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Modeling frequent debris flows to design mitigation alternatives

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Abstract

Debris flows are a common problem in Western Washington State. One persistent location of debris flows is Slide Ridge. Glacial till deposits erode in debris flows which travel to Lake Chelan, passing through the community of Shrine Beach in Washington State. In the early 1990s an unlined debris channel was constructed from the apex of Slide Ridge to Chelan lake and a large debris basin was constructed on the upslope side of the road crossing. Every 1-2 years there is a flow large enough to fill the basin, pass over the road to continue downstream to Lake Chelan, and the road is left covered in debris. The largest debris flows since 2003 have volumes estimated to be between 803 m^3 to 9863 m^3. Samples show the sediment is 85% gravels and dominated by angular cobbles. A number of models are being tested for their ability to predict future debris-flow volume, maximum debris-flow height, and runout distance. Results of the modeling will be used to design and evaluate mitigation measures that include the installation of grates, nets, altering the road configuration, and combination of these measures.

Keywords: debris flow; Cascades; debris channel; mitigation

1. Introduction

Slide Ridge basin is a steep mountainous catchment with rock outcrops split by numerous scree (loose rock) slopes and very sparse areas of soil or vegetation. Based on cursory inspection, the upslope rocks are highly fractured, unstable and are frequently mobilized into debris flows. The occurrence of debris flows in the area has a long history and the GLO maps (circa 1890's) call out the area as "Rock Slide 1000 ft deep". Over geologic time, debris flows have transported sediment from the upper reaches and built an alluvial fan to Lake Chelan. The downstream area of the fan and lakefront have been developed in recent decades despite the prevalence of debris flows. With increased development, the occurrence of road closure due to debris-flow deposition became an issue. The road provides the only year-round access to properties located uplake along the south/west shore.

Debris flows were unmanaged on Slide Ridge until the 1990s. Following a sequence of large debris flows that took multiple paths down the alluvial fan and caused a significant amount of property damage, the County developed an Environmental Impact Statement and options for debris-flow mitigation. The EIS called for construction of a debris flow channel on Slide Ridge to funnel future debris flows to a depositional basin upslope of the road, a culvert under the road to allow for debris passage without overtopping the road, and earthen check dams in the upslope channel to reduce the debris volume transported downstream. These features were built and have been maintained since 1994, but the incidence of debris deposition on the road and around downslope properties has continued. The debris basin was built with 3058.2 m^3 (4000 yd^3) capacity, and the largest recorded debris-flow volume was 12156.4 m^3 (15900 yd^3) in 2005.

This presentation presents the results of a mitigation alternatives evaluation for Slide Ridge. The history of the ridge and debris flows were investigated and aided by a large debris flow occurring during the study time frame. Field data collected following this debris flow were combined with historical data to calibrate a DFLOWZ model. This model was used to predict deposition from a range of different debris-flow volumes, including volumes larger than

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any previously recorded, under a range of mitigation alternatives. Alternatives were developed with the goal of reducing or eliminating road closures, reducing the required maintenance, and reducing the public safety hazard. Alternatives included increasing the size and/ or number and location of debris basins, installing a herringbone style debris breaker, and altering the defined debris-flow channel geometry and slope to increase the volume transported into the lake during a debris flow. This presentation focuses on how the alternatives have been selected and analyzed.

2. Site

Lake Chelan is located on the eastern side of the Cascade Range in Washington State. The lake has an upper and lower basin connected by a constricted, shallow reach known as the Narrows. The upper basin, Wapato Basin, was carved by the Chelan glacier and the lower basin, Lucerne Basin, by the Okanogan-Columbia Valley lobe of the Cordilleran Ice Sheet (Kendra and Singleton, 1987). The lake drains to the Columbia River.

Slide Ridge is on the southwest side of Lake Chelan immediately downstream of the Narrows. It is a steep, mountainous catchment of coarsely crystalline granites, schists, and gneisses with well developed jointing. Vegetation is sparse, and outcrops are separated by scree slopes. Debris flows have built an alluvial fan over time, and many historic remnant channels and flow deposits are visible across the fan. Large debris-flow events have deposited sediment into Lake Chelan over time. In 1967, bathymetry measurements identified 45 m of sediment accumulation in the channel center, and it was inferred to have originated with flows off Slide Ridge (Whetten, 1967). Shoreline bathymetry from 1987 were used to estimate the off-shore slope at 11%. LiDAR was collected over the study area in May, 2018.

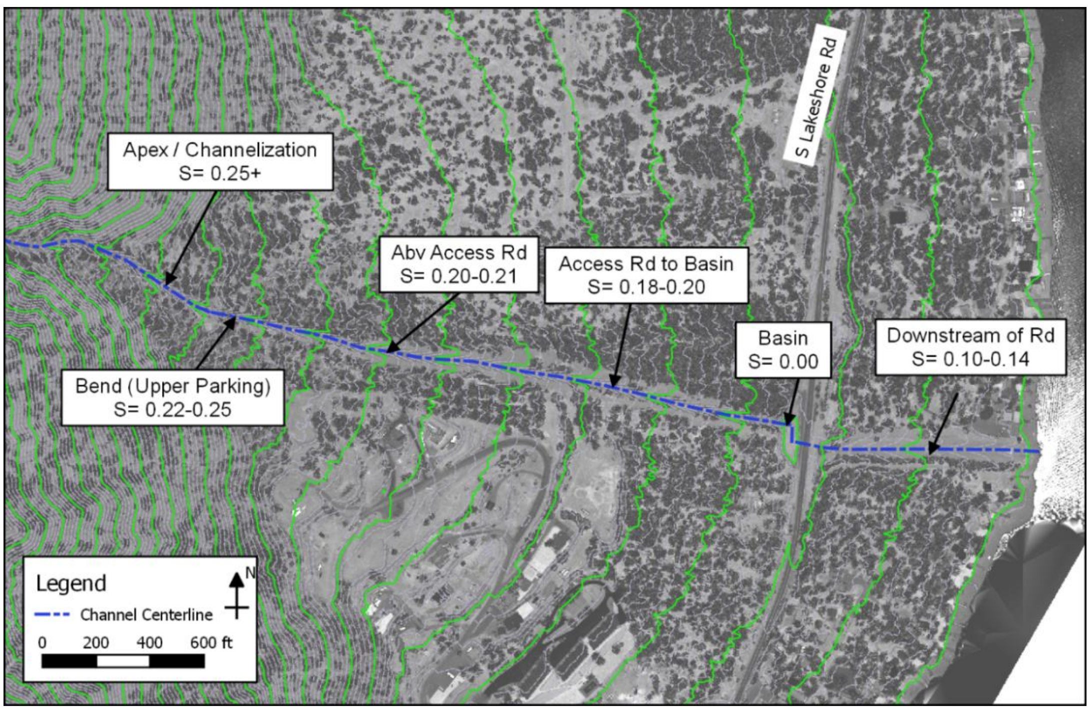

Fig. 1. Channel slopes based on 2018 Lidar for Slide Ridge debris channel.

The existing Slide Ridge geometry channelizes the debris flows from the apex to efficiently convey flows to S Lakeshore Road. Above the apex the upper basin slopes are 45 degrees or more and rapidly contribute water and debris down a dendritic series of steep channels. There is a 30-foot high rock step in the main flow path of this system where the “channel” generally begins. From this step to the apex, hill slopes vary dramatically throughout the year as small events deposit debris and large events scour and transport the debris downstream. Using this surface, measured hillslopes measured from the 2018 LiDAR ranged from 25 to 40% from the step to the apex (Figure 1). The channelization begins at the apex, with a levee attached to the left/north valley wall. The slopes for the channelization gradually decrease from 25% at the apex to 18% above the debris basin as shown in Fig. . The channel slope locally increases to an average of 22% leading into the debris basin, which is flat. Debris flows entering the basin must turn right/south 90 degrees, travel across the flat basin, then turn 90 degrees through a constrictive 2 m (H) by 3.2 m (W) (6.2 ft (H) by 10.5 ft (W)) corrugated culvert. The bottom of the basin is about 4.3 meter (14 ft) below the road surface. This geometry has effectively conveyed small debris flows to the basin, but also encouraged large debris flow deposition over the road.

3. Debris-Flow History

The recent history of debris-flow timing and volumes have been documented locally since the 1970s. In 1972 a large debris flow scoured a channel 4.6-6.1 meter (15-20 ft) deep along the upper hillslope. As this flow traveled downstream, it spread out and deposited among homes and damaging properties downslope of Lakeshore Road. A broad channel was constructed between the road and lake in response with side levees to contain future flows. The channel downstream of the road has slopes ranging from 14% at the upstream end near the culvert outlet to 8-10% at the lake.

In 1990 two large debris-flow events overwhelmed the downstream channel, depositing on the road and houses. A larger mitigation effort was deemed necessary as development around the Lake continued, and in 1994, the deep and narrow debris channel with levees was constructed from the apex to the road to constrain debris flows and convey them down the constructed channel corridor. Plowed earth check dams were included in the upper channel. A debris basin was built on the upstream side of the road with a 3058.2 m^3 (4000 yd^3) capacity. A culvert ran under the road with the plan that debris could pass through the culvert and continue downslope to Lake Chelan. This system remains in place. The channel sections vary in size upstream and downstream of the road. The upstream channel section is confined with a bottom width of 4.3-6.1 meter (14 to 20 ft), steep side slopes, 10.7-13.7 meter (35 to 45 ft) top width and depths of 4.3-5.5 meter (14 to 18 ft). The downstream channel is broader with a bottom width of 12 to 20 feet, gradual side slopes, 55 to 80 feet top width and depths of 2.4-3 meter (8 to 12 ft). Channel and basin are cleaned of sediment and the earthen check dams are re-built following debris flows.

Debris-flow volumes overwhelm the basin capacity every few years, requiring road closure, emergency county excavation of the road, and typically contracted excavation of large debris volumes deposited in the basin and channel. The County recorded volumes for those debris flows requiring basin clean outs for the past 15 years. There are 8 recorded events, and it is suspected that many smaller events occurred within this time period that were not recorded. The volumes recorded reflect only the amount deposited on the road and in the basin. We were able to visit the site within days of the 2017 debris-flow event.

Based on our observations, survey, and field measurements following this event, we estimate an additional 764.6 m^3 (1000 yd^3) of debris/sediment deposited in and around the debris basin that is in addition to the reported volume for basin clean out. Therefore, this estimate has been used to increase volumes from the historic record to account for the entire debris-flow volume (Table 1).

Table 1. Historic debris-flow volumes reported at Lakeshore Road since 2003. Dates were estimated based on available background data (rainfall records, photos), and may not be the exact date of debris flow for all events.

Year	Date	Estimated total volume (m^3)	Estimated total volume (yd^3)
2003	Nov. 11	8,594	11,240
2005	May 10	12,156	15,900
2006	June 11	4,293	5,615
2010	Aug. 3	8,410	11,000
2011	June 10	7,454	9,750
2014	June 13	2,600	3,400
2015	Dec. 9	803	1,050
2017	Oct. 22	7,034	9,200

4. Hydrologic Analysis

Gage records of rainfall intensity and duration in the vicinity of Slide Ridge were analyzed to determine if a correlation exists between observed rainfall and debris-flow volumes. Although there are three nearby rain gages, there is considerable spatial variability in local storm events. The rain gages have varying record lengths, and the longest had recorded data as far back as the 2003 event. Storm data from the dates when large debris flows were documented were used to develop rainfall threshold curves to estimate when a debris flow is likely to occur. A separate threshold curve was created for each gage due to spatial variability in rainfall patterns (Figure 2). Seven of the eight documented debris flows were well represented by the data. The 2011 event was poorly recorded and may have been a more localized thunderstorm.

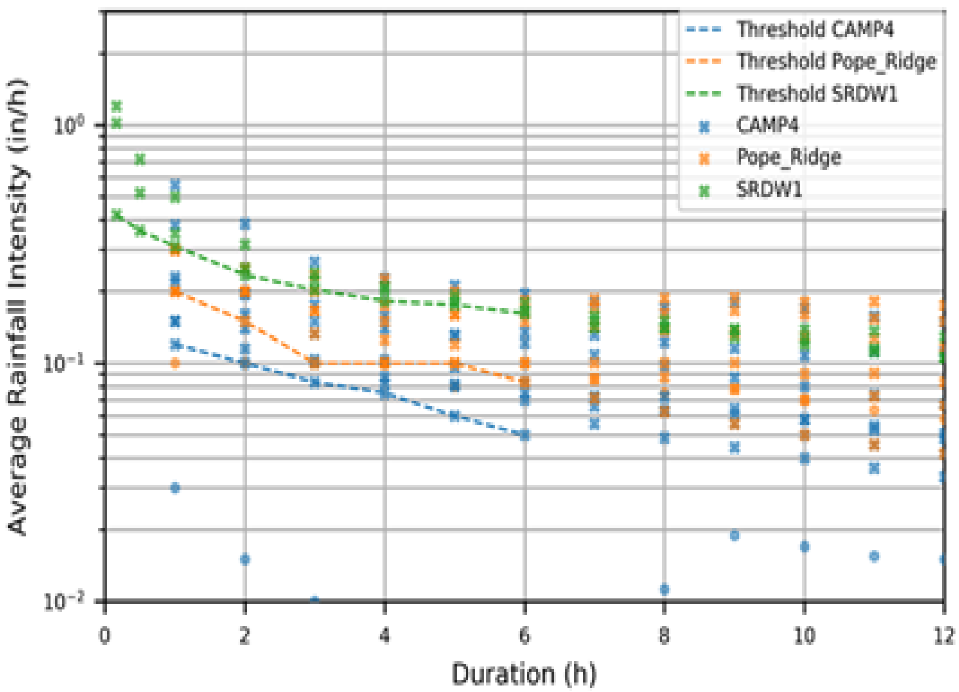

Fig. 2. Duration plot of debris flow events for all 3 rain gages. Historic debris flow events are shown a x. The calculated minimum rainfall thresholds for each gage are shown as dashed lines.

Spearman and Pearson tests showed the 2-hour rainfall duration had the highest statistical correlation between debris flow and rainfall events. A regression curve was fit to the rain gage data for the 2-hour rainfall intensities to provide an approximation of debris-flow volume for predicted average 2-hour rainfall intensities (Figure 3). While highly speculative, this correlation enables managers to begin planning debris-flow mitigation measures.

5. Debris-Flow Characteristics

Field investigations were conducted in 2017 and 2018 to collect sediment samples and evaluate the debris channel. Sediment samples were collected from multiple locations in the defined debris channel (Figure 4). The first site visit was 2 days after the October 2017 event. Samples were collected from the debris slurry downslope of the road (SR1) and in the channel area upstream of the debris basin (SR2). Water contents were measured by weight at 8.2% water for the main part of the debris flow (SR2) and 17.2% water in the runout slurry sample (SR1). The SR1 sample was a suspended liquid, and the SR2 sample from the debris flow was deformable under body weight even with the presence of large angular cobbles. The combination of low water content, silts, and cohesive sediments created the slurry capable of transporting 3 to 4-foot boulders downslope. Three additional samples were collected during a second visit in December, 2017. The full debris channel was investigated during this visit and samples were taken at the apex (SR5), and at major slope breaks on the upper slope (SR3, SR4). There was an abundance of boulders that are commonly 3 to 4 feet in diameter were abundant in the area and evidenced periodic mobilization by debris flows. The matrix of smaller sediment sizes was saved from these samples and sieved (Figure 5). Samples SR3-5 indicate the matrix in the upper slope area was composed of approximately 10% sand.

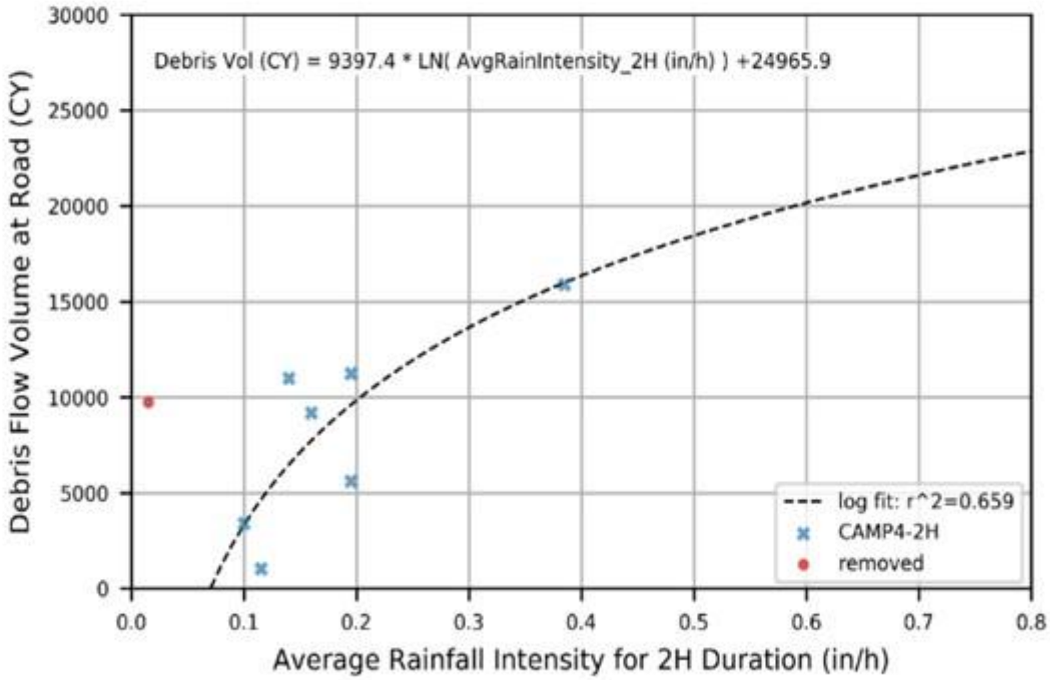

Fig. 3. Regression equation for Slide Ridge debris-flow volume based on Camp4 rain gage intensity (at 2 hour duration). The 2011 event did not appear to be captured by the Camp4 gage and was removed from the fit.

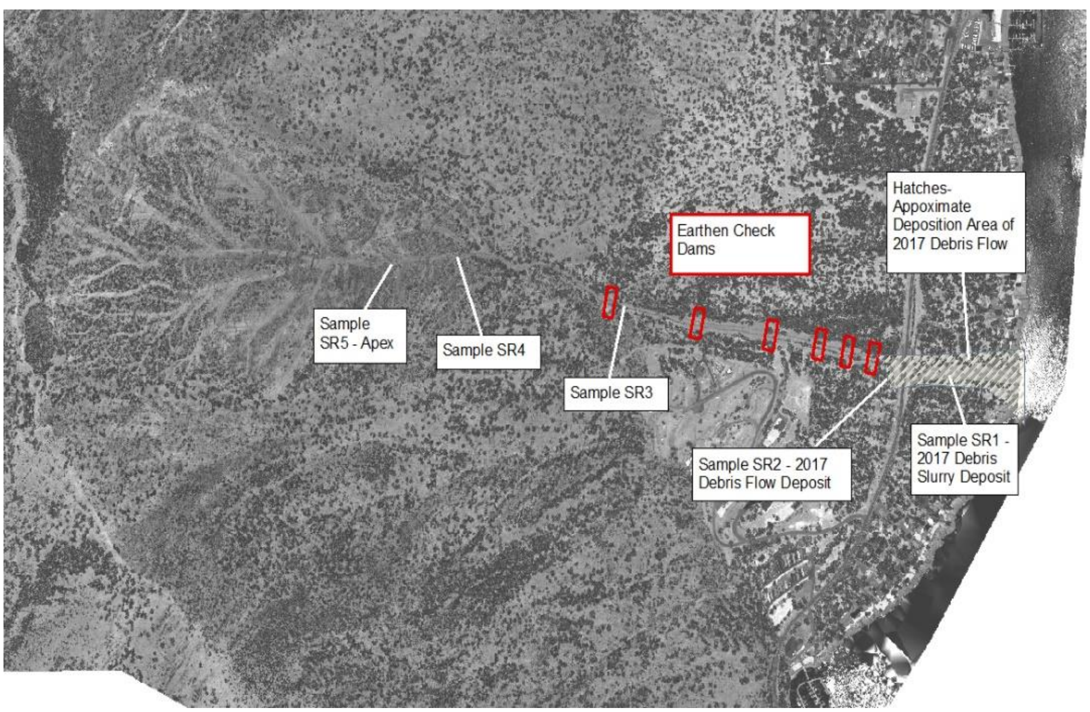

Fig. 4. Locations of sediment samples (call out boxes), earthen check dams (red rectangles), and deposition from the 2017 debris flow on Slide Ridge (grey hatch marks). The background image is the 2018 LiDAR of the site.

The runout length of a debris flow is highly dependent on the water content in the debris-flow front (aka debris-flow snout) and the grain sizes within the debris. Observation and sediment samples indicate that for Slide Ridge the grain size distribution will remain relatively constant. The water content and debris volume will vary with event and act as the main controls over run out lengths and widths. Evidence of rapidly deposited debris snouts were apparent throughout the upper debris channel for flows that did not travel to Lake Chelan. Deposition on the reach between the road and the lake evidenced continued movement of the smaller gravels that had been part of the larger debris-flow matrix. The combination of slope break and culverted basin immediately upstream of the lower reach acted to arrest movement of the largest boulders. Maximum gravel sizes downslope of the road reach 0.5 meter. The debris slurry is much more mobile and extends beyond boundaries of debris deposition. Following the 2017 event, slurry had filled open space in the debris basin, flowed down the road and side ditches, and flows past the debris deposition and into the Lake. It is suspected that slurries associated with large debris events follow this general pattern with a large amount flowing into the Lake.

The earthen dams constructed in the debris channel act as accumulation points for small debris flows and normal bedload transport events that occur between large debris-flow events. Sediment deposits immediately upstream of these dams were observed during field reconnaissance. These check dams may be mobilized during large debris events, adding to debris-flow bulking with distance downslope.

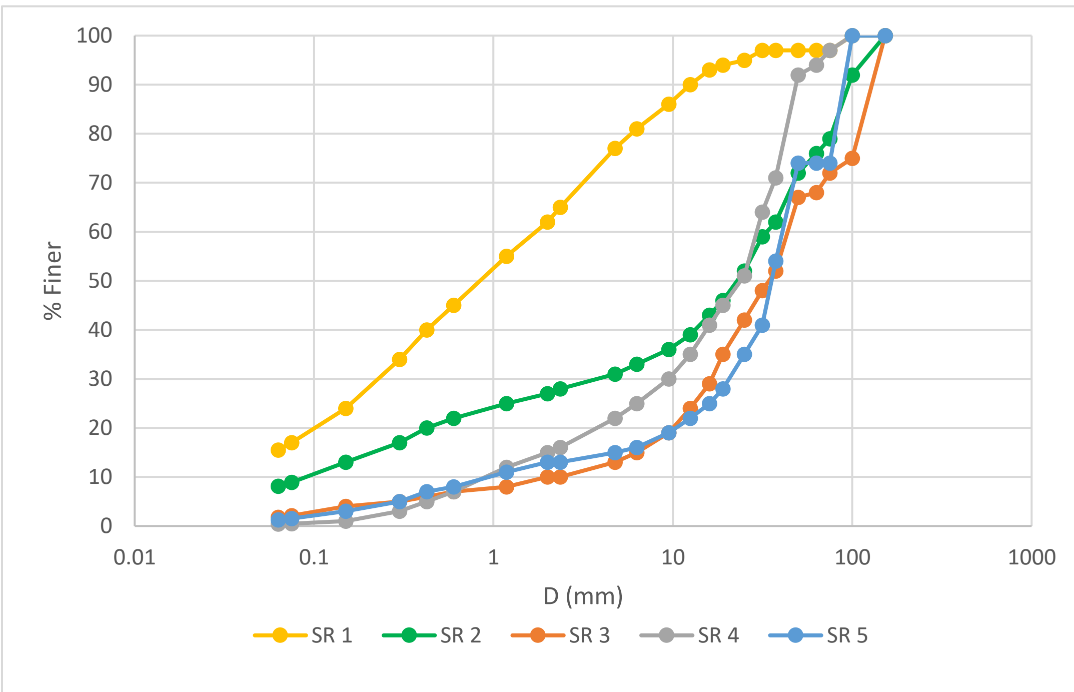

Fig. 5. Grain size distributions for slide ridge samples SR1 to SR5. Samples SR1 and SR2 were taken 2 days after a large debris flow in October, 2017. SR1 is from the debris-flow slurry. SR2 is debris deposited at the road. Samples SR3, SR4, and SR5 were taken from the upper debris channel in December, 2017.

6. Debris-Flow Model

Data were used to calibrate the debris-flow model DFLOWZ. The DFLOWZ model is used to simulate runout length and area for given debris volume events. This information will help determine a mitigation strategy that can reduce maintenance in the future. The model predicts debris-flow runout length and area with a maximum uncertainty of 3 that can be improved upon with calibration data. The model is fully described in Berti and Simoni (2007), Simoni, Mammoliti, and Berti (2011), and Berti and Simoni (2014). We employed the version DFLOWZ_J. Calibration parameters are used to adjust the cross-sectional and planimetric depositional areas for a given debris-flow volume and path. The grain size distribution and water content are used as guides in setting the calibration parameters.

The model was calibrated to within 10% of the documented depositional area and volume from the October 2017 event. The measured grain size and water content were used to guide the calibration. Water content was the least constrained parameter and was the focus of the calibration. Grain size information was assumed to be constant between model runs, while event volume is varied to simulate historic or recurrence interval debris flows. The model does not simulate the slurry deposition downstream of the main debris deposit. Once calibrated to the 2017 event, the model was used to simulate the depositional area and depths associated with the past debris flows documented in Table 1. This was done to evaluate the severity of these debris flows, including when and where debris deposits extended outside the defined channel area. These results were compared to historical photos and evaluated by County staff familiar with the area to provide a qualitative model check. The model calibration was refined using information gained on the past flows.

7. Mitigation Alternatives

The calibrated model was used to aid in conceptual evaluation of mitigation options. Debris flows of larger volume were simulated to predict runout pattern and volume. These present a 'worst case' scenario useful when considering possible mitigation and changes in current management practices at the Slide Ridge site. As described above, the existing system is effective at causing debris deposition at the road crossing, however the existing basin is undersized and debris frequently deposits on the road. Alternatives were developed with the goal of reducing or eliminating road closures, reducing required maintenance, and reducing the public safety hazard. A number of alternatives were investigated, and the most promising were to increase debris retention on the channel slope, alter the water content of the debris flow to arrest downstream movement of the largest boulders, and to alter debris channel geometry and slope to increase the volume of debris transported into the lake.

Trapping and storing the debris flow in a retention basin is a proven management technique to trap debris where it can then be more easily hauled away after a debris flow. The existing basin could be lowered to provide additional volume. A large debris basin could be added into the existing system anywhere upstream of S Lakeshore Road. Locating a debris basin below the apex is a typical management strategy as it allows debris flows to be captured from a known location, without relying on the conveyance channel to contain all events. The debris-flow volumes would require that the basin either be very large, or a series of smaller basin be constructed. In either case there is a large disruption to an already unstable slope with little vegetation.

As an alternative to retaining all the debris during an event, systems have been designed that capture only the largest particles allowing the remaining debris flow to have increased water and sand content. Such a system could result in longer runout distances for the remaining debris flow. Installation of the herringbone style debris breaker detailed in Xie et al. (2016, 2017) could be placed in the upstream channel or at the existing basin. The system would arrest the movement of the larger particles in the flow while allowing the smaller gravels to transport downstream in a slurry with a now relatively larger water content. Therefore the grain size distribution of the debris was adjusted to represent an artificially increased water volume. A rough estimate is that about 3058 m^3 (4,000 yd^3) of 0.3 meter or larger material would reach the road during a 100-year event. If that amount were extracted and retained, the remaining debris would be much more likely to be conveyed to the lake.

An alternative to convey the entire debris flow to the lake in an unlined channel was evaluated. The evaluation included frequent reference to the October 2017 event and historic performance. Different system geometries were evaluated using the DFLOWZ model, following an empirical technique presented by Rickenmann (1999) and with consideration of site geometric constraints. The debris-flow model was applied to determine how debris flows would deposit in the reach from the existing basin to the lake if there were a debris channel for that distance. To simulate this, the current debris basin and road were removed from the model surface. A new debris channel was graded to have a consistent slope from the end of the current channel (just upstream of the existing debris basin) to the lake. Channel slopes of 12% and 14% were tested. The 14% slope is the same as the slope immediately downstream of the road. The slope quickly lessens as the channel approaches the lake and a 12% slope was also tested.

A number of scenarios were tested in the debris-flow model for runout pattern and length. The effectiveness of the alternatives was determined from the ability of the alteration to maintain the debris flow within a contained channel, the relative amount of debris transported to the lake, and the height of the debris at the site of the road. Channelizing the debris flow downstream of the road crossing aiding in transport to the lake. It was quickly found that a channel lined with berms would be necessary to prevent debris deposits from extending into properties near the lakefront while conveying debris to the lake. Different berm and channel geometries were testes, and berm heights over 6 feet did not increase the amount of deposition in the lake. The width of the berm had a greater influence than height on the elevation of the debris deposits. Berms widths up to 75 feet reduced the height of the deposit at the road. Debris-flow runout length was not found to be sensitive to the channel slope. Altering the slope between 12% and 14% had little influence on the area covered by debris deposition. Debris volumes up to 7646 m^3 (10000 yd^3) were contained within the area of the channel for all scenarios. Deposition became significant when the debris volume exceeded 15291 m^3 (20000 yd^3).

8. Summary

Debris flows are a common on Slide Ridge, on the shores of Lake Chelan in Washington State. Glacial till deposits continue to generate debris flows that travel to Lake Chelan, passing through the community of Shrine Beach. In the early 1990s an unlined debris channel was constructed from the apex of the ridge to Chelan lake and a large debris basin was constructed on the upslope side of the road crossing. Every 1-2 years there is a flow large enough to fill the basin, pass over the road to continue downstream to Lake Chelan, and the road is left covered in debris. Debris deposits are 85% gravels and dominated by angular cobbles. Field data were collected and used to calibrate a DFLOWZ model of the system. Modeling enabled formation and testing of a number of mitigation alternatives.

The analysis of mitigation alternatives for debris flows on Slide Ridge in Washington State is under refinement. While a large number of alternatives mitigation options exist, those deemed most appropriate for Slide Ridge included expanding the system of debris storage upslope, increasing conveyance of debris to Lake Chelan through slope and debris channel manipulation, and installation of a herringbone style debris breaker to arrest movement of the largest boulders while increasing relative water content in the debris flow.

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