The Cheekeye Debris-Flow Barrier – unique features of a proposed open check dam in Canada

Emily Mark1*, and Alex Strouth2
1BGC Engineering, Vancouver, BC, Canada
2BGC Engineering, Golden, CO, USA

Abstract. The proposed Cheekeye debris-flow barrier in Squamish, BC, Canada is an open check dam with a very large storage capacity of 2.4 million m³. There are several unique features of the design that deviate from standard international practice, including the very low probability (1 in 10,000 years) design event, the use of a single large structure, the selected construction material, the crest design, and the outlet design. These features were selected for the Cheekeye barrier due to idiosyncrasies of the site specifically, and of debris-flow mitigation in Canada, in general.

1 Introduction

The Cheekeye River fan in Squamish, BC, Canada is subject to debris flows from the Mount Garibaldi volcano. These debris flows pose intolerable risk to existing and proposed development. A debris-flow mitigation system has been proposed to reduce risk to a tolerable level. As of summer 2022, the detailed design of the mitigation has been completed and construction is anticipated to begin in the next few years.

There are several unique features of the Cheekeye mitigation system, particularly compared to how the system may have been designed if it was situated elsewhere in the world. The purpose of this paper is to highlight these design features and share the designers’ rationale for this deviation from standard international practice.

2 Project Overview

Existing development on the Cheekeye fan includes two schools, businesses, residential areas with about 1,400 residents and the major highway that connects Vancouver and Whistler, BC (Fig. 1). Additional development in the at-risk area is conditional on the construction of debris-flow mitigation by the developer, to reduce risks for both existing and proposed development.

The principal component of the proposed mitigation system is a 24 m tall barrier with a 6 m wide vertical slit outlet and a design storage capacity of 2.4 million m³ of debris (Fig. 2). The proposed barrier is located at a natural bedrock constriction near the upper apex of the Cheekeye Fan. This location provides a naturally confined basin and is efficient for sediment and debris retention (Fig. 1).

The barrier is sized to manage a 10,000-year return period debris flow with 2.8 million m³ volume. It is a symmetrical gravity dam with 45-degree inclined slope faces composed of roller compacted concrete. A 6 m wide, vertical slit outlet that extends from the riverbed to the barrier crest allows routine Cheekeye River flows to pass, but restricts debris-flow discharge to a value that can be conveyed downstream with tolerable risk. Seven horizontal steel beams, each 1.3 m square, span across the slit outlet in the upper 19 m of its height to encourage blockage of the slit by boulders during debris flows. If future changes to the barrier performance are desired (e.g., to adjust the of balance residual risk and sediment removal cost), the spacing of the beams is adjustable, allowing beams to be added or removed to promote blockage or passage of sediment.

3 Design Event Selection

The use of a 1 in 10,000-year design event for the Cheekeye barrier is a particularly unique characteristic of the design, compared to debris-flow mitigation systems designed elsewhere in the world. In other countries, design events for debris-flow mitigation typically range from about 100 to 300 years, with up to 1,000-year events being considered in circumstances involving high-density development or critical infrastructure [1].

For the Cheekeye project, the design event was selected through a comprehensive life-loss risk assessment process. The process included input from the local government, the provincial government, and an independent expert review panel, as well as decades of hazard assessment on the fan and in the watershed.
Figure 1: Map of the proposed barrier location and the Cheekeye fan.

Figure 2: A rendering of the proposed Cheekeye barrier, looking upstream (provided by Sqomish Sea to Sky Developments LP).
In 2015, the expert review panel determined that the mitigation design needed to account for (but not necessarily directly mitigate) the largest credible debris flow that could occur: a 5.5 Mm$^3$ rock-avalanche-generated debris flow from Mount Garibaldi. Table 1 shows the frequency-magnitude relationship for Cheekeye River debris flows that was the basis for design [2]. The expert panel were also involved in the selection of risk tolerance criteria for the project, which were equivalent to those adopted in Hong Kong for landslides, and were adopted by the local government in the absence of regional or federal criteria in Canada [3]. Risk greater than 0.1 lives lost in 100-years was considered intolerable.

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Scenario Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Class (VC)</td>
<td>Return period (years)</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
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<tr>
<td>4</td>
<td>1000</td>
</tr>
<tr>
<td>5</td>
<td>3000</td>
</tr>
<tr>
<td>6</td>
<td>10,000 (best estimate)</td>
</tr>
<tr>
<td>7</td>
<td>10,000 (upper bound)</td>
</tr>
</tbody>
</table>

Using the frequency-magnitude relationship as a starting point, extensive numerical run-out modelling and risk analysis were completed to assess the life loss risk to existing and proposed development. Figure 3 shows the results of the assessment in terms of the risk contribution from each debris-flow volume class (VC).

![Figure 3: Risk contribution by volume class (dashed line) compared to intolerable risk threshold (solid line).](https://doi.org/10.1051/e3sconf/202341506014)

The only tolerable debris-flow scenarios are VC1 and VC7. VC1 is high probability, but low consequence because the event is not expected to cause fatalities. VC7 is high consequence, but the risk is tolerable because the probability of occurrence is so low.

The mitigation system is required to reduce intolerable risks to a tolerable level: in other words, any scenarios that plot above the solid red line on Figure 3 need to be reduced to below the red line. Therefore, the system was designed to manage the VC6 (2.8 Mm$^3$) event, with a return period of approximately 10,000 years, because it is the largest magnitude event that poses intolerable risk. The barrier has a retention capacity of 2.4 Mm$^3$, and up to an additional 0.4 Mm$^3$ can be passed through the outlet with tolerable risk.

To our knowledge, the selection of such a low probability/high magnitude design event is unique in debris-flow mitigation. This exceedingly rare design event is the primary reason for several of Cheekeye’s unique design features. Design norms that make sense for a 100- or 200-year return period design event become less practical for a 10,000-year return period event.

### 4 Unique Features of the Design

#### 4.1 Single Large Structure

Many debris-flow mitigation systems use a “functional chain” of structures to manage risk at multiple points in the watershed or channel. For example, a debris regulation barrier might be combined with a series of closed check dams to limit channel erosion, a parallel sediment basin, or even watershed scale management including hundreds of structures (see Tateyama Caldera, Japan).

At Cheekeye, debris-flow management relies on a single large debris-flow barrier for several reasons. The barrier is located at the downstream end of a natural basin, which is efficient and sufficient for retaining the required sediment volume. The land downstream of the barrier to the fan apex is within a Provincial Park, where construction and development are prohibited (Fig. 1). Finally, construction of additional structures at the fan apex or on the lower fan was ruled out due the distribution of elements at risk, and potential for a mitigation structure to cause risk transfer by diverting flows to other areas of the fan.

#### 4.2 Lack of Excavated Basin

The proposed design does not include basin excavation in the area upstream of the barrier, because excavation would change the natural channel gradient and inhibit the passage of sediment during clearwater floods or small debris flows. Retention of this sediment would unnecessarily increase maintenance costs and may also cause sediment starvation downstream. In the current condition, tens of thousands of cubic meters of sediment are transported annually by the Cheekeye River by clearwater flows. This sediment is beneficial for the major fish-bearing rivers downstream, and the design seeks to maintain connectivity of this sediment.

#### 4.3 Construction Material

The proposed Cheekeye barrier is a gravity dam composed of roller compacted concrete (RCC). RCC is a concrete mixture (cement, sand, and gravel) that is placed in horizontal lifts and compacted. RCC is a common material for water dam construction, and a
similar construction material is commonly used for debris-flow barriers in Japan, known as Sabo Soil Cement. RCC was selected for Cheekeye because it is more cost effective than alternative construction materials (e.g., earthfill with an erosion protection cover) that result in similar performance.

The main body of the gravity barrier does not include reinforced concrete; instead, the cohesive strength of the horizontal joint interfaces of the RCC is sufficient to resist the debris-flow impact. The dynamic impact force of the design event is estimated to be in the range of 300 to 1,000 kPa, with a flow depth of 2 to 12 m and a velocity of 6 to 20 m/s.

The barrier will have 45-degree (1H:1V) side slopes, unlike the near vertical slopes often seen on reinforced concrete structures. This side slope angle allows the RCC to be placed and compacted without using formwork, and provides the mass needed for the gravity structure to resist the debris-flow impact.

RCC is more resistant to erosion and overtopping than earthworks, but less resistant than the structural or reinforced concrete that is used elsewhere in the world. However, unlike most other debris-flow barriers, the Cheekeye barrier will not be overtopped, except by very low probability events.

### 4.4 Crest Design and Overtopping Management

The Cheekeye barrier’s unique crest design is also informed by the high magnitude, low probability design event that was selected through the risk assessment process. Rather than designing to withstand regular overtopping, the Cheekeye design reduces the frequency of overtopping by providing more debris storage. This approach resulted in changes to the barrier crest profile and downstream erosion management compared to other structures.

#### 4.4.1 Crest profile

The crests of typical debris-flow barriers have an overflow section or spillway, with high abutments (wingwalls) to direct flow and prevent overtopping. These structures may be designed to retain the 100- or 200-year return period event, and pass an event of a similar magnitude and discharge over the spillway.

The Cheekeye barrier abutments are higher than the spillway, but not as high as they would be elsewhere. The estimated spillway discharge capacity (250-500 m$^3$/s) is only about 2-3% of the estimated peak discharge of the design event (15,000 m$^3$/s). The low discharge capacity of the spillway is acceptable because only small portions at the tail of very exceptional events will overtop the structure. The abutments of the Cheekeye barrier are protected against erosion and outflanking if the structure is overtopped.

#### 4.4.2 Downstream erosion management

The Cheekeye barrier foundation and downstream area includes both soil and bedrock zones, but the design does not include additional structures such as a sub-dam to manage downstream erosion. Instead, a reinforced concrete parapet wall will be constructed on the crest to direct overtopping flows toward the portion of the barrier that is founded on bedrock. In addition, the outlet structure is located on bedrock.

### 4.5 Outlet Design

The Cheekeye barrier has a 6-m wide vertical slit outlet with horizontal steel bars. The outlet size was selected to restrict discharge to the value that can be managed downstream, according to the methods outlined in [4]. The steel bars are necessary because there is some uncertainty about whether there is sufficient large woody debris to block the outlet.

Aside from size, the main unique feature of the outlet is the upstream funnel. The outlet is not a consistent width throughout the barrier; instead, it flares open to the upstream and downstream. Physical modelling suggested that an upstream funnel can promote the passage of large wood during floods because it encourages logs to align with the flow direction. Avoiding blockage of the barrier during routine and low risk flows is beneficial to passing sediment and reducing maintenance costs. The flared opening also facilitates access to outlet constriction for debris removal and maintenance.

### 5 Conclusions

At Cheekeye, the selection of a very low probability, high magnitude design event has led to the adoption of unique design features. Hopefully, it is informative for other professionals to understand the justification for these choices. We welcome further questions and comments, particularly in this period before the barrier is constructed.

Design of debris-flow mitigation involves considerable uncertainty due to the variability of debris flows. The design decisions were made to balance these uncertainties with the many political and geotechnical constraints to achieve the local government’s risk reduction objectives.

### References