencher un grand flux de débris. La rupture du barrage de Testalinden en Colombie-Britannique démontre le pouvoir destructeur d'un flux de débris déclenché par l'eau libérée par une brèche à travers un petit barrage mal entretenu. Le flux de débris a détruit des maisons et endommagé des propriétés. Cet article présente une méthodologie pour l'évaluation préliminaire du potentiel d'écoulement de débris causé par la rupture de petits barrages en terre. Le débit de pointe prévue de la brèche, le gradient du ruisseau et la hauteur estimée de l'eau, ou le débit par unité de largeur dans le canal du ruisseau, sont utilisés comme critères pour délimiter les emplacements possibles le long d'un ruisseau où un flux de débris peut s'initier. La classification des conséquences des ruptures de barrages devrait inclure une évaluation des flux de débris induits par les brèches.

1 INTRODUCTION

There are approximately 10,000 small earth dams in Canada, many of which are older than their design life (Grapple and Mitchelmore 2009). As these dams continue to age and as development continues in areas downstream, dam failures will become a more significant public safety issue. Worldwide, much attention is given to preventing the failure of medium to large size dams with little attention being paid to small dams (Pisaniello et al. 2006). Various agencies are working to improve criteria used to assess risks associated with dam failures, and Canadian provinces have implemented new legislation or are considering changes to existing legislation to improve dam management. Little attention is normally given to the risk of failure of small dams because dam failures are normally viewed in the context of the risk that is posed to life and property downstream of the dam caused by the flood triggered by a dam collapse. Floods caused by the failure of small dams are often considered to be an acceptable risk. However, the downstream risk can be high if the outburst flood changes into a debris or mudflow.

The frequency of small dam failures is higher than that for large dams. This is mainly because of poor design, poor quality construction, and deterioration due to lack of proper maintenance (FEMA 1987, Pisaniello et al. 2006). In addition, deterioration due to old age is also a factor contributing to dam failure. This study considers the largely unrecognized and specific hazard associated with debris flows triggered by the sudden failure of small earth dams. The creation of debris flows as opposed to flooding has rarely been considered as a failure consequence in the downstream dam risk assessment process, and it is not explicitly noted in dam safety guidelines.

The main objective of this paper is to present a method to identify conditions where debris flow initiation may occur as a result of a breach of a small earth dam. The method makes use of readily available data such as geological and topographical maps, GIS shape files, and Google Earth. To achieve this goal, the following tasks were performed.

- Determine practical and suitable methods to predict the dam breach peak outflow and hydrograph based on limited data available for small dams.
- Determine the factors that affect the triggering of debris flows.
- Collect data on selected dams and apply these in empirical equations.
- Verify results using published reports and photos.

2 SMALL DAMS AND DEBRIS FLOWS

The British Columbia dam safety guideline classifies dams into two groups based on the dam height. A small dam is a dam that is lower than 15 m high (MFLNRO 2016). Small dams are used for irrigation, municipal water supplies, or stormwater management. Therefore, they tend to be close to the service population in comparison with large dams that are typically used for hydroelectric generation. Because of cost constraints, less time and effort are typically spent on engineering and construction of small dams. This may lead to a substandard design and poor construction quality. Local contractors are often hired to construct, repair or maintain small dams. These contractors have limited resources and sometimes use farm dam practices during construction resulting in poor long-term performance.

The limited resources of a small dam owner can lead to a lack of monitoring, maintenance, and rehabilitation for dams. The minimal awareness of hazards associated with small dams could result in the downstream consequences of a dam failure not being fully recognized (Grapel and Mitchelmore 2009).

The issue investigated in this paper is the debris flow hazard that can be initiated by the outburst of a dam located high above a valley. The sudden failure of a dam on a creek, whether of a natural landslide dam or an artificial dam, can result in a large discharge of water downstream. The surge of escaping water can easily turn into a mudflow or debris flow by incorporating inorganic and organic debris from the creek channel. Because of the large volumes involved, debris floods and debris flows triggered by such events can travel for many tens of kilometres downstream and cause damage to houses and structures located downstream from the dam (Clague et al. 1985, Chen et al. 2004, Skermer and VanDine 2005, Takahashi 2007).

Tannant (2017) lists 12 historical dam failures in Okanagan Valley. Since then, two more historical dam failures have also been identified. This clearly indicates that dam failures are not isolated or singular occurrences, even when considering a relatively small watershed. The Testalinden Dam failure in 2010, which is the most recent dam failure, caused a massive debris flow and significant damage; this dam failure and debris flow is the main case-study investigated in this paper. Debris flow initiation caused by the outflow from a dam breach that erodes the channel bedding is investigated in this paper. A methodology is presented for predicting debris or mudflow initiation caused by a dam failure.

2.1 Debris flow initiation threshold

Debris flows may originate and mobilize in a variety of ways. The prerequisite conditions for debris flow initiation include 1) an abundant source of water, 2) an abundant supply of unconsolidated sediment, and 3) relatively steep slopes. Various researchers have studied debris flow mechanisms: initiation, routing, and deposition. Different thresholds have been developed for debris flow initiation such as rainfall intensity or Melton ratio (Godt and Baum 2010; Welsh and Davies 2011; Blahut et al. 2009; Wilford et al. 2004). In this paper, channelized debris flow initiation caused by dam-breached outflow is investigated. The thresholds that were developed by Takahashi (2007) and Berti and Simoni (2003) for debris flow initiation are used in this study. The common point in these studies is that they developed a threshold that considered all the main factors that cause debris flows, i.e., slope, streamflow, and gradient.

3 TESTALINDEN DAM CASE STUDY

On June 13, 2010, a small earth dam failed by overtopping and breaching on the upper watershed of Testalinden Creek, located south of the town of Oliver, BC (Figure 1). The water released by the breach initiated a debris flow that flowed down to the Testalinden Creek fan. The debris flow resulted in extensive property damage on the Testalinden Creek fan (Everest 2010; Culbert 2010, Tannant and Skermer 2013).

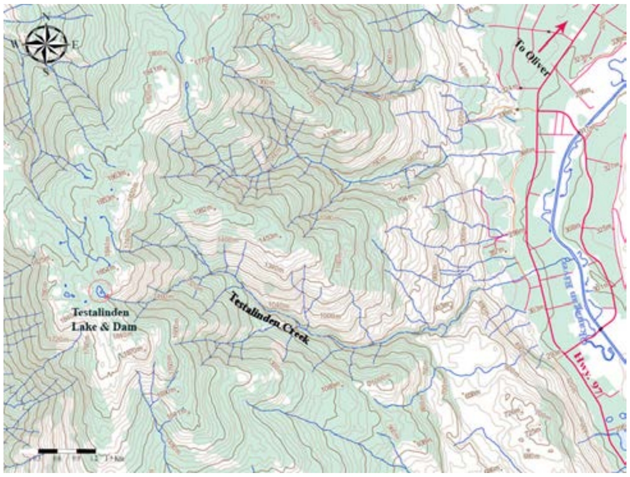

Figure 1. Topographic map of Testalinden Creek

Once the debris flow reached the lower gradient fan, deposition began forming a long asymmetrical triangle of sediment that buried the original channel and created a new one that is approximately 1.4 km long (Figure 2). The overall area on the fan affected was approximately 23.6 ha. According to the test pit results, and lidar surveys conducted on the fan, the estimated volume of the debris and sediment is 240,000 to 260,000 m^3 (Higman et al. 2011).

Figure 2. Debris flow deposit on Testalinden Creek fan

The debris flow destroyed or badly damaged five homes and caused significant damage to crops and farm equipment, covered 200 m of Highway 97, and blocked several secondary roads. In response to this failure, the BC government revised its dam safety program and legislation and increased emphasis on dam safety (Tannant 2015). The BC Deputy Solicitor General made a number of dam safety recommendations, and BC dam safety officers were busy for two years implementing these recommendations. Some these actions were performing a rapid dam assessment, revising the BC Dam Safety Regulation, updating of the dam registry, creating greater access to information by dam owners, providing local government and the public with tools such as dam locations and basic information in iMap and Google Earth (BC Dam Safety Program 2011; 2012).

The Testalinden Dam was rated as a “low” consequence dam on the BC Dam Safety Regulation Downstream Consequence Classification Schedule. A low classification is defined as the low potential for loss of life, low economic loss and cost, and low loss or deterioration of regionally important environmental or cultural habitats that may recover overtime without restoration. A low rating would imply the need for a dam audit every ten years. In hindsight, the low rating for the Testalinden Dam was inappropriate (Morhart 2010).

3.1 Testalinden Dam and Lake

The Testalinden Dam was located on the upper Testalinden Creek on Mount Kobau (Figure 1). It sits within the South Okanagan Grasslands Protected Area. The reservoir is locally known as Testalinden Lake. The dam was constructed in 1937 to store water for irrigation in the drier months of the year. Seasonal snowpack is the primary source of water stored in the reservoir (Morhart 2010). The reservoir capacity at the point of overtopping and its surface area were about 20,000 m^3 and 14,400 m^2, respectively (Tannant and Skermer 2013). It was the simple earth dam with a maximum height of about 2.5 m, and no engineering design and supervision occurred during construction. The most recent owner was responsible for the dam’s safety since 1985. There was sufficient evidence to see a consistent pattern of concerns and warnings about the condition of the dam dating back to the 1960s. There is no sign that actions had been taken to fix deficiencies in the dam structure that had persisted for decades (Morhart 2010).

3.2 Testalinden Creek

Testalinden Creek is a third-order stream channel with a total length of 8.8 km. The creek starts at Testalinden Lake at an approximate elevation of 1810 m near the top of the watershed. The uppermost elevations of the Testalinden Creek watershed are at an approximate elevation of 1850 m. Testalinden Creek flows eastward into the Okanagan River at an approximation elevation of 285 m. The drainage area of Testalinden Creek is 12.65 km^2. The creek gradient is one of the important factors needed to assess debris flow initiation using debris flow initiation thresholds. The slope of the channel was derived from a DEM of the studied area. The DEM grid cell size is 20 m, and cells are projected on a NAD83 UTM coordinate system. Two methods were used to determine the slope of the channel using ArcGIS software. The channel gradient was calculated by spatial and raster analysis, or a simple profile was created. Figure 3 presents the creek gradient.

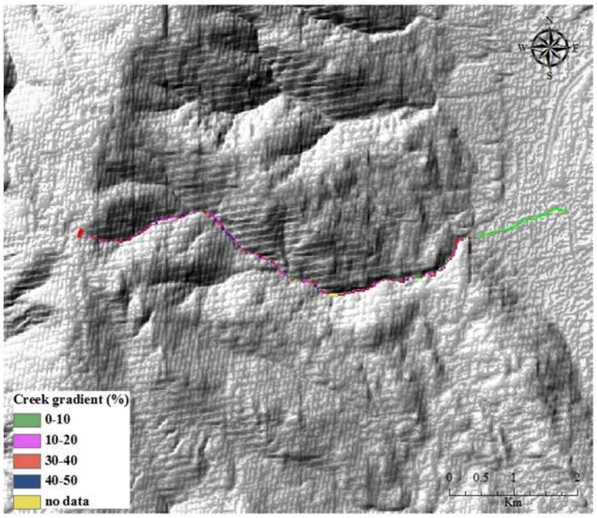

Figure 3. Testalinden Creek DEM and gradient

3.3 Surficial geology and creek bed sediments

An abundance of unconsolidated sediment is essential for debris flow occurrence. The amount and type of loose materials are important because they determine whether a debris flow can initiate, and they have an impact on the quantity of water required to trigger a debris flow (Wie et al. 2008). In this research, the surficial geology map of the studied area, engineering reports, and photos were used to evaluate the surficial geology conditions. After determining sediment type in different sections of the creek using a surficial geology map, the mechanical properties of the soil (average particle diameter, cohesion, and friction angle) were estimated. These properties were used in the empirical debris flow initiation thresholds.

Figure 4 shows that a length of 1526 m along the creek is located in glacial till, 546 m of the creek has colluvium in the creek bed, and there is no information on the sediment type available for the lower reaches of the creek.

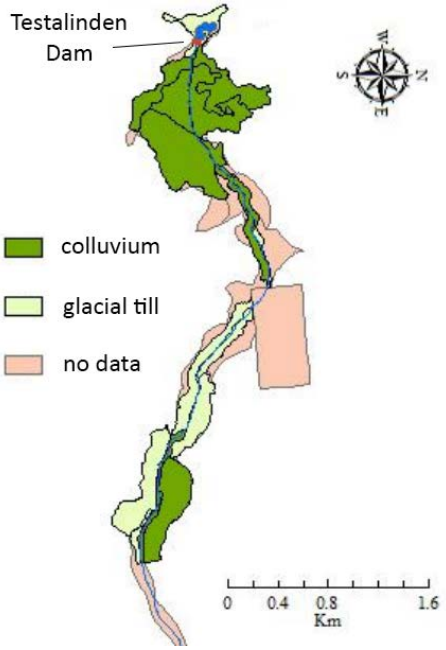

Figure 4. Surficial geology in the upper reaches of Testalinden Creek

3.4 Testalinden Dam breach outflow

On June 11, 2010, a hiker noticed water flowing across the road that ran along the crest of the dam (Morhart 2010). The report of his observations was not passed along to the appropriate authorities until after the breach occurred at approximately 2:15 pm on June 13, 2010. The breach in the dam released approximately 20,000 m^3 of water. The released water descended the creek to the Okanagan valley entraining materials from the creek, initiating a large debris flow, and growing to more than 240,000 m^3 in volume by the time it reached the alluvial fan.

The technical reasons for the dam failure were investigated, and it is likely that a combination of late-season snowmelt and rainfall, which overtopped the roadway/dam, and an ineffective culvert were contributing factors (Morhart 2010).

Figure 5 shows a photograph of the breach, along with a simplified cross-section of the breach. Based on the cross-section geometry, the height of water above the bottom of the breach at the time of dam failure was 2.2 m, and the volume of water in the reservoir was estimated to be slightly more than 20,000 m^3. The breach width was approximately 6 m, as seen in Figure 5.

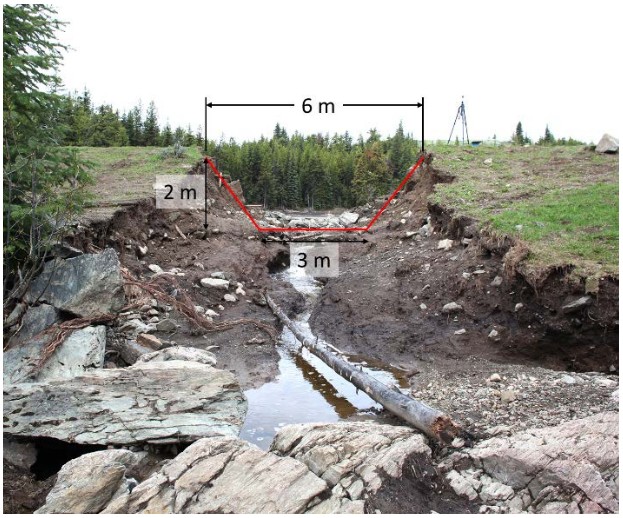

Figure 5. Testalinden Dam breach

The peak outflow from the Testalinden dam breach was estimated by applying various existing empirical dam breach equations. These equations predict a peak outflow ranging from 1 to 300 m^3/s. Thus there, is considerable uncertainty in the prediction of peak outflow using these regression equations. Wahl (2004, 2010) did an uncertainty analysis of various equations used to predict peak outflow for 108 case studies and suggested that Froehlich's (1995) method has the least error. Froehlich's equation predicts a peak breach outflow of 30 m^3/s for the Testalinden Dam, which seems to be a reasonable estimate.

3.5 Analysis of debris flow initiation

Two methods were used to investigate debris flow initiation in Testalinden Creek: Takahashi (2007) and Berti and Simoni (2003). In Takahashi (2007), debris flows are predicted to occur in a gully bed steeper than a critical gradient and when surface water flow exceeds a discharge flow rate that can wash out the creek bedload. Berti and Simoni (2003) stated that when the Factor of Safety is less than unity, a debris flow can initiate. More information about the parameters and thresholds used in these methods can be found in the referred references. Figure 6 shows a map of the reaches along the Testalinden Creek where debris flows are predicted to occur when applying the Takahashi (2007) and Berti Simoni (2003) thesholds in an ArcGIS raster analysis.

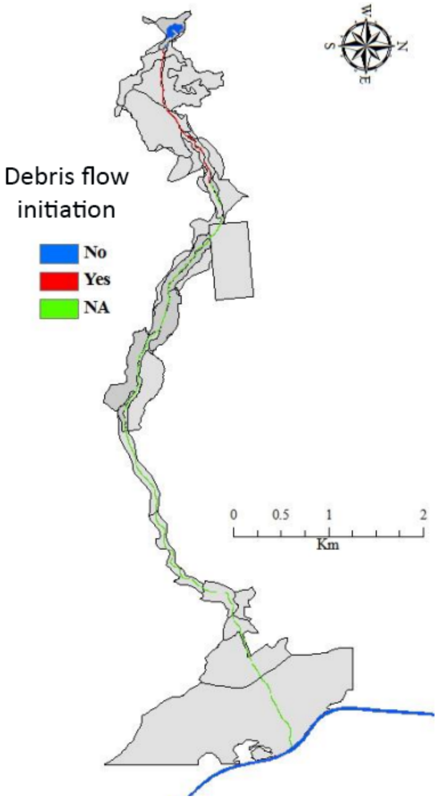

Figure 6. Sections of Testalinden Creek where debris flow initiation is predicted to occur

3.6 Testalinden debris flow initiation results

The estimated discharge from the Testalinden Dam was predicted to be capable of triggered debris flows in reaches with a slope greater than 10°. Since most of the creek is confined to a V-shaped valley with a slope greater than 10°, a debris flow was easily able to initiate and grow as the water released by the breach in the dam travelled down toward the valley bottom.

Figure 7 shows Google Earth aerial photographs captured before and after the dam failure. Evidence of the debris flow is visible. The highlighted circle indicates a point along the channel where evidence of debris flow scour of the channel becomes obvious. This location is where more substantial quantities of sediment and debris were expected to be present in the channel. At this point, evidence of scouring and vegetation removal starts and continues down the channel all the way to the fan. This spot is located 2 km downstream from the dam. The starting point matches a reach where debris flow is predicted to initiate in Figure 6.

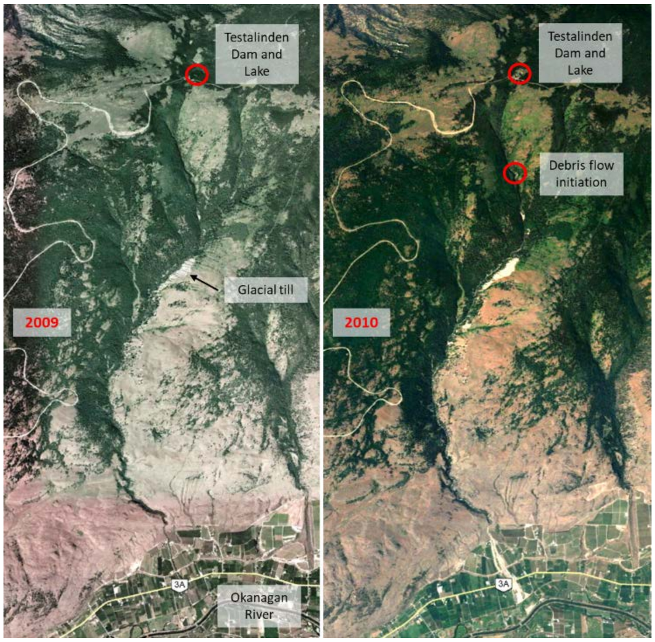

Figure 7. Probable debris flow initiation location

4 CONCLUSION

This study highlights a situation where a small earth dam on a steep creek perched high above a main valley can create a significant debris flow hazard. If the dam fails and suddenly releases stored water, which then triggers a debris flow, the resulting debris flow can be far larger and more destructive than a flood of water. Flood hazard assessment typically used for assessing the consequence of dam failure may be insufficient. This paper demonstrates a situation where debris flow initiation is more important and must be considered when determining the failure consequence of a dam.

Due to a large number of privately owned small earth dams in British Columbia and the lack of rigorous monitoring of these dams, debris flow initiation should be included in future hazard assessments and downstream analysis. Figure 8 summarizes a proposed methodology for quickly screening and assessing whether a dam can potentially initiate a debris flow if the dam were to fail. Three factors are required to assess debris flow initiation: 1) the height of water or unit discharge in the creek, 2) the depth and shear strength (cohesion and friction angle) of sediment in the creek, and 3) the creek gradient. The methodology provides a means to improve dam failure consequence classification with minimal data requirements. Moreover, the methodology can be implemented in GIS-based software for spatial and raster analysis.

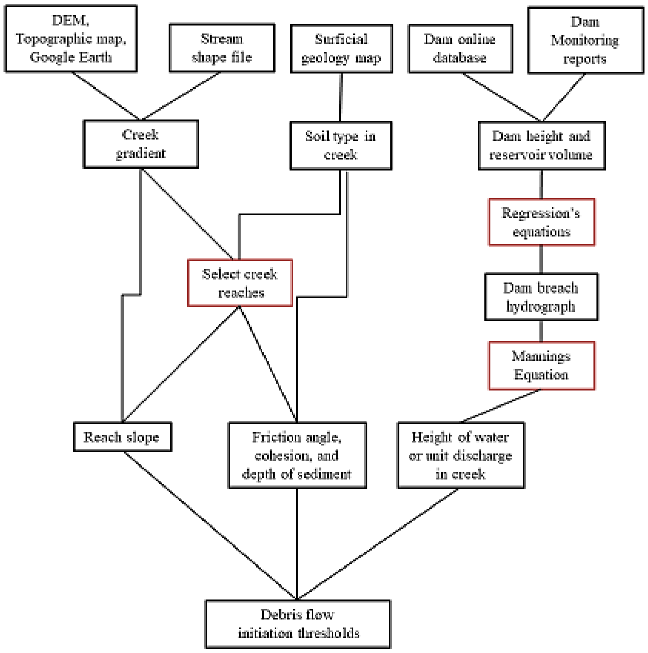

Figure 8. Methodology developed to assess debris flow initiation caused by the failure of earth dams

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