SLIDE RIDGE CULVERT REPLACEMENT PROJECT

Bridge Feasibility Report and Alternatives Analysis: Appendix A-F

July 2020 | Final Report

kpff
Consulting
Engineers

APPENDIX A

FIELD EXPLORATIONS

APPENDIX A: FIELD EXPLORATIONS

Appendix A contains written and graphical borehole logs presenting the factual and interpretive results of our exploratory program on the subject site. The descriptions of the materials encountered in the subsurface explorations are based on the soil samples extracted from the borings. The sample descriptions are augmented by observation of the drilling action and drill cuttings brought to the surface during field operations. The paragraphs below describe the field operations and sampling procedures used during the geotechnical field explorations.

FIELD EXPLORATIONS

The subsurface exploration program consisted of drilling two test borings at the site on November 28, 2018. The borings were drilled at the approximate expected locations of new abutments for the replacement structure. The borings were designated PG-1 and PG-2 and were advanced total depths of 46.3 and 33.0 feet, respectively. Both PG-1 and PG-2 encountered drilling refusal at the initial drilling locations at depths of 10 and 18.5 feet, respectively. After refusal was encountered, the drilling steel (hollow stem auger) was extracted, the drill rig was relocated approximately 5 feet from the initial drilling location and the augers were advanced to the previous depth of refusal where normal drilling and sampling procedures were resumed.

The approximate locations of the test borings are shown on Figure 2, Site and Exploration Plan. A representative of PanGEO logged the test borings. Soil samples were collected from selected intervals in the borings. The test borings were drilled using a truck-mounted drill rig equipped with hollow stem augers and an automatic hammer sampling system provided and operated by Holocene Drilling of Graham, Washington. The locations of the test borings were measured from existing site features and should be considered no more accurate than this method implies.

SAMPLING METHODS

Standard penetration tests were taken at 5-foot intervals, starting at 5 feet below the existing ground surface and continuing to the bottom of each boring. The number of blows to drive the sampler each 6 inches over an 18-inch interval was recorded and indicated on the boring log. The number of blows to drive the sampler the final 12 inches is termed the SPT resistance, or N-value, and is used to evaluate the strength and consistency/relative density of the soil. The hammer used to perform SPT sampling was an automatic trip mechanism. The SPT N-values reported on the borehole logs are field values, and are therefore not corrected for hammer efficiency, overburden stress or rod lengths.

A geologist from PanGEO was present throughout the field exploration program to observe the borings, assist in sampling, and to prepare a descriptive log of the explorations. Soils were classified in general accordance with the guidelines shown on Figure A-1. Summary boring logs are included as Figures A-2 and A-3, respectively. The stratigraphic contacts shown on the summary log represents the approximate boundaries between soil types; actual stratigraphic contacts encountered at other locations in the field may differ from the contact elevations shown on the logs, and may be gradual rather than abrupt. The soil and groundwater conditions depicted are only for the specific date and locations reported, and therefore, are not necessarily representative of other locations and times.

RELATIVE DENSITY / CONSISTENCY

SAND / GRAVEL			SILT / CLAY		
Density	SPT N-values	Approx. Relative Density (%)	Consistency	SPT N-values	Approx. Undrained Shear Strength (psf)
Very Loose	<4	<15	Very Soft	<2	<250
Loose	4 to 10	15 - 35	Soft	2 to 4	250 - 500
Med. Dense	10 to 30	35 - 65	Med. Stiff	4 to 8	500 - 1000
Dense	30 to 50	65 - 85	Stiff	8 to 15	1000 - 2000
Very Dense	>50	85 - 100	Very Stiff	15 to 30	2000 - 4000
			Hard	>30	>4000

UNIFIED SOIL CLASSIFICATION SYSTEM

MAJOR DIVISIONS		GROUP DESCRIPTIONS	
Gravel 50% or more of the coarse fraction retained on the #4 sieve. Use dual symbols (eg. GP-GM) for 5% to 12% fines.	GRAVEL (<5% fines)	GW	Well-graded GRAVEL
		GP	Poorly-graded GRAVEL
	GRAVEL (>12% fines)	GM	Silty GRAVEL
		GC	Clayey GRAVEL
Sand 50% or more of the coarse fraction passing the #4 sieve. Use dual symbols (eg. SP-SM) for 5% to 12% fines.	SAND (<5% fines)	SW	Well-graded SAND
		SP	Poorly-graded SAND
	SAND (>12% fines)	SM	Silty SAND
		SC	Clayey SAND
Silt and Clay 50%or more passing #200 sieve	Liquid Limit < 50	ML	SILT
		CL	Lean CLAY
		OL	Organic SILT or CLAY
	Liquid Limit > 50	MH	Elastic SILT
		CH	Fat CLAY
		OH	Organic SILT or CLAY
Highly Organic Soils		PT	PEAT

Notes:

1. Soil exploration logs contain material descriptions based on visual observation and field tests using a system modified from the Uniform Soil Classification System (USCS). Where necessary laboratory tests have been conducted (as noted in the "Other Tests" column), unit descriptions may include a classification. Please refer to the discussions in the report text for a more complete description of the subsurface conditions.

2. The graphic symbols given above are not inclusive of all symbols that may appear on the borehole logs. Other symbols may be used where field observations indicated mixed soil constituents or dual constituent materials.

DESCRIPTIONS OF SOIL STRUCTURES

Layered:	Units of material distinguished by color and/or composition from material units above and below	**Fissured:**	Breaks along defined planes
Laminated:	Layers of soil typically 0.05 to 1mm thick, max. 1 cm	**Slickensided:**	Fracture planes that are polished or glossy
Lens:	Layer of soil that pinches out laterally	**Blocky:**	Angular soil lumps that resist breakdown
Interlayered:	Alternating layers of differing soil material	**Disrupted:**	Soil that is broken and mixed
Pocket:	Erratic, discontinuous deposit of limited extent	**Scattered:**	Less than one per foot
Homogeneous:	Soil with uniform color and composition throughout	**Numerous:**	More than one per foot
		BCN:	Angle between bedding plane and a plane normal to core axis

COMPONENT DEFINITIONS

COMPONENT	SIZE / SIEVE RANGE	COMPONENT	SIZE / SIEVE RANGE
Boulder:	> 12 inches	Sand	
Cobbles:	3 to 12 inches	Coarse Sand:	#4 to #10 sieve (4.5 to 2.0 mm)
Gravel		Medium Sand:	#10 to #40 sieve (2.0 to 0.42 mm)
Coarse Gravel:	3 to 3/4 inches	Fine Sand:	#40 to #200 sieve (0.42 to 0.074 mm)
Fine Gravel:	3/4 inches to #4 sieve	Silt	0.074 to 0.002 mm
		Clay	<0.002 mm

TEST SYMBOLS

for In Situ and Laboratory Tests listed in "Other Tests" column.

ATT	Atterberg Limit Test
Comp	Compaction Tests
Con	Consolidation
DD	Dry Density
DS	Direct Shear
%F	Fines Content
GS	Grain Size
Perm	Permeability
PP	Pocket Penetrometer
R	R-value
SG	Specific Gravity
TV	Torvane
TXC	Triaxial Compression
UCC	Unconfined Compression

SYMBOLS

Sample/In Situ test types and intervals

- 2-inch OD Split Spoon, SPT (140-lb. hammer, 30" drop)
- 3.25-inch OD Spilt Spoon (300-lb hammer, 30" drop)
- Non-standard penetration test (see boring log for details)
- Thin wall (Shelby) tube
- Grab
- Rock core
- Vane Shear

MONITORING WELL

- ∇ Groundwater Level at time of drilling (ATD)
- ▼ Static Groundwater Level
- Cement / Concrete Seal
- Bentonite grout / seal
- Silica sand backfill
- Slotted tip
- Slough
- Bottom of Boring

MOISTURE CONTENT

Dry	Dusty, dry to the touch
Moist	Damp but no visible water
Wet	Visible free water

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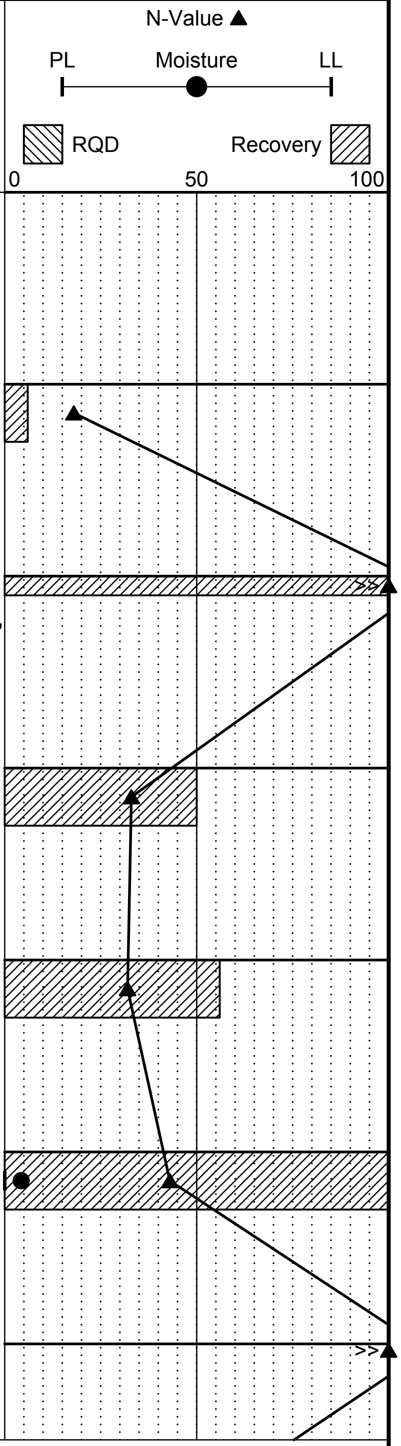
Terms and Symbols for Boring and Test Pit Logs

Figure A-1

Project: Slide Ridge Culvert Replacement
Job Number: 17-425
Location: S. Lakeshore Road, Lake Chelan, WA
Coordinates: Northing: , Easting:

Surface Elevation: 1,210.0ft
Top of Casing Elev.:
Drilling Method: HSA
Sampling Method: SPT w/autohammer

Depth, (ft)	Sample No.	Sample Type	Blows / 6 in.	Other Tests	Symbol	MATERIAL DESCRIPTION
0						Medium dense, brown to orange-brown, poorly graded GRAVEL with silt and sand to silty GRAVEL with sand (GP-GM), moist. Large gravel and cobbles in drill cuttings.
5	1	☒	5 8 10			Low recovery, fine to medium sand, subrounded to subangular gravel.
10	2	☒	14 50/0			Very dense, increase in gravel content of various lithologies. **Practical refusal, grinding on boulder. Move borehole 5 feet south, re-drill to 15 feet and resume sampling.**
15	3	☒	12 19 14			Dense; gravel coarse and angular. Some mechanical fracturing due to drilling action. Decrease in sand content.
20	4	☒	29 17 15			Increase in sand content. Trace pink gravel (rhyolitic).
						Rough drilling.
25	5	☒	22 22 21	GS		Amphibolite and rhyolitic gravel, weathered, with orange-brown silty sand matrix. Sample 5; 14.1% fines.
						Increased rough drilling.
30	6	☒	50/4			No recovery. Drill rig bouncing on cobble/boulder.



Completion Depth: 46.3ft
Date Borehole Started: 11/28/18
Date Borehole Completed: 11/28/18
Logged By: S. Swenson
Drilling Company: Holocene Drilling

Remarks: Location: Station 146+29, 37' Rt. (S. Lakeshore Road stationing)

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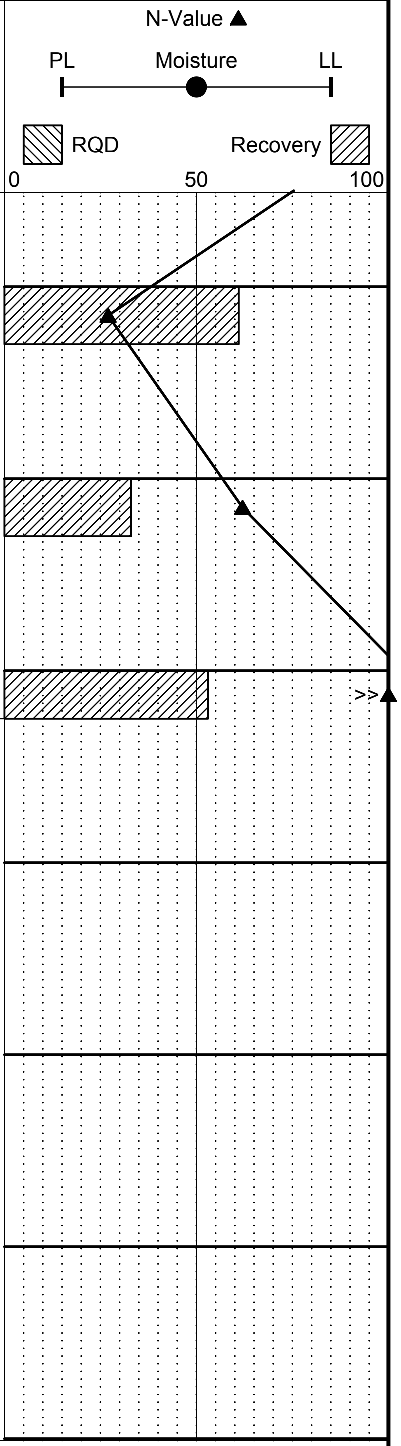
LOG OF TEST BORING PG-1

Figure A-2

The stratification lines represent approximate boundaries. The transition may be gradual.

Project:	Slide Ridge Culvert Replacement	Surface Elevation:	1,210.0ft
Job Number:	17-425	Top of Casing Elev.:	
Location:	S. Lakeshore Road, Lake Chelan, WA	Drilling Method:	HSA
Coordinates:	Northing: , Easting:	Sampling Method:	SPT w/autohammer

Depth, (ft)	Sample No.	Sample Type	Blows / 6 in.	Other Tests	Symbol	MATERIAL DESCRIPTION
						Medium dense, brown to orange-brown, poorly graded GRAVEL with silt and sand to silty GRAVEL with sand (GP-GM), moist. Large gravel and cobbles in drill cuttings. *(Continued)*
35	7	☒	13 12 15			Gravel weathered.
40	8	☒	39 34 28			Very dense. Mechanically fractured drill fragments of amphibolite and tonalite.
						Smooth drilling action to 43', then rough drilling.
45	9	☒	18 35 50/3			Practical drilling refusal. Drill teeth expended.
						Bottom of boring. Groundwater not observed at time of drilling.
50						
55						
60						
65						



Completion Depth:	46.3ft
Date Borehole Started:	11/28/18
Date Borehole Completed:	11/28/18
Logged By:	S. Swenson
Drilling Company:	Holocene Drilling

Remarks: Location: Station 146+29, 37' Rt. (S. Lakeshore Road stationing)

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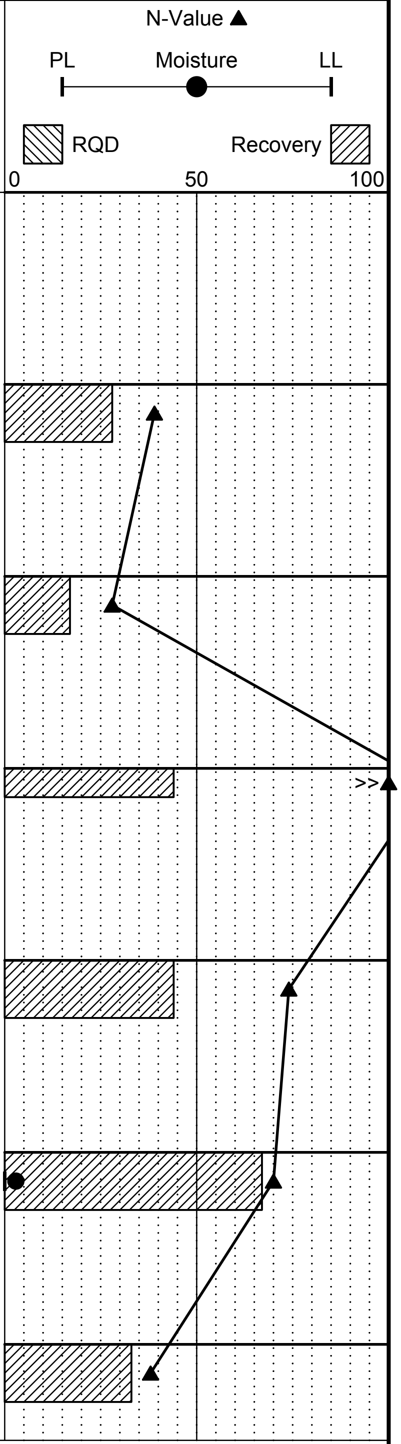
LOG OF TEST BORING PG-1

Figure A-2

The stratification lines represent approximate boundaries. The transition may be gradual.

Project:	Slide Ridge Culvert Replacement	Surface Elevation:	1,208.0ft
Job Number:	17-425	Top of Casing Elev.:	
Location:	S. Lakeshore Road, Lake Chelan, WA	Drilling Method:	HSA
Coordinates:	Northing: , Easting:	Sampling Method:	SPT w/autohammer

Depth, (ft)	Sample No.	Sample Type	Blows / 6 in.	Other Tests	Symbol	MATERIAL DESCRIPTION
0						Dense, light brown to gray, silty GRAVEL with sand to poorly graded GRAVEL with silt and sand (GP-GM), moist.
5	1	☒	13 20 19			Gravel mostly mechanically fractured due to drilling action. Sand fine to medium, gravel subrounded to subangular. Pink granite/rhyolitic gravel. Very rough drilling.
10	2	☒	23 10 18			Very dense. Mechanically fractured amphibolite fragments. Drill rig bouncing on boulder/cobble.
15	3	☒	20 50/3			
						Practical refusal at 18.5 feet. Move 5 feet south, re-drill to 20 feet and resume sampling.
20	4	☒	12 33 41			Mechanically fractured tonalite and amphibolite gravel with orange-brown silty sand matrix; gravel subrounded to subangular.
25	5	☒	14 32 38	GS		Gravel fine to coarse; increase in sand content. Sample 5; 14.1% fines.
30	6	☒	17 18 20			Dense, gray to brown, poorly graded GRAVEL with silt and sand, moist. Decreasing sand content.



Completion Depth: 33.0ft
Date Borehole Started: 11/28/18
Date Borehole Completed: 11/28/18
Logged By: S. Swenson
Drilling Company: Holocene Drilling

Remarks: Location: Station 145+78, 34' Rt. (S. Lakeshore Road stationing)

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LOG OF TEST BORING PG-2

Figure A-3

The stratification lines represent approximate boundaries. The transition may be gradual.

Project:	Slide Ridge Culvert Replacement	Surface Elevation:	1,208.0ft
Job Number:	17-425	Top of Casing Elev.:	
Location:	S. Lakeshore Road, Lake Chelan, WA	Drilling Method:	HSA
Coordinates:	Northing: , Easting:	Sampling Method:	SPT w/autohammer

Depth, (ft)	Sample No.	Sample Type	Blows / 6 in.	Other Tests	Symbol	MATERIAL DESCRIPTION	N-Value ▲ PL Moisture LL ▧ RQD Recovery ▨ 0 50 100
						Rough drilling, practical drilling refusal at 33 feet. Bottom of boring. No groundwater observed during drilling.	
35							
40							
45							
50							
55							
60							
65							

Completion Depth:	33.0ft
Date Borehole Started:	11/28/18
Date Borehole Completed:	11/28/18
Logged By:	S. Swenson
Drilling Company:	Holocene Drilling

Remarks: Location: Station 145+78, 34' Rt. (S. Lakeshore Road stationing)

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LOG OF TEST BORING PG-2

Figure A-3

The stratification lines represent approximate boundaries. The transition may be gradual.

APPENDIX B

LABORATORY TESTING

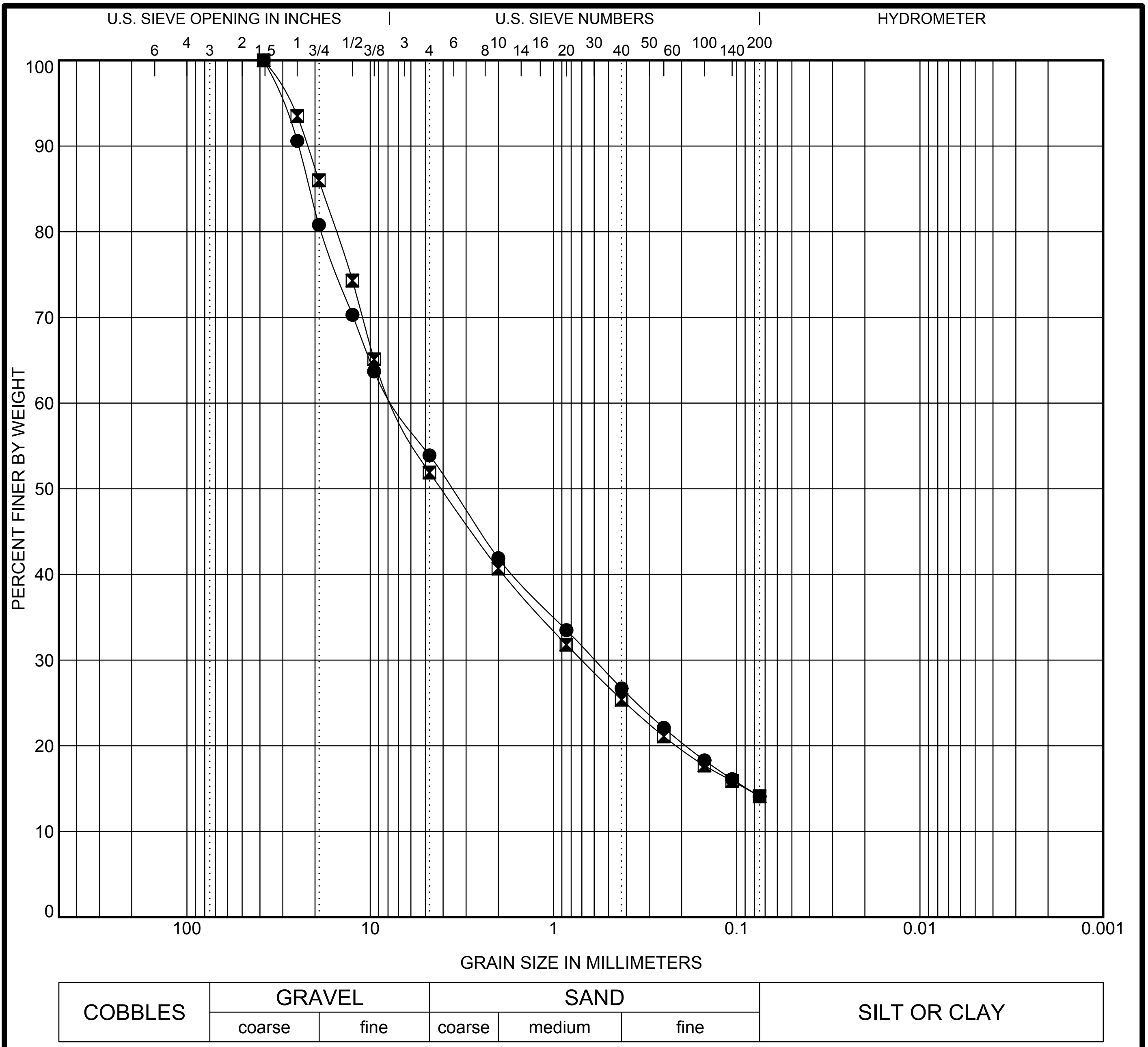
APPENDIX B: LABORATORY TESTING AND RESULTS

This appendix contains descriptions of the procedures and results of physical (geotechnical) laboratory testing conducted on soil samples retained during the field explorations at the Slide Ridge culvert replacement project site. The methodology of the soil sampling from the borings is described in Appendix A. The samples were tested to determine basic physical index properties of the soils for purposes of classifying the material types encountered and to measure or correlate parameters used in the geotechnical design.

Laboratory testing was performed in general accordance with the following ASTM Standard Test Methods (STM):

D 2216	STM for Laboratory Determination of Water (Moisture) Content of Soil and Rock
D 422	STM for Particle-Size Analysis of Soils

Grain size analyses are presented on Figure B-1. Moisture contents are included on the logs of test borings in Appendix A.



	Specimen Identification		Classification	LL	PL	PI	Cc	Cu
●	**PG-1**	**@ 25.0 ft.**	**SILTY GRAVEL with SAND(GM)**	**NP**	**NP**	**NP**		
☒	**PG-2**	**@ 25.0 ft.**	**SILTY GRAVEL with SAND(GM)**	**NP**	**NP**	**NP**		

	Specimen Identification		D100	D60	D30	D10	%Gravel	%Sand	%Silt	%Clay
●	**PG-1**	**25.0**	**38.1**	**7.325**	**0.595**		**46.1**	**39.8**	**14.1**	
☒	**PG-2**	**25.0**	**38.1**	**7.28**	**0.699**		**48.1**	**37.8**	**14.1**	

GRAIN SIZE 17-425 SLIDE RIDGE CULVERT REPLACEMENT.GPJ PANGEO.GDT 2/15/19

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GRAIN SIZE DISTRIBUTION

Project: Slide Ridge Culvert Replacement
Job Number: 17-425
Location: S. Lakeshore Road, Lake Chelan, WA

Figure B-1

APPENDIX C: TECHNICAL MEMORANDUM

GEOTECHNICAL DATA REVIEW AND PRELIMINARY RECOMMENDATIONS SLIDE RIDGE CULVERT REPLACEMENT

PanGEO
INCORPORATED
Geotechnical & Earthquake Engineering Consultants

TECHNICAL MEMORANDUM

TO: Anne Streufert, P.E., S.E.
KPFF Consulting Engineers

PREPARED BY: Robert E. Kimmerling, P.E., L.E.G.

SUBJECT: **GEOTECHNICAL DATA REVIEW AND PRELIMINARY RECOMMENDATIONS**
SLIDE RIDGE CULVERT REPLACEMENT
Chelan County, Washington

PROJECT NO.: 17-425

DATE: August 17, 2018

PanGEO, Inc. (PanGEO) prepared this technical memorandum summarizing the results of our review of existing geotechnical information and our recommendations for preliminary design of the subject project. This summary is based on a review of readily available geologic and geotechnical information, site history and data provided by Chelan County, a site reconnaissance and site-specific LIDAR data collected by the project team.

Preliminary, conceptual foundation recommendations are also provided for the culvert replacement structure.

EXISTING INFORMATION REVIEW

The review of existing and available information included the following:

- Geologic mapping and accompanying pamphlet
- Google Earth^{TM} satellite imagery
- Final Environmental Impact Statement (FEIS) for Chelan County Public Works Slide Ridge Control Channel, tentative issue date December 15, 1993.
- Tabulated history of debris flow events and estimated or computed volumes
- LIDAR mapping of the project area and Slide Ridge

Soil and Rock

Geologic mapping of the project area is available at the 1:100,000 scale of the Chelan 30′ by 60′ Quadrangle[1]. The project area, including Slide Ridge, is part of the Chelan Mountains Terrain. Bedrock and surficial geologic units identified by this mapping in the Slide Ridge area include:

Amphibolite and Hornblendite Migmatite (Kca) – Includes pods and lenses of hornblendite and dark amphibolite ranging from centimeters to several hundred meters across.

Tonalite (Kct) – Hornblende-biotite and biotite tonalite. Rock is commonly strongly gneissic in outcrop. Locally the tonalite is cut by lighter colored tonalite dikes.

Rhyolite dikes (Tcrd) – Predominantly white to yellow or brown rhyolite with small phenocrysts of plagioclase and/or quartz.

Incipient blockslides (Qlsi) – Large nonrotated mass of bedrock extensively crevassed as a result of slight movement toward nearby free faces. Crevasse-arrow symbol shows direction of movement.

Alluvium (Qa) – Alluvium includes poorly sorted gravelly sand or sandy gravel of alluvial fans. The fans of Shrine and Hollywood Beaches are of this material, and also constitute the lower slopes of the glacially eroded trough now occupied by Lake Chelan.

In addition to the above summarized geologic information, a feature named Granite Slide is mapped upslope and west of the project area and encompasses an area from the crest of Slide Ridge and the entire northern flank and ridge that separates the drainage above Shrine Beach and that of Hollywood Beach. The pamphlet that accompanies the Chelan 30′ by 60′ Quadrangle map discusses this mass as follows:

> “Two incipient blockslides perched on steep slopes 1,000 m above water bodies—one above Lake Chelan, another above Lake Wenatchee—could be severe hazards during future large earthquakes. Although both of these incipient slides

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[1] Tabor, R.W., Frizzell, Jr., V.A., Whetten, J.T., Waitt, R.B., Swanson, D.A., Byerly, G.R., Booth, D.B., Hetherington, M.J., and Zartman, R.E., 1997. Geologic Map of the Chelan 30-Minute by 60-minute Quadrangle, Washington, Miscellaneous Investigations Series, Map I-1661, Department of the Interior, U.S. Geologic Survey.

> may have been in their present form and positions during the largest historic earthquake of the region (in 1872), it is only a matter of time before they will fail and descend to the lakes either gradually or swiftly. The existence of ancient slide deposits in Lake Chelan is suggested by the lake-bottom topography (Whetten, 1967) and the narrowing of the lake (see cross section B-B', map sheet). During the 1872 earthquake a small slide 6 km north of Entiat swept into the Columbia River (Russell, 1900, p. 202). The Columbia is now a series of reservoirs, and any future slides will descend into lake water, where displacement could be locally devastating. Should one of the incipient blockslides above Lake Chelan or Lake Wenatchee suddenly detach, it would probably acquire great speed and momentum on its descent. When the slide enters a lake, water would be suddenly displaced to generate a wave that could devastate the shoreline area for many meters if not tens of meters above lake level. Water thus catastrophically displaced by landslides has devastated shoreline areas in Norway, Japan, and Alaska (Miller, 1960), and at Vaiont Reservoir, Italy (Kiersch, 1964)."

SITE RECONNAISSANCE

A visual reconnaissance of the project site was made by representatives of PanGEO on May 25, 2018. The first portion of the reconnaissance traversed up the existing control channel from South Lakeshore Road to the apex of the alluvial fan. The primary purpose of this part of the reconnaissance was to assess the topography with respect to the potential for a debris flow event to avulse, or "jump" from the current flow channel to alternative flow channel(s) down the alluvial fan. It was judged that the potential for such an avulsion was relatively low provided that:

a) The debris flow event is of similar size and energy to those historically observed, and,

b) The apex of the channel is not choked with debris and rockfall (i.e., maintained in a manner consistent with such maintenance that the County has provided following the construction of the Control Channel, FEIS, 1993).

The only anomaly observed that could potentially be in conflict with the above conclusion is the presence of automobile-sized boulders exposed in the channel sidewalls midway down the fan. The presence of this size of material many hundreds of feet below the apex of the fan suggests energies associated with a debris flow event much larger than historically observed.

The second portion of the reconnaissance attempted to access the top of Granite Slide from Slide Ridge in hopes of observing surficial clues as to why this feature is expressly mapped as “incipient slide block” on the Chelan 30′ by 60′ Quadrangle. While this reconnaissance afforded good views of the drainage basin above Hollywood Beach, direct access into the upper portion of the mapped area of Granite Slide has hampered by dense vegetation and limitations of time. The views into the basin above Hollywood Beach did provide some insight as to potential rockfall sources and mechanisms, including large-scale toppling potential in and on the ridge that forms the common flank between the two drainage basins.

SITE SEISMICITY

The project site is located within the uplifted bedrock complex of the Cascade Range. This area is not as seismically active as is the area west of the Cascades but does experience seismic activity. The nearest fault to the site that is thought to be potentially active is the Class B Straight Creek/Evergreen Fault system. This is a north-south trending feature mapped about 50 miles west of the site (Lidke, 2016; Tabor et al., 1993). No faults currently thought to be active intersect with the project site.

At a distance of approximately 65 miles south and southeast of the project site is the Yakima Fold Belt, an area of roughly east-west trending folds along the west margin of the Columbia Plateau. The folds began to develop originally in the late Miocene and deformation may continue into the present day. Seismicity on the Columbia Plateau tends to be generally shallow and associated with thrust faults along the north limbs of the anticlinal structures. Seismicity in the fold belt is generally limited to micro-earthquake swarms that may contain up to 100 individual events in a limited time frame. These occur at shallow depths, normally 3 to 5 kilometers (DOE, 1987, Tillson, 1989). These events rarely exceed 3.5 in magnitude. Concentrations of swarms have occurred in the area of the Saddle Mountains on the north margin of the Pasco Basin, and in the Walla Walla area.

The largest historical earthquake observed to date in Washington, with an estimated magnitude of approximately 6.5 to 7.0, occurred on December 14, 1872 in the northern Cascade Mountains. Some recent research and thinking suggests that this event may have taken place on a postulated Chelan Seismic Zone (Crider, et al., 2003), which is located about 10 to 15 miles to the southeast of the project site within a prolific zone of micro-earthquakes referred to as the Entiat cluster.

Seismic Design Parameters

For seismic design, an acceleration coefficient of 0.139g is recommended per the current acceleration map in AASHTO (2017). The recommended acceleration coefficient is based on expected ground motion at the project site that has a 7 percent probability of exceedance in a 75-year period (approximately 1000-year return period).

Design response spectra presented in AASHTO (2017) are considered appropriate for seismic design of the bridge. A horizontal response spectral acceleration coefficient at a period of 0.2 seconds (S_S) is 0.306 and the horizontal response spectral acceleration coefficient at a period of 1.0 seconds (S_1) is 0.099.

Based on understanding of the regional geology, the soils at the site are preliminarily considered Site Class D. The associated site factors, F_{pga}, F_a and F_v, are 1.522, 1.555 and 2.40, respectively, from which values for A_S, S_{DS} and S_{D1} of 0.212, 0.477 and 0.237, respectively, are obtained. The site is therefore in Seismic Performance Zone 2. The site class may be re-evaluated based on site-specific field explorations and test borings.

Liquefaction Potential

Based on our understanding of the regional geology and characteristics of the alluvial fan of Shrine Beach, liquefaction is not expected to develop at the site under the design earthquake conditions due to the lack of loose, granular and saturated soils in the upper 80 feet of the soil profile and the relatively low peak ground acceleration of the design event. Therefore, no special design considerations are currently recommended regarding liquefaction.

GEOLOGIC HAZARDS

The following sections discuss geologic hazards considering the information review and collection described above.

Debris Flow Events

Slide Ridge and the drainage basin above Shrine Beach have a persistent history of producing mass wasting events. As described in the FEIS for the Slide Ridge Control Channel, “Granite Slide was subjected to a major storm and runoff event on June 10, 1972 that scoured a 15-foot deep channel and deposited debris in the area of South Lakeshore Road and adjacent residential buildings. Since that time, several storms and debris flows have filled that channel, and created debris dams that caused creation of additional storm channels leading to South Lakeshore Road.” The FEIS further states: “The Shrine Beach fan has many debris flow channels with levees indicating flood events throughout its history. In fact, Slide Ridge was named so by early settlers because of the frequent mud and debris flows.”

The FEIS also states that: "Debris flows larger than those of the historic past are unlikely if the character of the basin remains unchanged due to the small size of the drainage area. The County Engineer has estimated previous slide debris occurrences which have blocked the south Lakeshore Road at 5000 - 7000 cubic yards of material deposition. Current literature and field observations indicate that an approximate range of 3,500 to 11,000 cubic yards of debris could be produced per occurrence." [citations omitted]

Information provided by Chelan County on the frequency and volume of debris flow events since the time of FEIS preparation (~1993) are generally consistent with the above ranges, the exception being a 12,900 cubic yard event in 2005. The presence of very large boulders in the channel sidewalls as discussed under Site Reconnaissance, above, does suggest the potential for larger debris flow events. However, the recurrence interval for such an event is difficult, at best, to establish without historical or other substantiating temporal data.

Seismic-induced Landslide

As noted above, there is potential for a seismic event to set the incipient slide mass in motion. However, the 1872 shock, a relatively strong event, did not do so, even though a similar slide was induced along the Columbia River at Ribbon Cliff by that event. Current thinking, although not reflected in the probabilistic-based seismic design code, is that the recurrence interval along the fault structure responsible for the 1872 event is relatively long, on the order of 1,000 to 5,000 years. Therefore, inclusion of consideration of such an event (i.e., earthquake or earthquake induced landslide) as part of this project's design criteria would probably be overly-conservative and certainly cost-prohibitive.

NEW STRUCTURE FOUNDATIONS

From a geotechnical engineering perspective, both deep and shallow foundations are conceptually feasible for support of the replacement structure for the existing culvert. However, scour considerations may result in bearing depths for spread footings that are undesirably deep.

Deep foundations consisting of either driven piles or drilled shafts are both considered feasible, although drilled shafts are expected to be a higher cost option relative to driven piles. However, drilled shafts have the advantage of being able to penetrate obstructions such as boulders that could cause difficulties for driven piles. Due to the presence of cobbles and boulders in the alluvial fan soil profile, high displacement piles such as cast-in-driven shell (WSDOT) piles or pre-cast, pre-stressed concrete piles are not recommended as these types of piles may refuse on shallow obstructions or be difficult to drive within location tolerances. Low-displacement piles such as heavy H-pile sections with driving shoes have been found to obtain penetration with less location control difficulties in these types of soil profiles.

Micropiles are also geotechnically feasible, but the slenderness of these types of elements make them more vulnerable to scour damage and less resistant to lateral load effects.

The following table summarizes pros and cons for foundation options:

Option	Pros	Cons
Spread Footings	• Relatively low cost • Ease of construction if bearing elevation is for scour protection does not require shoring	• Depending on scour depth, large excavations and/or shoring may be required for construction
Driven H-Piles	• Low to Moderate axial resistance achievable (200-400 kips ultimate; 110-220 kips factored) for pile lengths in the range of 60 to 80 feet • Local contractors may elect to self-drive piles	• Moderate potential for pile damage during driving, even when fitted with pile driving tip protection • Less resistance to scour damage relative to larger diameter drilled shafts
Shafts	• High capacity achievable (3,500-5,000 kips ultimate) depending on diameter and length of shaft • Can penetrate obstructions, including large boulders	• Likely higher overall cost relative to piles • Normally requires specialty subcontractor • High equipment mobilization cost due to relatively remote site access

STRUCTURE APPROACH EMBANKMENTS

Some raising of the approach roadway may be necessary to match the geometry of the replacement structure. Due to the granular nature of the existing roadway and alluvial fan foundation soils, settlement of new approach embankment is expected to be negligible provided the embankment is constructed in accordance with the WSDOT *Standard Specifications* (2018) for Roadway Embankment. Side and end slopes of approach embankments should be constructed no steeper than 2H:1V to maintain stability and reduce the potential for erosion. Locally derived material is likely suitable for construction of embankments.

CONSTRUCTION CONSIDERATIONS

The following items should be considered during conceptual plan development for the project.

1. Temporary pits, slopes or shoring may be required to construct new foundations. The design of temporary shoring and/or slopes should be the responsibility of the contractor.

2. Pile location and alignment should be controlled by driving piling with fixed top and bottom leads. If pile leads are fixed at the top only (i.e., “flying” leads), a fixed template should be used to control location and alignment of piles.

3. Excavation for shafts foundations will likely require casing to control sidewall and base stability. Shaft excavations are likely to encounter caving ground conditions if casing is not used.

ADDITIONAL STUDIES

Additional geotechnical services are recommended to support final design and Plan, Specification and Estimate development. These services should include, as a minimum:

1. Subsurface explorations at the locations of proposed new foundations.

2. Engineering analysis to provide site-specific design parameters for bridge foundations, including axial resistances and soil-structure interaction spring constants for lateral analysis.

3. Development of Special Provisions for geotechnical elements such as shaft foundations or driven piles.

CLOSURE

PanGEO prepared this technical memorandum for KPFF and Chelan County to support the Slide Ridge culvert replacement project. The recommendations contained in this technical memorandum are preliminary in nature and based only on a visual site reconnaissance, review of pertinent site and subsurface information, and our understanding of the project.

The scope of PanGEO’s work did not include environmental assessments or evaluations regarding the presence or absence of wetlands or hazardous or toxic substances in the soil, surface water or groundwater at this site. PanGEO does not practice or consult in the field of safety engineering. PanGEO does not direct the contractor’s operations and cannot be held responsible for the safety of personnel other than our own on the site; the safety of others is the responsibility of the contractor.

PanGEO is pleased to support KPFF and Chelan County with geotechnical engineering recommendations related to this bridge replacement project. If you have any questions regarding this technical memorandum, please call (206) 262-0370.

Appendix F

Slide Ridge Debris Flow – Hydraulic Alternatives Analysis Report

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INDICATOR
ENGINEERING

JUNE 13, 2019

TECHNICAL REPORT

TO:	**FROM:**
Anne Streufert, PE (KPFF)	**Pat Flanagan, PE**
Jason Pang, PE (KPFF)	**Joanna Curran, LG**
CC:	**PROJECT:**
Paula Cox & Jason Detamore, Chelan County Public Works	**10029**
Via: Email	

RE: Slide Ridge Debris Flow – Alternatives Analysis Hydraulic Report - Revised

This document summarizes the hydrologic, hydraulic and geomorphic analysis of the Slide Ridge debris flow with a focus on the County's S Lakeshore Road crossing. Alternatives to manage the debris flows are presented with the goals of to reduce road closures, operations and maintenance (O&M) and public safety hazard. This report was originally prepared in October 2018, and this document revises and completes section 5 to discuss the preferred alternative in support of the bridge Type, Size and Location (T,S&L) study (KPFF 2019).

The document is presented in the following sections:

1 HISTORIC DEBRIS FLOWS

SITE LOCATION

The project site is located along S Lakeshore Road on the southwest side of Lake Chelan, where the Slide Ridge debris flow channel crosses the road (Figure 1). The road provides the only year-round access to properties located uplake (north and west) along the south/west shore of Lake Chelan. Slide Ridge is also labeled "Granite Slide" on many historic and topographic maps.

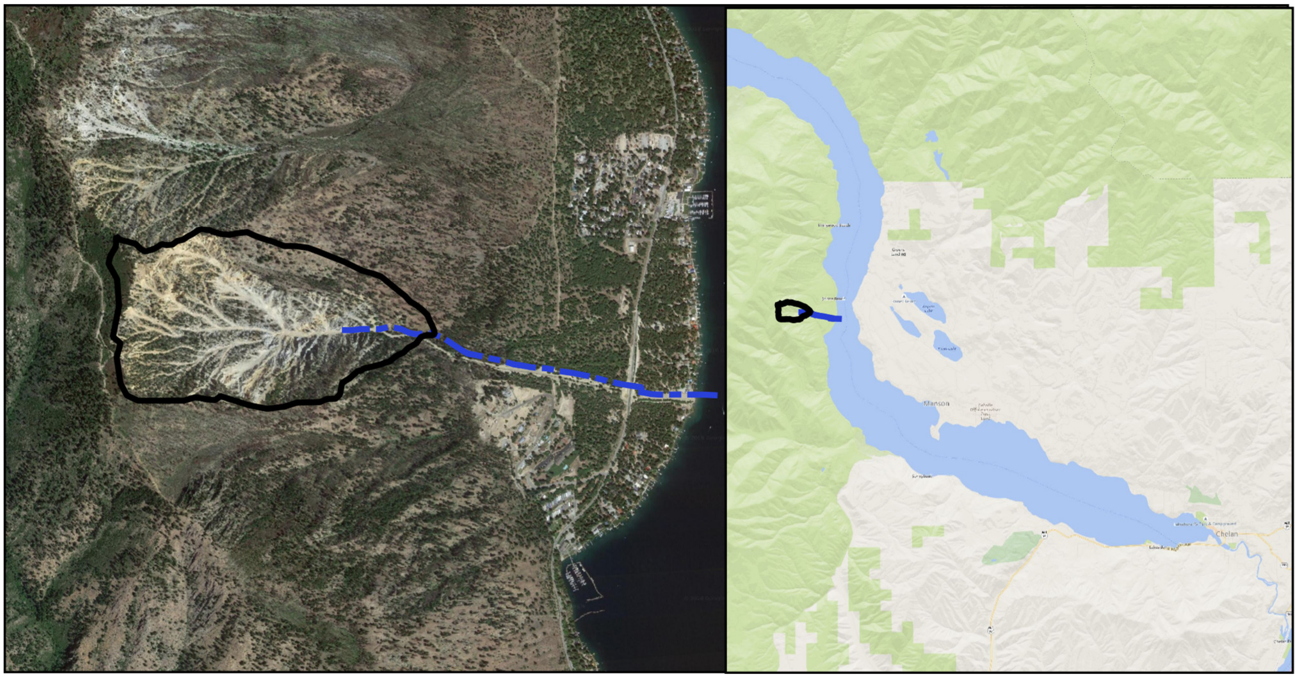


Figure 1. General location of Slide Ridge basin and project site. The upper basin boundary (black) and channel (blue) are shown in both the local map on the left and the area map on the right.

SITE HISTORY

The 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 scales, debris flows have transported sediment from the upper reaches to the basin apex, and then built an alluvial fan between the apex and Lake Chelan. Many historic remnant channels are still visible across the fan, which is where roads and development has occurred.

The recent history of debris flow timing and volumes is of most interest to the current study as the problem to be mitigated. The following general history is based on the 1993 Slide Ridge EIS:

- 1972: Large Debris Flow occurs and closes S Lakeshore Road. Scours Channel 15-20 feet deep in new location. Escapes channel downstream and flows between lake homes damaging several properties.
- 1970's (later, exact date unknown): Broad flood channel is constructed from S Lakeshore Road downstream to the lake to contain debris flows.
- 1990: Two large events, first in the summer and second in November, caused significant debris flows to "swarm around homes and block the County road (sic)". The November event escaped the primary flow channel damaging different homes than the summer event.
- 1994: As a result of the 1993 EIS a deep and narrow debris channel with levees was constructed from the apex to S Lakeshore Road to contain debris flows. This channel was designed to constrain the path of debris flows in the fan and convey the flows down the constructed channel corridor. Plowed earth check dams were included in the upper channel. A *small* debris basin was constructed on the upstream side of the road crossing, which was made with a primary culvert and small secondary overflow culvert.
- 1994-2018: The system geometry is largely unchanged. Fires may have occurred in the upper basin, but do not appear to have had a significant effect on flows due to the sparse vegetation. Check dams are periodically maintained. Debris flows are believed to have been contained within the constructed

channel upstream of the road. The debris basin, channel upstream and downstream, culvert crossings and check dams have all required routine maintenance, typically every 1 to 5 years.

RECENT DEBRIS FLOW HISTORY

The debris basin can hold 4,000 CY of sediment based on the 2017 survey by Chelan County. 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 has provided reported volumes for clean out events over the last 15 years. Based on observations, survey, and field measurements following the October 2017 event, we estimate the county crews cleared approximately 1,000 cubic yards (CY) of debris/sediment from the road. This is in addition to the reported volume and, therefore, this estimate has been used to increase volumes for the historic record to account for the entire debris flow volume. Table 1 shows the debris flow volume reported and the estimated total volume that accounts for the emergency County clean up volume. The estimated total volume does not include debris flow that escaped downstream to the lake via three observed paths: the downstream channel; north on the road then east along private roads and between homes to the lake; and south along the road ditch to the marina parking lot and lake.

Table 1. Historic debris flow volumes reported at S Lakeshore Road since 2003. (CY = cubic yards)

Year	Date[1]	Reported volume, CY	Estimated total volume, CY	Notes
2003	Nov 18	10,240	11,240	Many events in October may have activated large amounts of debris.
2005	May 10	12,900	15,900	Largest event. Debris in lake, did not appear to overtop downstream levee. 12 ft (approx.) high at road.
2006	Jun 11	4,615	5,615	
2010	Aug 3	10,000	11,000	June and August events. June may have made available large amounts of debris for August event.
2011	Jun 10	8,750	9,750	Missed rain gages. May be localized thunderstorm.
2014	Jun 13	2,900	3,400	Several small events.
2015	Dec 9	1,050	1,050	Several small events.
2017	Oct 22	8,200	9,200	Post-event observations and sediment samples. 8-ft high at road crossing.

[1] Dates were estimated based on available background data (rainfall records, photos), and may not be the exact date of debris flow for all events.

The average annual debris removed by Chelan County over the last 15 years is about 4,000 to 4,500 CY. The largest single debris event was in 2005 and was over 1.5 times larger than the recent October 2017 debris flow event. A few select photos showing the scale of the 2005 and 2017 events are provided in Appendix B. Two of the eight events were contained in the debris basin, while six events overtopped the road. The events and cumulative total volume removed since 2003 are plotted in Figure 2.

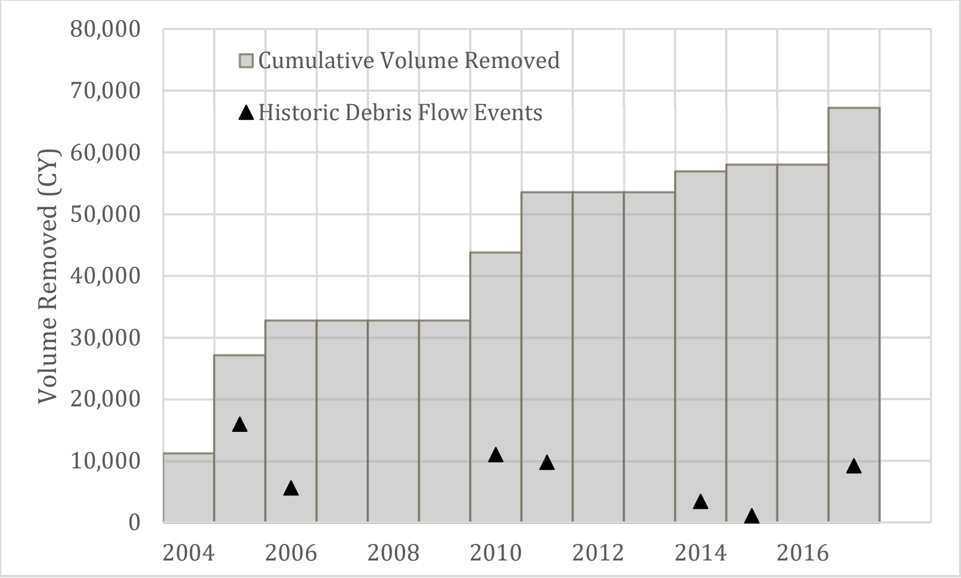


Figure 2. Historic debris flow volumes (adjusted) at S Lakeshore Road.

FREQUENCY ANALYSIS OF EVENTS

The frequency and magnitude of Slide Ridge debris flow events has been analyzed by hand fitting a log-normal distribution to the total debris flow volumes using median plot position for the 15-year record (HEC-SSP). The resulting frequency analysis is shown in Figure 3 and Table 2. The analysis estimates a 10,000 CY event to have a 5-year return period, while a 100-year return period would deposit approximately 20,000 CY of debris.

There are no debris flow cleanouts reported for about half of the years in the record, as the basin was only cleaned out 8 of the 15 years. Therefore, the frequency curve has been fit beginning at a 2-year return period corresponding to about a 50% chance that no debris cleanout will be performed in a given year. The largest recent historic event has been estimated at 14,000 to 16,000 CY in 2005 and would be a 20 to 25-year event. The 4,000 CY existing debris basin provides approximately a 3-year level of service.

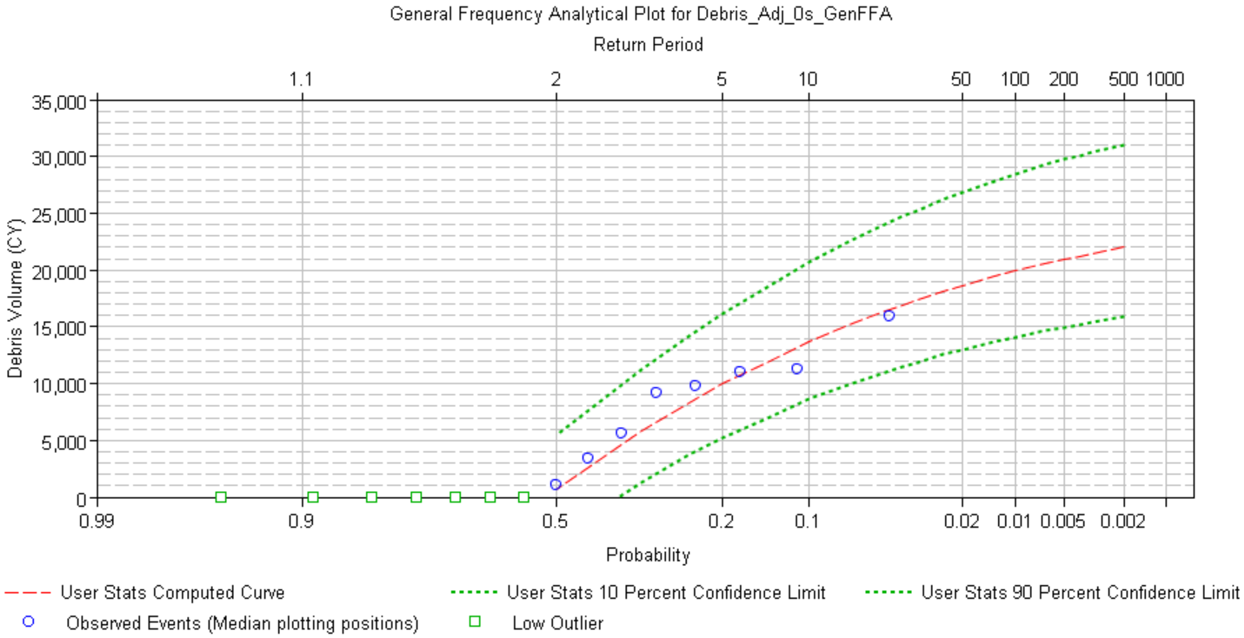


Figure 3. Frequency analysis of annual debris flow volume removed by Chelan County at S Lakeshore Road.

Table 2. Estimated recurrence intervals for debris flow volume removed. (CY = cubic yards)

Return Period (Years)	Annual % Exceedance	Debris Volume, CY
2	50 %	710
5	20 %	10,000
10	10 %	13,700
25	4 %	16,900
50	2 %	18,600
100	1 %	19,900
200	0.5 %	21,000
500	0.2 %	22,000

2 HYDROLOGIC ANALYSIS

Rain gage records in the vicinity of Slide Ridge were analyzed to determine if a correlation exists between observed rainfall and debris flow volumes. Three nearby rain gages were selected as the likely most representative rainfall record for Slide Ridge basin. Each rain gage captures rainfall during storm events differently due to spatial variation, and thus the nearest gages were selected as shown in Figure 4: Slide Ridge (SRDW1), Camp 4 (CMFW1), and Pope Ridge (PPRW1). The rain gages also have varying record lengths and only the Camp 4 gage had recorded data as far back as the 2003 historic event.

Figure 4. Rain gage locations in the vicinity of Slide Ridge site. Slide Ridge gage (center right of figure) is just north of the basin at the top of the ridge, with the best representation of rainfall. Manson gages are at lower elevations than Slide Ridge.

Debris flow storm event rainfall volumes were calculated for the selected rainfall records and represented as rainfall intensity (in/hr) for durations from 10-min to 24-hours. Only the Slide Ridge gage had 10-minute interval data, while the other gages had hourly data. Each gage was then analyzed for the eight recent historic debris flows (2003-2017) by plotting the maximum rainfall at each duration and figures are included in Appendix A. The gage data was then used to develop rainfall threshold curves to estimate when a debris flow is likely to occur (see plots). The Slide Ridge and Camp 4 gages appear to be reasonably representative of the Slide Ridge debris flows, with the exception of the 2011 event that was not well captured at the Camp 4 gage. The rainfall magnitudes vary significantly by gage, thus the rainfall threshold envelope for debris flow occurrence is not readily transferable between the rain gages (e.g. the Camp 4 threshold should not be applied to data from the Slide Ridge rain gage).

Statistical tests were performed to evaluate how well correlated the rainfall amounts were to the historic debris flow volumes. The tests showed the Camp 4 rain gage to provide the only statistically significant results, with the 2-hour rainfall duration showing the highest correlation (for both Spearman and Pearson tests). The Slide Ridge rain gage record is too short to develop reliable correlation, and the Pope Ridge gage was poorly correlated with the debris flow record. A regression curve was fit to the Camp 4 rain gage data for the 2-hour rainfall intensities as shown in Figure 5. The regression and threshold curves allow for predicted rainfall to be translated into an estimate of the potential for large debris flow volumes, though this has not been tested and should be viewed as approximate.

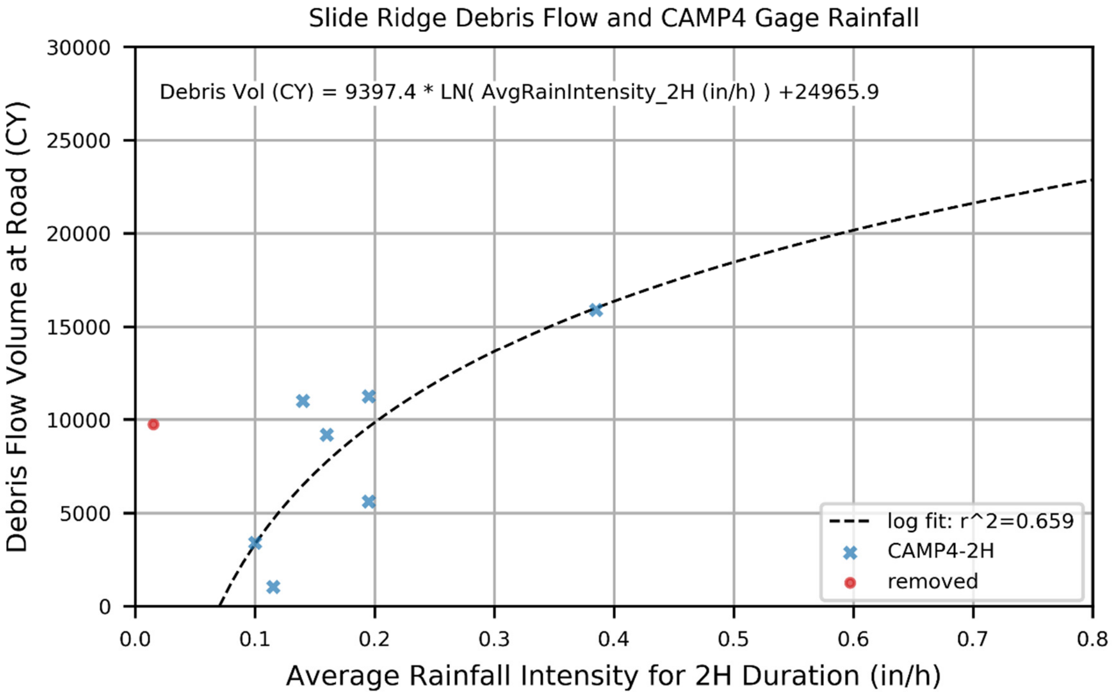


Figure 5. Regression equation for Slide Ridge debris flow volume based on Camp4 rain gage intensity (at 2 hour duration). The 2011 event did not appear to be captured by the Camp4 gage and was removed from the fit.

3 DEBRIS FLOW CHARACTERISTICS

Indicator Engineering visited the Slide Ridge site several times in 2017 and 2018 to investigate and observe the channel, road crossing, debris basin, check dams, operations and maintenance following the October 2017 event, and upper basin characteristics. The following evaluation is provided based on our observations, field samples, review and site-specific analysis. Select photos are provided in Appendix B.

DEBRIS FLOW PHYSICAL BEHAVIOR

Debris Flow Basics

The material in a debris flow is a mixture of mud, sand, and boulders that has a consistency often described as wet cement. The fluid matrix is generally non-cohesive, and debris flows can occur without any content of fine material (silts, sands, clays). Debris flows can have relatively little water content, and are often over 80% solids by weight, which contributes to their ability to transport boulders over slopes as low as 3-5 degrees.

Slide Ridge Flow

Sediment samples were collected at Slide Ridge from areas along with the debris channel and from the debris runout following the 2017 event. Two samples were collected 2 days after the October 2017 event and represent the slurry (SR1) and the upper portion of the deposited material at the road (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 combination of low water content, silts, and cohesive sediments creates the slurry capable of transporting 3 to 4-foot boulders downstream.

Not all flow events in the debris channel create debris flows. There are precipitation events that are "*normal*" clear-water runoff events with associated bedload transport of sands, gravels and cobbles, but not a debris flow. The bedload transports a limited distance downstream with each event, creating gravel wedge deposits in the channel. These gravel wedges moved downstream as sediment waves with subsequent bedload transport events. The amount of scour generated by bedload transport is approximately equal to the size of each deposit, creating an overall balance in the channel. Debris flows excavate these deposits and scour into the debris channel to excavate additional sediments. Debris flow volumes increase as these deposits are scoured.

Sand content has two roles in debris flow channels:

- High quantities of sand in the sediment matrix increase the friction within the debris flow and limit the runout length.
- High amounts of sand increase the movement of medium size cobbles and gravels during bedload transport events.

Based on the field observations and sediment samples collected from the Slide Ridge site, there is an abundance of boulders that are commonly 3 to 4 feet in diameter. The sediment samples collected after the October 2017 event (SR1 and SR2) had higher sand and silt/clay content than the bed samples collected from the upstream channel. This is primarily a result of the presence of the slurry material in SR1 and SR2, which is conveyed all the way to Lake Chelan in most flows. 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 matrix of smaller sediment sizes was collected to measure the grain size distribution, shown in Figure 6. For the SR3, SR4 and SR5 channel bed sites 10 to 15% of the sieved samples consisted of sediment 2 mm or smaller. This is a low value indicating a channel dominated by larger gravels and little sand deposition in the upstream channel. Where a channel is dominated by the larger gravel, the sand mobilizes less frequently. The limited sand size fraction also indicates that the smaller sizes travelling in the slurry of the debris flow do not tend to deposit in the upstream channel.

Key findings:

- Sediment that moves down the debris flow channel as bedload or small debris flows between the large debris flow events will accumulate within the debris flow channel. The runout length depends on the magnitude of the event, with many smaller events depositing material upstream of the debris basin
- Check dams may be adding to debris flow volumes by storing sediment behind the dams, which then fail during debris flows activating the stored material.

- Smaller debris flow events occur and run to varying lengths. These events loosen debris in the upper basin, transport to the apex, and some may deposit debris within the flow channel and behind check dams. These small events create readily available material for large debris flow events to transport the road.
- Debris flows at Slide Ridge maintain a low water content, likely 15 to 30% water by weight during typical events.

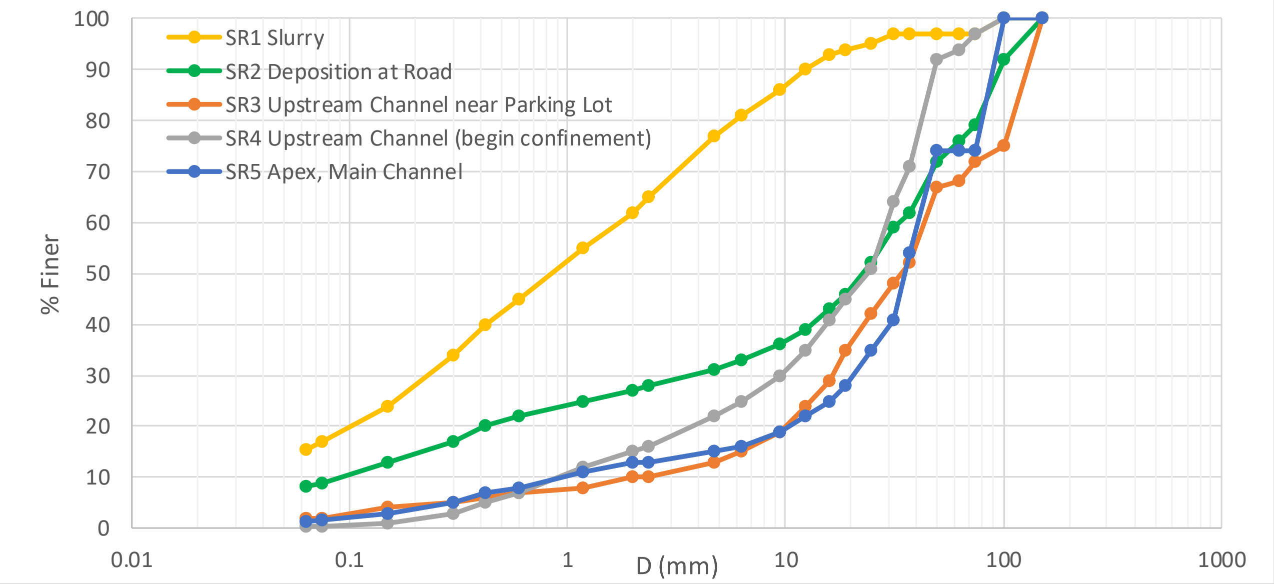


Figure 6. Grain size distributions for slide ridge samples SR1 to SR5.

DEBRIS FLOW RUNOUT CHARACTERISTICS

The runout length of a debris flow is highly dependent on the water content of the flow and the grain sizes within the debris. For Slide Ridge, the grain size distribution will remain relatively constant and water content vary by event controlling runout length.

The front or leading edge of the debris flow is called the “snout”. A debris flow will develop a snout at its leading edge where large sediments accumulate and travel as a coherent unit at the front of the flow. Because of the movement of the snout as a unit, shear stresses are highest in narrow bands along the edges of the debris flow front. The gravels in a debris flow, particularly in the snout, are large enough to dissipate energy through collision as they travel within the debris flow. Because of this loss of energy, the debris flow may cease to travel despite being on a steep slope. The snout will deposit rapidly, which has often been described as freezing. The rest of the debris flow will deposit in place upstream of the snout. Increases in the water content cause the debris flow to travel further by altering the internal resistance within the flow. An increase of less than 5% water content can dramatically increase the debris flow’s runout length.

Figure 7 and Figure 8 diagram a typical debris flow snout and show an actual debris flow snout. Note the accumulation of boulders in the snout and the low flow in the channel preceding the debris flow.

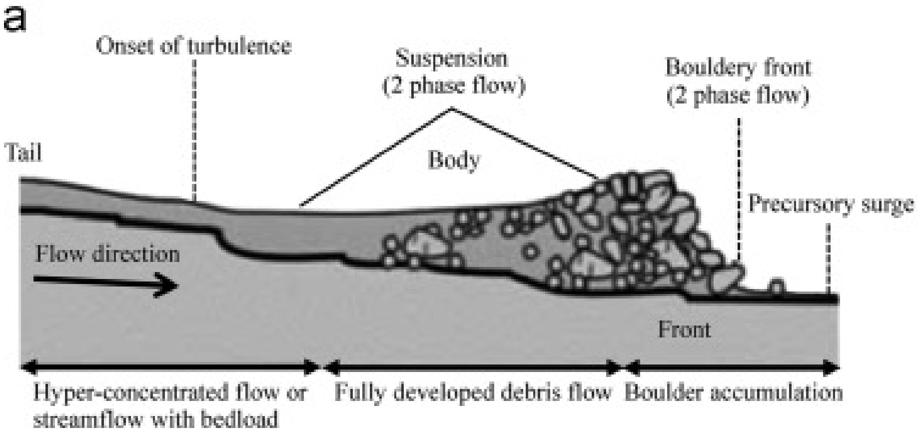


Figure 7. Diagram of typical debris flow (Pierson 1986).

Figure 8. Image of a debris flow front traveling downstream. (Petley/Illgraben 2016)

NUMERICAL MODELING OF DEBRIS FLOW

A numerical model of the Slide Ridge debris flow has been developed to simulate the runout length and debris volume of events. This information will help determine a mitigation strategy that can reduce maintenance in the future. The model has been developed using a computer program specifically designed for debris flows called DFLOWZ. The model predicts debris flow runout length and deposition area (Simoni, Mammoliti, and Berti, 2011). The model was calibrated to the October 2017 event, specifically the water content and other flow parameters, since significant information was available from that event. Water content is the least constrained parameter and was the focus of the calibration. Grain size information is assumed to be constant between model runs, while event volume is varied to simulate historic or recurrence interval debris flows. The modeling informs the following important questions for the Slide Ridge site:

- Can future debris flows reach the lake and deposit within the lake?
- What is the likelihood that future debris flows will overflow the defined channel?
- What is the maximum volume and height of a future debris flow?

Figure 9 shows the model domain and the predicted deposition area of the 2017 event. The volume predicted to deposit was 8140 CY of which 90% deposited in the immediate area of the road and basin. An important model assumption is that the slurry runout is not simulated, and the slurry should be evaluated separately as flow that may continue downstream. This was certainly the case during the October 2017 event where the majority of the debris flow was deposited in the basin and over the road, while the slurry continued to the lake via three paths:

- The channel downstream of S Lakeshore Road, via either the culverts or road overtopping.
- North, first along S Lakeshore Road, then driveways to the east and between buildings to the lake.
- South, along S Lakeshore Road in the roadside ditch, then crossing the road to the marina.

Figure 10 shows a cross section immediately upstream of the debris basin with results from the October 2017 calibration. The orange line is the depositional area predicted by the DFLOWZ model. Depositional volume was calculated from the cross sections.

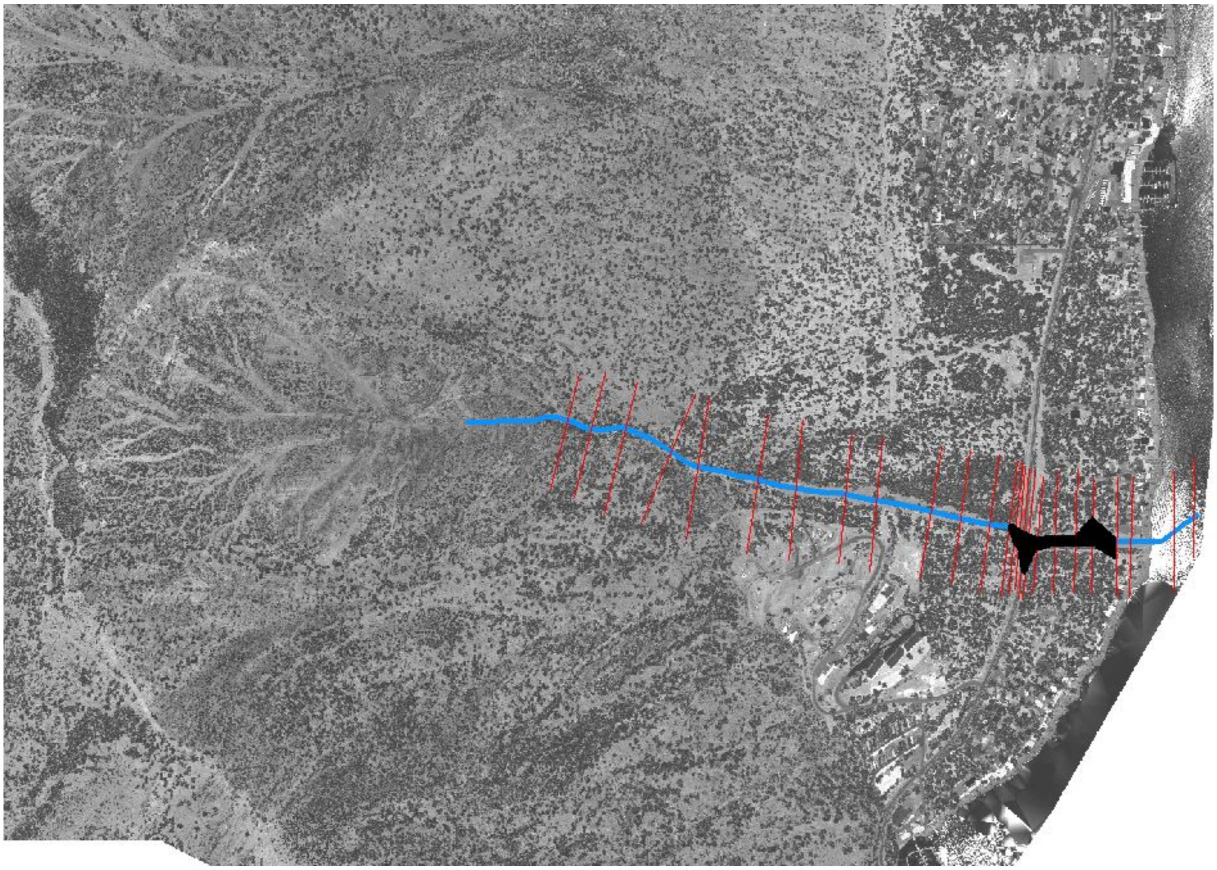


Figure 9. DFLOWZ model cross sections (red) and simulated deposition for the October 2017 event. The model predicts a large amount of deposition at the debris basin and road as occurred during the event.

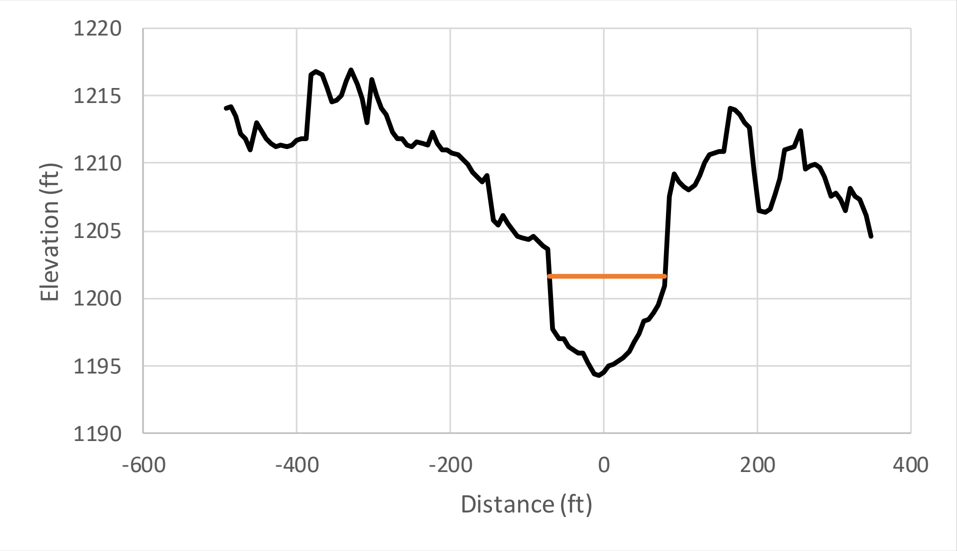


Figure 10. DFLOWZ model simulated result for cross section immediately upstream of the existing debris basin for the October 2017 event.

EXISTING PERFORMANCE

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, the channel slopes vary dramatically throughout the year as small events deposit debris and large events scour and transport the debris downstream. The project Lidar collected in May 2018 shows channel slopes ranging from 25 to 40% in this reach from the step to the apex. 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 Figure 11. 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 6.2-ft (H) by 10.5-ft (W) corrugated culvert. The bottom of the basin is about 14-feet below the road surface. This geometry has proven to effectively convey small to large debris flows to the basin and then encourage deposition in the basin and road. The 2005 event is the largest in the last 15 years and appears to be the only event where debris overtopped the road and continued in the downstream channel to the lake. 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.

The channel sections vary in size upstream and downstream of the road. The upstream channel section is confined with a bottom width of 14 to 20 feet, steep side slopes, 35 to 45 feet top width and depths of 14 to 18 feet. 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 8 to 12 feet.

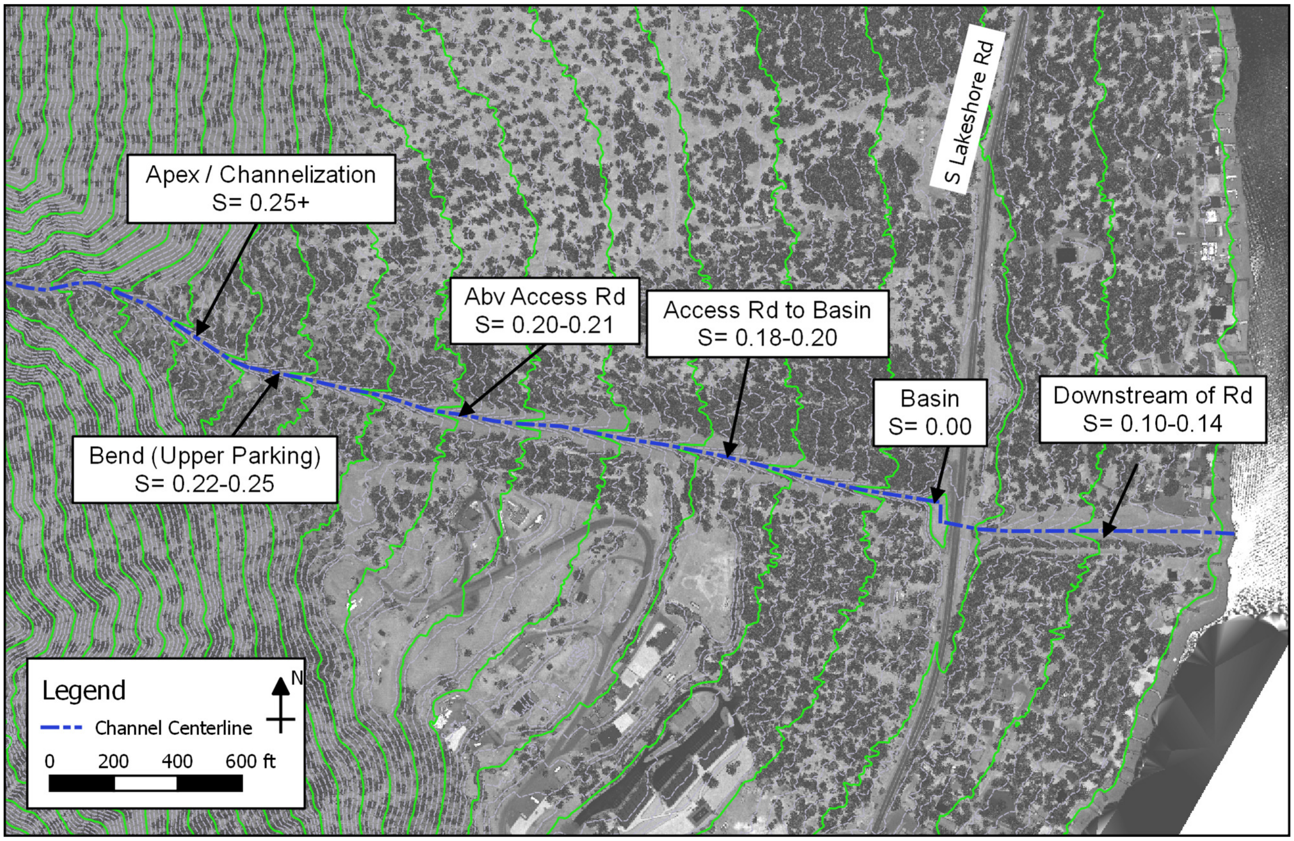


Figure 11. Channel slopes based on 2018 Lidar for Slide Ridge debris channel.

4 IMPROVEMENT ALTERNATIVES

Several alternatives have been developed and evaluated to improve the management of debris flows 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 provides a low level of service. Alternatives were developed with the goal of reducing or eliminating road closures, reducing O&M effort, reducing the public safety hazard, and in consideration of cost, reliability, and ease of operation. Alternatives were conceptually grouped into the following categories, and are described in the sections below:

- Conveyance to the lake
- Debris Retention
- Modified Operations and Maintenance

Many other solutions were considered, but ultimately did not appear as feasible for the Slide Ridge site as the proposed alternatives described below. Debris flow management varies throughout the world and the following other concepts were reviewed: upper basin slope stabilization, horizontal debris brakes, sabo/check dams, debris nets, and siphon systems. Depending on the preferred alternative, these other concepts may be considered in conjunction during a subsequent phase.

CONVEYANCE TO THE LAKE

The conveyance alternative has a higher level of uncertainty than the retention alternative. Debris flows vary from event to event and the physics are not well enough understood to be definitively designed. With that in mind, 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, an empirical technique presented by Rickenmann (1999) and with consideration of site geometric constraints. The DFLOWZ analysis predicted varying results and is described in further detail in Appendix C. Subsequent to the DFLOWZ analysis, empirical calculations by Rickenmann were used to size the channel and bridge.

Proposed Conveyance Geometry

A conceptual geometry has been developed to convey the 100-year debris flows to Lake Chelan with reduced risk of overtopping the road or downstream channel. The major components and the proposed channel alignment are shown in Figure 12 and described from upstream to downstream as follows:

- Upstream Channel Transition: Connect from west edge of road to existing channel for 100 to 150 ft at a slope of 19-21%. The debris basin to be filled in and create a transition channel with a 20-ft bottom width and 1 to 1 side slopes, and contain depths up to 16-ft.
- Bridge 40-ft: Construct a bridge with a 40-ft wide channel opening along the proposed alignment. The bridge skew to the existing road centerline would be about 24 degrees. Beginning at the west edge of the road the channel slope would be reduced to 11%. Boulders may be used to reduce the channel section width to 20 feet to better convey low flows. Depths are expected to be up to 14.9-ft.
  - The road (and bridge) may need to be shifted east of the current road, or elevated. Freeboard is recommended as feasible; however, this is the 100-year event and the upstream channel may not support this or larger events. The scour depths are not expected to be significant, on the order of a few feet, and will be developed for a preferred concept. Impact should be avoided if possible, as the snout may carry boulders up to 4 feet in diameter at a velocity range of 20 to 26 ft/s for the 100-year event.
- Downstream Channel Improvements: Regrade the existing channel at a slope of 11% beginning about 500 feet downstream of the existing culvert outlet. The channel would be regraded to have a 30-ft bottom width and 1 to 1 side slopes, for depths up to 15-ft. This would require raising the channel levees an additional 4 to 7 feet.

The conveyance concept was developed by attempting to preserve the existing road location and elevation as possible. A steeper channel through the road crossing (such as 14%) would more reliably convey debris flows downstream, however this would require raising the road significantly given the existing Lake Chelan shore location. The transition at the road to 11% would be a potential brake on the debris flow and could cause rapid settling of some flows. We recommend monitoring and adapting the geometry after a few events if this transition proves too severe and causes deposition. To reduce the likelihood of debris deposition at this location, the minimum velocity of 12 to 13 ft/s in the upstream channel during historic events was calculated and the proposed channel attempts to maintain that velocity or higher during moderate to large debris flows (October 2017 or larger).

Excavation and maintenance will still be required with this alternative, as we anticipate that smaller debris flows may not runout to the lake and would require excavation to maintain the channel geometry. If this alternative is chosen, then the check dams should be reconsidered with a management strategy, and freeboard should be evaluated in the upstream and downstream channels.

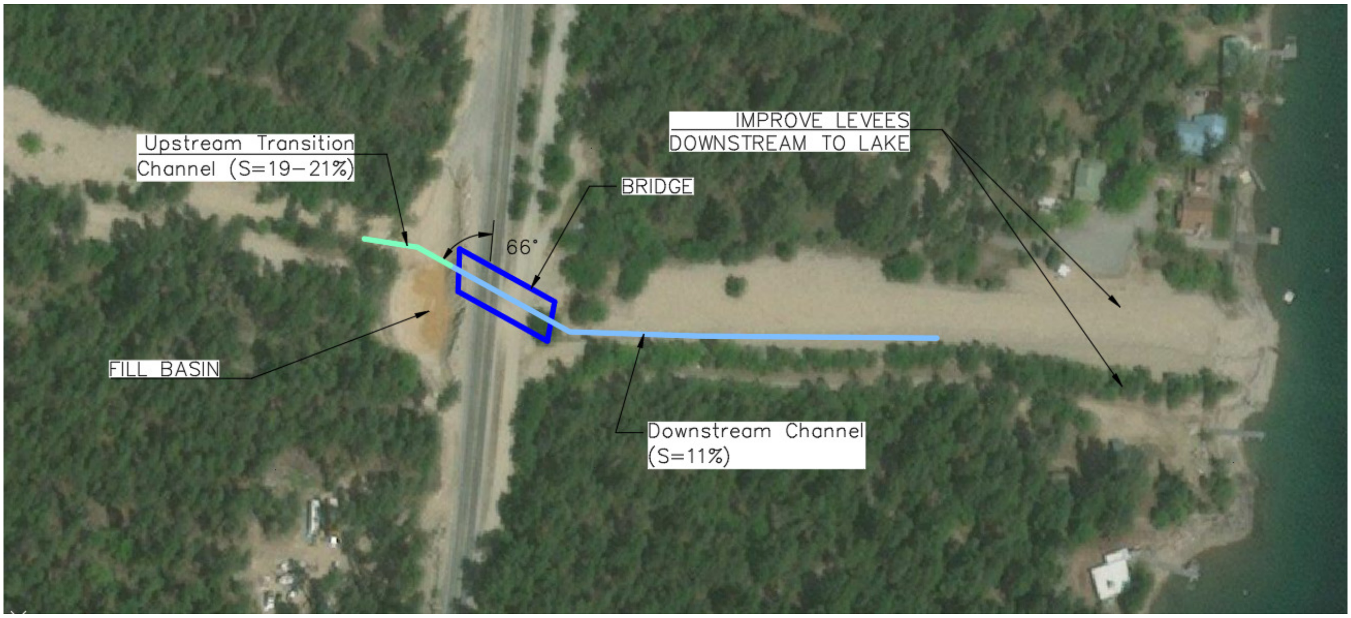
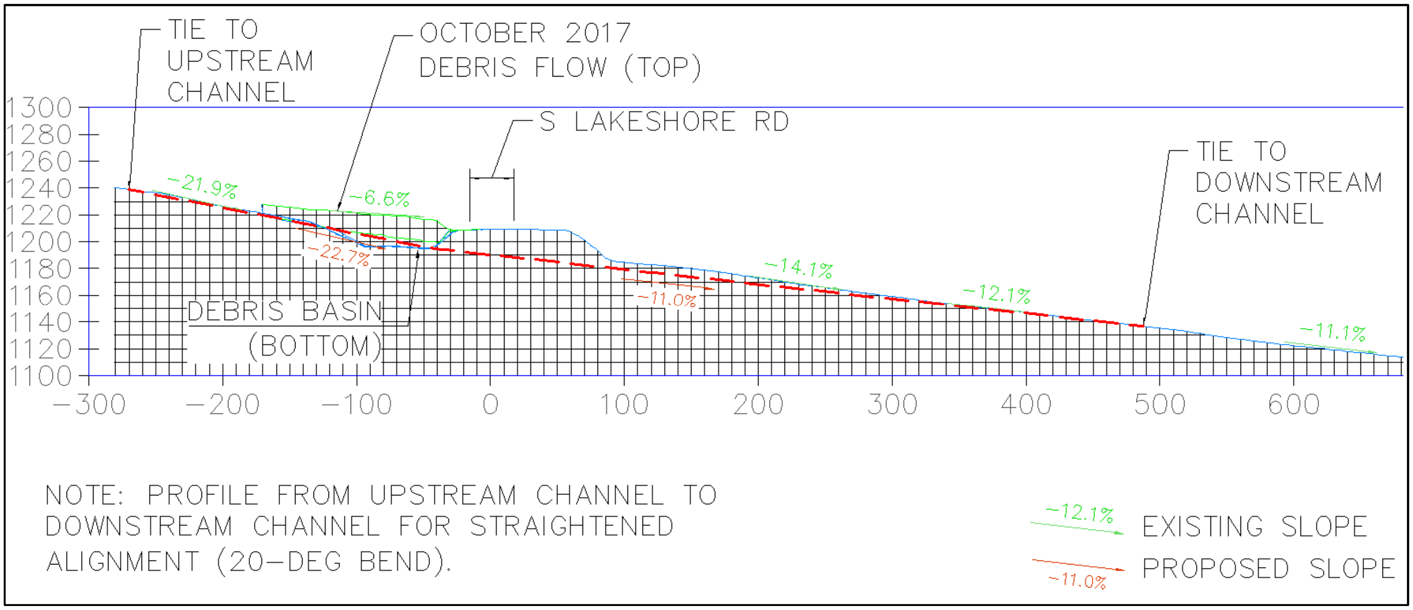


Figure 12. Conceptual layout of proposed improvements for conveyance alternative.



NOTE: PROFILE FROM UPSTREAM CHANNEL TO DOWNSTREAM CHANNEL FOR STRAIGHTENED ALIGNMENT (20-DEG BEND).

Figure 13. Profile along proposed channel alignment showing conveyance alternative. Dimensions are feet.

DEBRIS RETENTION

Trapping and storing the debris flow in a retention basin is a proven management technique and could be incorporated into the Slide Ridge system. The debris basin could be designed to contain the anticipated 100-year volume of 20,000 CY. The system would require regular maintenance to haul away debris accumulated in the basin. While these excavation and haul costs would be similar to the existing basin and system, this alternative would eliminate road closures and associated public safety and emergency operations.

A large debris basin could be inserted into the existing system anywhere upstream of S Lakeshore Road. Two logical sites are presented below, however alternate sites may be preferred depending on other factors such as landownership.

Expanded Existing Basin

The existing debris basin upstream/west of the road could be expanded to provide additional volume. If land can be acquired the basin could be expanded without lowering the bottom of the existing basin. The existing basin bottom elevation is 1194 to 1195 feet, which is well below the road elevation of 1208 to 1209 feet.

Alternatively, if additional area is limited, the existing basin could be lowered to provide additional volume. Figure 14 shows a concept that would provide about 15,000 CY of debris storage by lowering the bottom to elevation 1180. This is elevation is a few feet below the culvert outlet and could be easily tied into the downstream channel. The culvert would be replaced with a bridge large enough to provide equipment access and tall (25-30 feet) walls would be located along the road. The flat basin and road with relatively small opening would likely provide sufficient constriction for debris flows, however a dam or breaker system may be added to the outlet of the basin to encourage debris retention.

Additional input is needed from the project team for siting an expanded debris basin at the road.

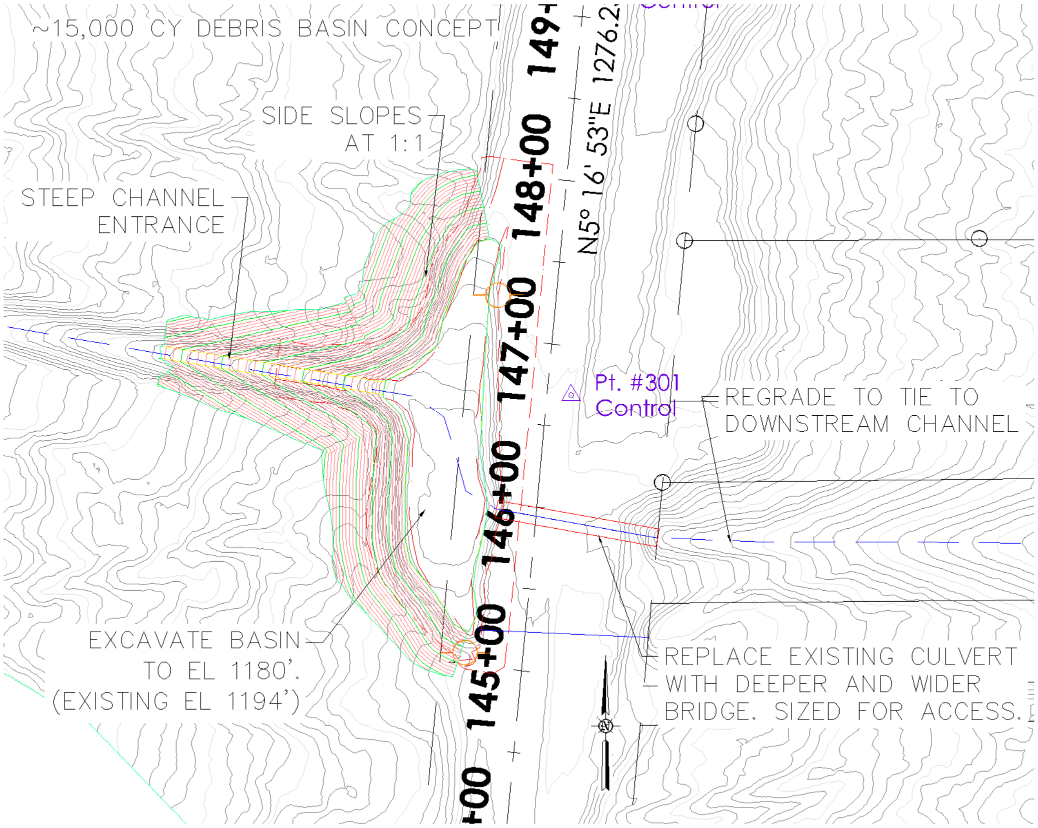


Figure 14. Conceptual layout of approximately 15,000 CY basin at location of existing basin.

Upstream Basin Nearer the Apex

A large debris basin could be constructed near the upstream end of the conveyance channel. Just below the apex where this would be located 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. This location was previously proposed in the 1993 EIS. Figure 15 shows the approximate location with two potential sized basins. The basin would need a large footprint to contain the debris flows given the steep slopes in the area. Alternatively, a series of smaller basins could be used. The slopes of the fan are 20-30% in this area and that steepness relative to the top angle of the deposited debris flow results in the large area requirement. Debris breakers come in many forms and could be applied either within a single basin, or at the outlet of a series of basins.

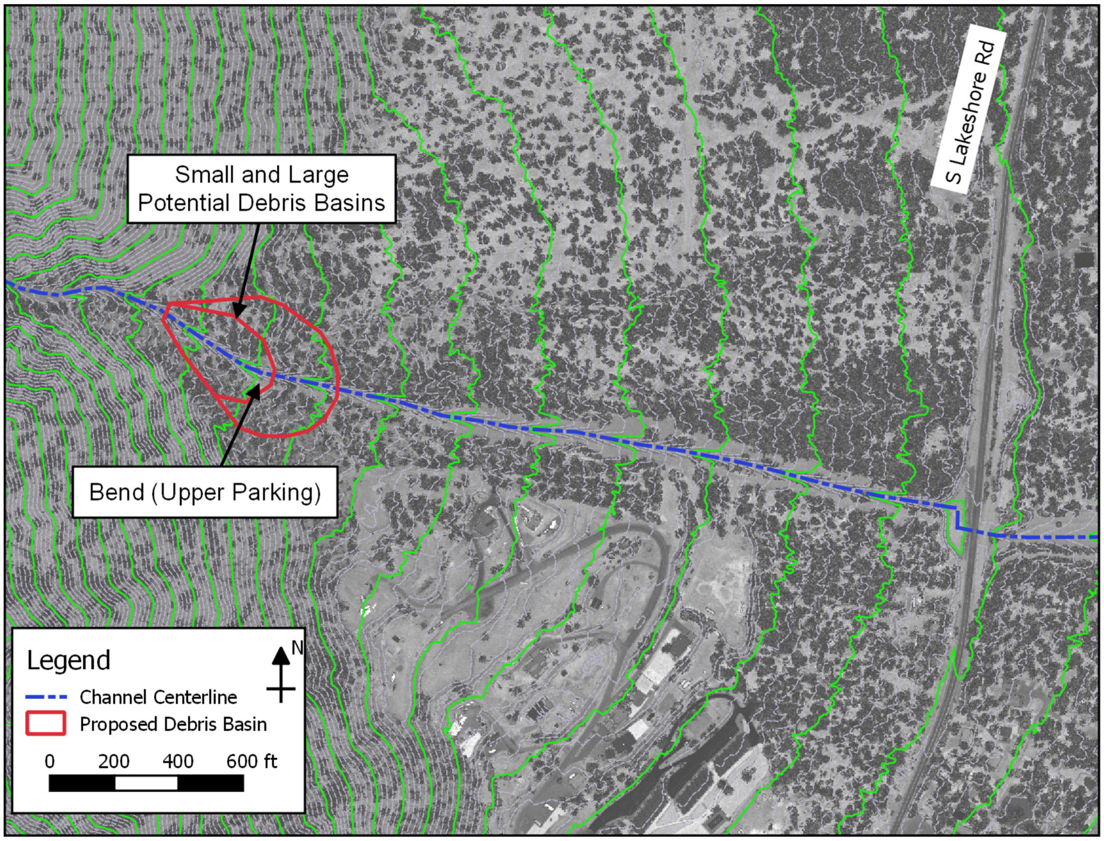


Figure 15. Conceptual Layout of Proposed Improvements for Conveyance Alternative.

MODIFIED OPERATIONS AND MAINTENANCE

The above alternatives will require significant capital projects, so more readily implementable solutions were considered. A few alternatives are described below that would make smaller changes to the existing system. The trade-off is less effective and reliable performance.

Eliminate Check Dams

Based on several site visits and a review of historic photographs, the check dams are effective at slowing smaller debris flows and bedload events. This stores debris in the channel behind the check dams. Our understanding is that historically this debris was not removed from the channel. The check dams erode and fail during larger debris flow events, which then allows the previously stored material to be activated and transported to the road. The volume transported during the large events that overtop the road could be reduced by either/both:

- Eliminating the check dams, thus reducing the material stored in the upstream channel.
- Routinely monitoring and excavating the upstream channel to prevent debris accumulation between large events.

This modified operation scheme would make no difference some years where no or very few small debris flows occur. However, during years of many frequent small to medium debris flows, an upper estimate of debris stored in the upstream channel is 3,000 to 4,000 CY.

Taking the October 2017 event as an example: approximately 9,200 CY deposited at the road and the basin has a capacity of 4,000 CY. If that event were to be reduced by 3,000 CY then only 6,200 CY would be conveyed to the road, with 4,000 CY in the basin and only 2,200 CY overtopping. That is half the amount over basin capacity and would require significantly less emergency cleanup as only a fraction of the overcapacity volume is deposited on the road surface itself (with the rest deposited at higher elevations in the debris basin). The debris flow would also have increased water content which furthers runout distance. That may translate into more of the debris flow making it through the existing culvert, however the culvert is still undersized, and the system is graded to overflow in multiple directions.

Increase Water Content

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. This results in longer runout distances for the remaining debris flow. The herringbone style debris breaker shown in Figure 16 could be placed in the upstream channel or at the existing basin and would extract and retain only the larger portion of the particles in the debris flow. A rough estimate is that about 4,000 CY of 1-ft or larger material would reach the road during a 100-year event. If that was extracted and retained, and coupled with a new road crossing, the remaining debris would be much more likely to be conveyed to the lake. This alternative should be considered as fairly experimental, however is promising and could be incorporated with other alternatives to increase performance.

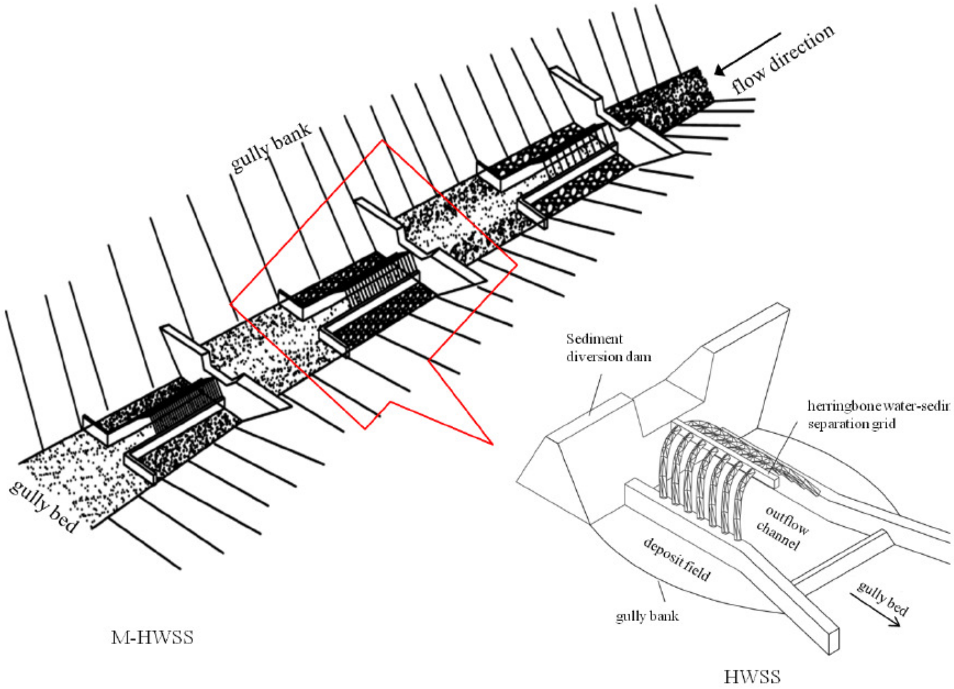


Figure 16. Conceptual water sediment separation system, from Xie et al (2016).

5 PREFERRED ALTERNATIVE

Conveyance to the lake is the preferred alternative selected by the County with input from the project design team. The system will be reconfigured to convey debris flows from the upstream channel, through a new bridge crossing of the road, and to the lake. This is a modified version of the alternative presented above and will include construction of:

- Transition channel upstream of the road. A conveyance channel will be constructed through the existing debris basin upstream of the road that maintains a relatively steep slope and similar bottom width to the existing upstream channel.
- An open channel with a new road crossing and bridge. Beginning at the upstream face of the bridge a new trapezoidal conveyance channel will be constructed through the road crossing. The latest design concept uses a constant channel slope from the upstream bridge face to the lake of 10 to 11%. The

design uses a wider channel bottom to maintain peak depth of the debris flow. The channel surface will be concrete lined across the road crossing to prevent erosion that could otherwise undermine the proposed bridge foundations. The existing road crossing will be abandoned or removed. Information on the bridge and road is provided in the main T,S&L report (KPFF 2019).

- Improve the channel downstream of the road. Improvements to the channel downstream of the road are proposed to contain the debris flows. Channel grading will be performed to create a constant slope and section. Channel banks would be raised to contain the calculated 100-year debris flow.

FREEBOARD AND BRIDGE IMPACT

A minimum of 3.0 feet of freeboard above the 100-year debris flow surface elevation is recommended to provide conveyance considering the analytical uncertainty associated with debris flows and potential for deposition. This freeboard applies to both the bridge low chord elevation and the top of the proposed channel. The 100-year debris flow elevation has been calculated using methods described above and assumes the proposed conveyance channel is clear of debris from smaller events. The proposed design channel geometry has a profile and section break at the bridge, with a corresponding drop in velocity that may cause deposition during smaller events. While the channel profile and section should be maintained between events, channel excavation maintenance may not be realistic between events that occur within a short period of each other (hours or days). Additional freeboard up to 5.0 feet should be considered as feasible at the bridge crossing given the position of the bridge relative to the channel profile break and potential for deposition.

Boulders which may transport downslope during a debris flow reach a maximum of four feet in diameter (as described above). These will travel at the front, or snout, of the debris flow. They will move by rolling and sliding within a thin slurry. If enough boulders are present during a large debris flow then large boulders may extend to the top of the debris flow as shown in Figure 17. The largest boulders are not anticipated to strike the bridge given 3.0 feet of freeboard and a maintained channel section and profile.

While the likelihood of boulders impacting the bridge is low, the size and velocity of boulders during a debris flow could result in substantial damage if impacting a typical bridge. We recommend the bridge design consider some form of impact protection at the upstream low chord.

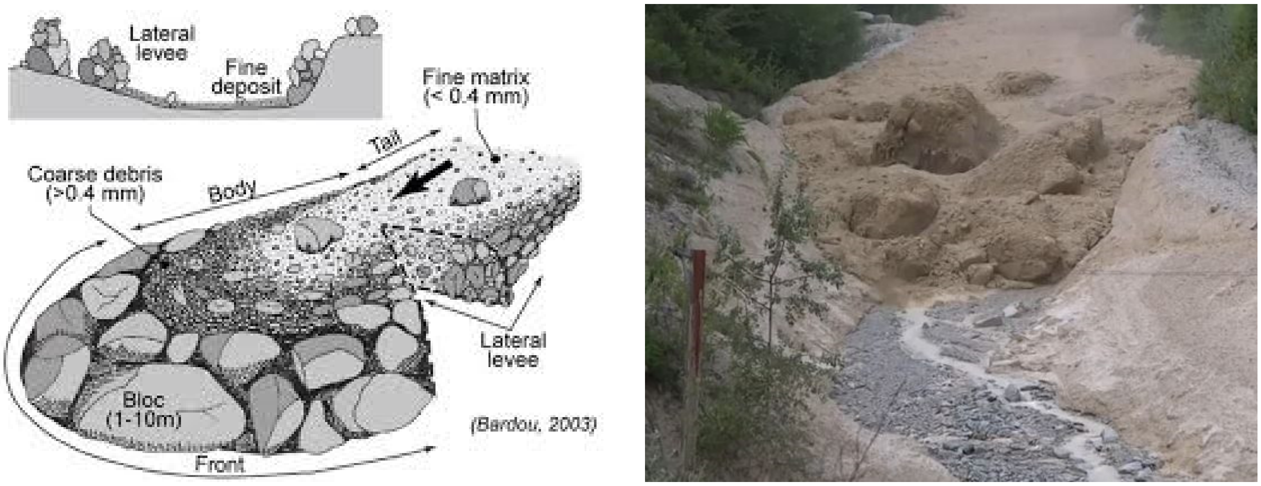


Figure 17. Debris flow schematic (left, Bardou 2003) and image (right, Petley 2016) showing boulder location at snout.

EFFECTS OF CONVEYING DEBRIS TO LAKE

Lake Chelan is unique in its depth and steep descent. This is an advantage for the movement of the debris flows. When the debris sediment reaches the lake it will build out over the shallow area, as apparently happened in

2005. The lake bed elevation then drops quickly, causing the sediment to continue downslope to the bottom of the lake (Figure 18). The area of possible concern is the immediately off-shore reach where sediment accumulation occurred after the large event in 2005. The new downstream channel configuration should provide the continuous slope needed to enable large event to move sediment off the near shore and into the lake depths. However, smaller events may deposit in the near shore area. Shoreline currents may be enough to erode any sediment accumulation and quickly remove the deposit.

The following options are offered for the County's consideration during the design phase to further quantify the transport of the debris flow material within the lake:

- A study can be performed to estimate the number of years for which debris flows can contribute sediment to the lake without causing a negative impact on the shoreline. There would need to be new depth soundings taken of the shoreline and off-shore area where the debris flow would deposit. Using these sounding, the area available for sediment accumulation can be estimated, and indirectly the length of time, assuming no transport of sediment by lake waters.
- Alternatively, if there is significant stakeholder interest, a more detailed study could be performed by measuring the shoreline and lake currents and then developing a detailed model of how the sediment that reaches the lake may be transported once it deposits. This would require measurements over a year to obtain the different patterns and a multi-dimensional numerical modeling effort. This is not recommended at this point.
- The County can take an adaptive management approach. There is a low likelihood in the near-term of multiple large debris flows and significant near shore deposition. The County may consider measuring shoreline bathymetry every 5-10 years. Any deposit will be able to be identified from the bathymetry measurements and maintenance activities could be evaluated at that time.

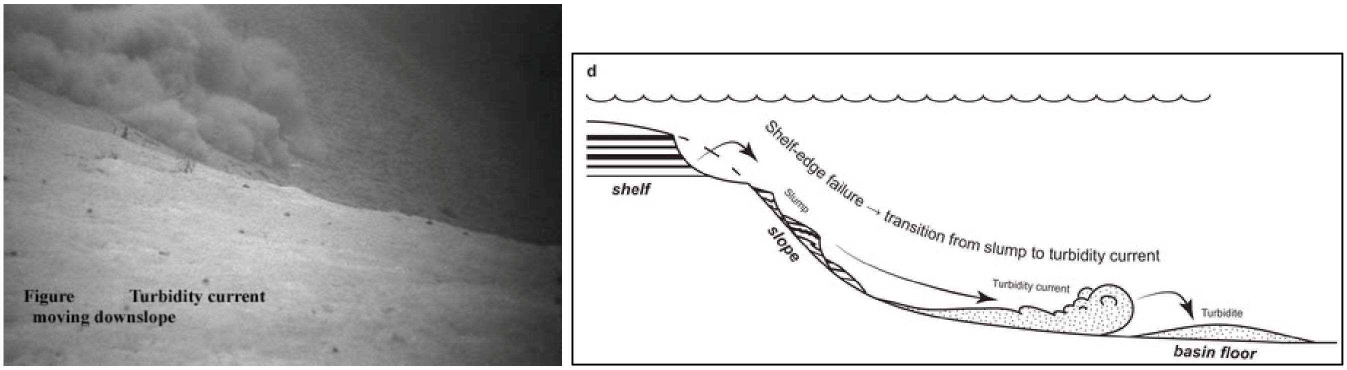


Figure 18. Debris flows entering lake may deposit initially and then fail, or immediately continue to the basin floor. Debris flows become known as turbidity currents as they enter the lake. Photo (top, Morelock 2005) and schematic (bottom, Covault 2011) of turbidity current in lake.

PHASING AND CUT-FILL VOLUME BALANCE

The 30% channel design requires regrading about 1,000 feet of channel. The grading volumes are calculated to be 7,750 CY of cut and 22,500 CY of fill. The majority of the earthwork (82%) is downstream of the road, with 13% upstream and 5% under the road. The net result is cut-fill volume imbalance requiring about 14,750 CY of imported material for channel construction. The initial channel grading plan was revised to reduce the fill volume by only constructing the channel upstream of the road and not filling the existing debris basin.

Phasing the channel grading has also been considered. Coincident with the new bridge construction, we recommend constructing the upstream channel with 3.0-ft of freeboard, the channel under the road, and the downstream channel improvements to the lake. The existing channel downstream of the road does not have adequate capacity to convey the 100-year debris flow and would be likely overtopped, threatening adjacent properties. The downstream channel improvements have been designed with 3.0-ft of freeboard, which could be considered for construction during a second phase. This would reduce fill volume (and corresponding import material) by about 4,000 CY. The downstream channel freeboard could be constructed with material from future debris flow maintenance.

Import material costs may be further reduced by sourcing the import material for the channel grading from elsewhere at the Slide Ridge site. Excavation at the fan apex would be ideal as that material is already loose and poised to be transported during a debris flow. There are also prior debris spoil sites along the upstream channel which could be used for borrow, while maintaining the capacity in the upstream channel.

The downstream channel grading may be further refined in the next phase of the design to account for interaction with road and bridge grading. The downstream channel section assumes 1 to 1 side slopes, which is flatter than many sections of the upstream channel. Fill volumes would be further reduced if a steeper side slope is feasible for the downstream channel banks.

6 REFERENCES

Bardou, E., Ancey, C., Bonnard, C. and Vulliet, L., 2003. “Classification of debris-flow deposits for hazard assessment in alpine areas.” In 3th International Conference on Debris-Flow hazards mitigation: mechanics, prediction, and assessment.(No. CONF). Millpress.

Chelan County 1993. Final Environmental Impact Statement for Chelan County Public Works Slide Ridge Control Channel. Prepared by Hammond, Collier & Wade – Livingstone Associates, Inc. EIS 1993.

Chelan County 2018. Personal communication, supplied historic and background data for Slide Ridge project. Various 2017-2018. Public Works Department.

Covault, J. A. (2011) Submarine Fans and Canyon-Channel Systems: A Review of Processes, Products, and Models. Nature Education Knowledge 3(10):4.

DFLOWZ 2014. M. Berti and A. Simoni. “DFLOWZ: a free program to evaluate the area potentially inundated by a debris flow.” Computers and Geosciences, 2014, 67, pp 14-23. Modified version provided by Dr Berti.

FHWA 2012. HEC-18: Evaluating Scour at Bridges. April 2012. Publication No. FHWA-HIF-12-003, Hydraulic Engineering Circular No. 18. Fifth Edition. USDOT FHWA.

GeoTerra Inc. 2018. LiDAR Technical Report: Slide Ridge Lidar. June 8, 2018. Presented to KPFF Consulting Engineers.

GLO map 1895. Map of Township No 28N, Range 21E, Willamette Meridian, Washington. October 9, 1895.

HEC-SSP version 2.1.1. HEC-SSP: Statistical Software Package. US Army Corps of Engineers, Hydrologic Engineering Center. Release date: January 5, 2017.

Morelock, J. 2005. Morphology. Geological Oceanography Program at the University of Puerto Rico at Mayaguez. Website: http://geology.uprm.edu/MorelockSite/morelockonline/7-morph.htm

Petley, D. 2016. Illgraben debris flow video. The Landslide Blog. American Geophyisical Union. July 28, 2016. Website: https://blogs.agu.org/landslideblog/2016/07/28/illgraben-debris-flow-video/. Linked to: “Illgraben 22.07.2016 - lave torrentielle, Murgang, debris flow”. Website: https://www.youtube.com/watch?v=0ENe7wDKP6I, last accessed on October 15, 2018.

Pierson, T.C. 1986. “Flow Behavior of Channelized Debris Flows, Mount St. Helens, Washington.” Geomorphology, January 1986. Hillslope Processes: p 269-296.

Rickenmann, D. 1999. “Empirical Relationships for Debris Flows”. Natural Hazards, vol 19, p 47-77.

Van Asch, T.W.J. et al, 2014. “An Integrated model to assess critical rainfall thresholds for run-out distances of debris flows”. Natural Hazards, vol 70, issue 1, pp 299-311.

Xie, X. et al. 2016. “Debris flow sediment control using multiple herringbone water-sediment separation structures”. Natural Hazards Earth Systems. 2016.

7 CLOSING

Indicator Engineering PLLC is pleased to provide hydraulic, hydrologic and geomorphic engineering analysis for the Slide Ridge project. We look forward to working with you on the design. If you have any questions or to discuss the design the above analysis, please contact Pat Flanagan via email or at (206) 651-5103.

Respectfully Submitted,

Indicator Engineering PLLC

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ENCLOSURE:

Appendix A Hydrologic Analysis

Appendix B Select Photos from Slide Ridge Debris Flow

Appendix C Debris Flow Modeling of Alternatives

APPENDIX A HYDROLOGIC ANALYSIS

Rainfall durations from 10-minutes to 12 hours are plotted in figures below. Figures A1 to A3 are colored by event. Figure A4 combines all the results to a single plot for comparison.

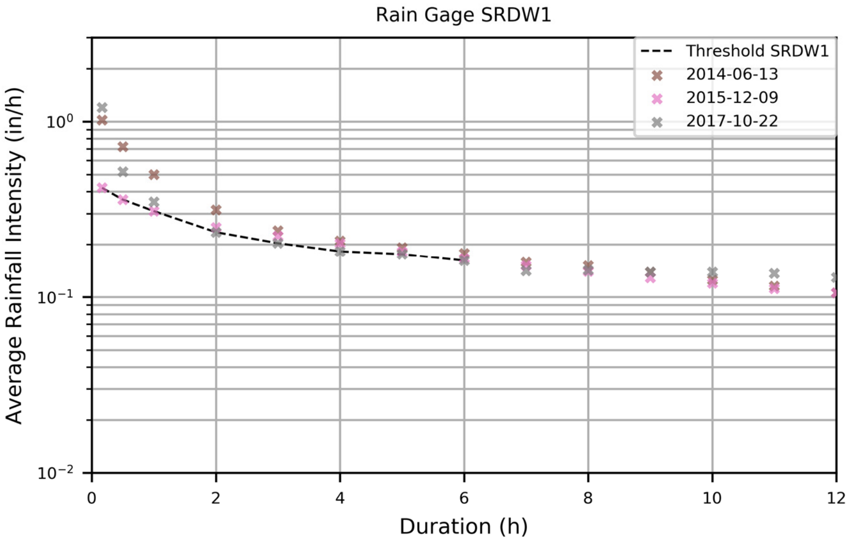


Figure A1. Duration plot of debris flow events for Slide Ridge rain gage.

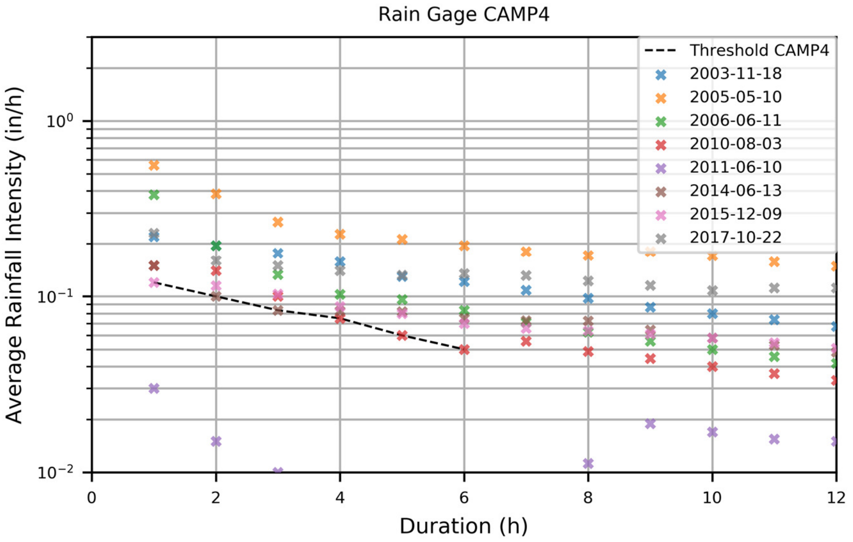


Figure A2. Duration plot of debris flow events for Camp4 rain gage. 2011 event was not captured well, and may have been a more localized thunderstorm, thus it was removed from determining the threshold.

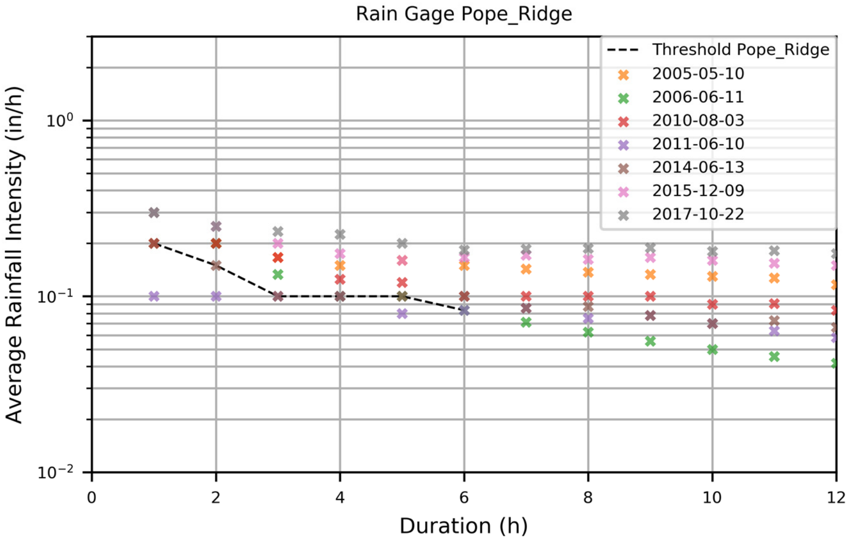


Figure A3. Duration plot of debris flow events for Pope Ridge rain gage.

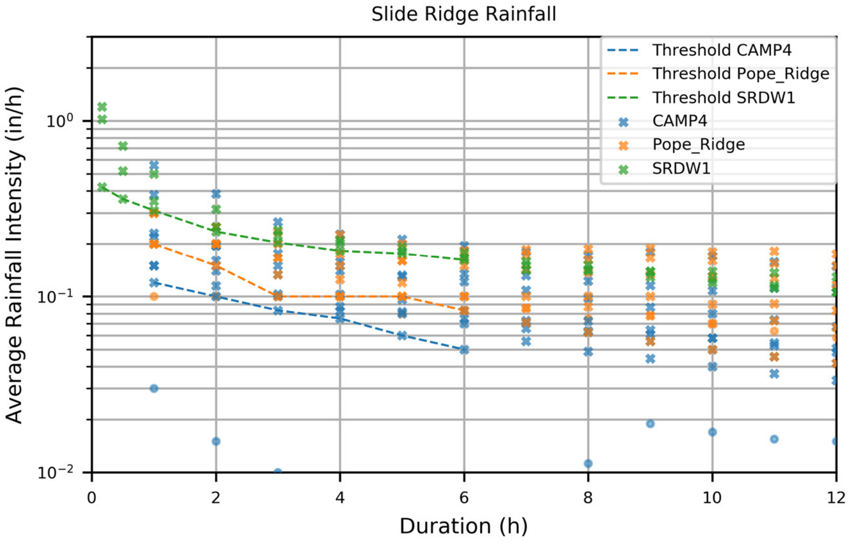


Figure A4. Duration plot of debris flow events for all 3 rain gages. Each 'x' represents a historic event at a given duration, while the 2011 Camp4 event is excluded and shown as 'o'. The calculated minimum rainfall thresholds for each gage are shown as dashed lines.

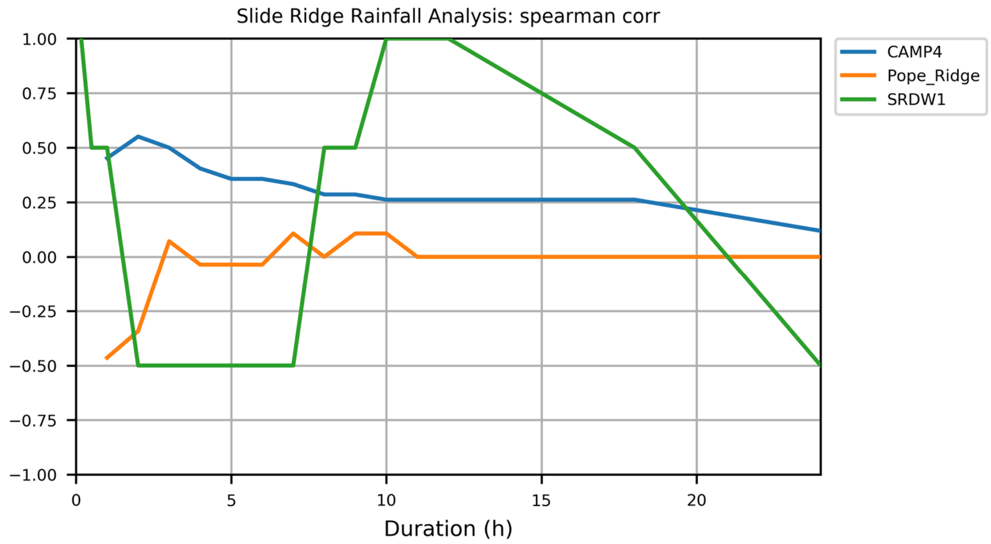


Figure A5. Spearman Correlation plot of Slide Ridge rain gage analysis. Spearman correlation values closer to 1 or -1 indicate stronger correlations. Camp4 gage is best correlated at 2-hour duration. Pearson correlation showed similar results. Slide Ridge gage doesn't have a long enough record for reliable statistics.

APPENDIX B SELECT PHOTOS FROM SLIDE RIDGE DEBRIS FLOW

Pre October 2017 event. Notice the small debris flow that had previously reached the basin.

October 2017 event during emergency cleanup of road, prior to re-opening.

Upper Basin August 2017. Appears very similar to 2010 photo.

June 14, 2010 photo showing multiple debris flows with storage in upper channel. Taken about mid-way upstream from road to channel bend.

May 10, 2005 is the largest event in last 15 years. Viewing north along S Lakeshore Road.

May 10, 2005 is the largest event in last 15 years. Viewing south along S Lakeshore Road.

May 10, 2005 is the largest event in last 15 years. Debris flow ran all the way to the lake in the downstream channel.

2018 August, looking at inlet of primary culvert from debris basin.

2018 August, viewing south to the 48” overflow culvert at the south end of the debris basin.

2018 August, viewing downstream at a check dam. Typical channel conditions for post-maintenance, prior to and debris deposition.

APPENDIX C DEBRIS FLOW MODELING OF ALTERNATIVES

Conveyance Alternative DFLOWZ Modeling Evaluation by Joanna Curran

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 is 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. The slope and geometry of the debris channel were altered to develop testing scenarios. A sequence of berms was created parallel to the sides of the channel to prevent debris from flowing outside the defined channel area downstream of the road. The same berms were extended for a second set of model runs to determine the berm height necessary to contain the debris flow on the road. All debris flow channels had a 14-foot-wide base. Berm location defining the channel top width were tested at 45 foot. 72 foot, and 95 foot.

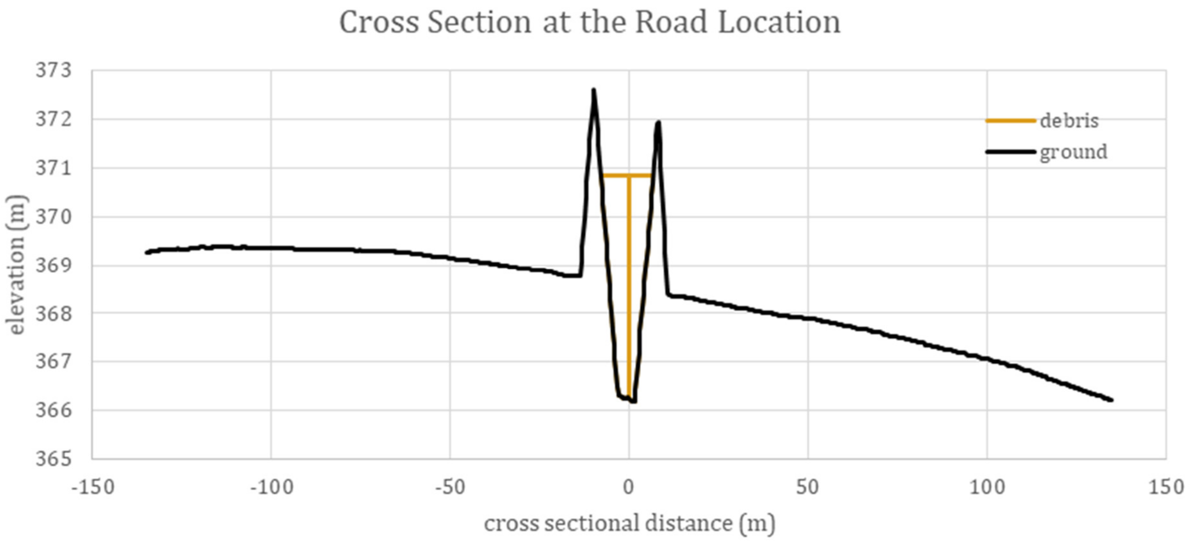
Model coefficients are adjusted to reflect relative water content in the debris flow (affects primarily the runout length) and the grain size distribution (affects primarily the width covered by the deposit). The model was calibrated to the 2017 event which had a volume of approximately 9200 CY. For the alternatives analysis, four debris flow volumes were tested: 9200 CY, 10,000 CY, 15,900 CY, and 20,000 CY. The largest volume represents the volume of a debris flow with a 1% probability of occurrence. In all situations we considered the debris flow as beginning deposition at the location of the debris basin. This location corresponds with what was observed following the 2017 event and allows for a robust test of deposition over the area of the basin and road for each alternative.

The most informative results from the alternatives tested are summarized in the table. Alternatives that were tested but produced unacceptable results are not shown. An example are the alternatives that led to debris extending down the road or breaking out of the downstream channel and depositing laterally where there are currently houses. Only the results using the 14% slope channel are shown because there was not a difference in the results when the slope was lowered to 12%. It is possible that a change in the results would occur if the change in slope were greater.

Channelizing the debris flow downstream of the road crossing aiding in transport to the lake. However, 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 volumes up to 10000 CY were able to remain within the area of the channel at the road for all scenarios. An example of a debris flow deposit that fills part of the excavated channel at the road is shown in the figure below (scenarios with 9200 CY of debris). When the volume increased to 15900 CY, there was a very small amount of deposition outside of the channel as the height of the deposit exceeded the excavated channel. Deposition became significant at the 20000 CY event and remained significant under all scenarios tested. The wider berm alternatives were able to transport a greater amount of debris directly to the lake and lowered deposit elevations within the channel. There was not a difference in the runout lengths of deposit heights between the 6- and 9-foot berms once the distance between the berms was widened to 75 feet.

Berm height (ft)	Distance between berms (ft)	Volume, yd3	total length of deposit (ft)	length in lake (ft)	deposit height at road (ft)	deposit depth over road (ft)
0	45	9200	977	135	1216.7	7.3
0	45	10000	977	135	1217.2	7.8
0	45	15900	977	135	1220.3	11.0
0	45	20000	977	135	1220.3	11.0
3	45	9200	1151	309	1216.7	7.3
3	45	10000	1151	309	1217.2	7.8
3	45	15900	1151	309	1220.3	11.0
3	45	20000	1151	309	1222.1	12.8
7	45	9200	1102	260	1216.7	7.3
7	45	10000	1102	260	1217.2	7.8
7	45	15900	1328	486	1220.3	11.0
7	45	20000	1102	260	1223.2	13.9
10	75	9200	1273	431	1216.7	7.3
10	75	10000	1102	260	1217.2	7.8
10	75	15900	1423	486	1220.3	11.0
10	75	20000	1328	486	1220.3	11.0
7	75	9200	1273	431	1216.7	7.3
7	75	10000	1273	431	1217.2	7.8
7	75	15900	1328	486	1220.3	11.0
7	75	20000	1328	486	1220.3	11.0



Empirical Channel Sizing Calculations

Slide Ridge debris flow sizing calculations were primarily adopted from Rickenmann (1999). The empirical relationships use the debris flow volume and channel parameters as inputs and estimate depths, velocities, and peak flows. Equations 1, 2, 17 and 21 were applied to estimate peak flows (1 and 2), Manning's n (17) and velocity (21). The results for the proposed conveyance channel are presented in the table below.

Debris Flow Volume (CY)	LOCATION	Peak Discharge (cfs)	DEPTH (ft)	Velocity (ft/s) (manning-strickler, eq17)	Velocity (ft/s) (eq21)	Slope (ft/ft)	Bottom Width (ft)	Side Slope (h:v)	Top Width (ft)
20000	us transition	10,838-8,752	13.5-15.2	19.4-20.3	24.6-26.4	0.19	20	1	50.4
20000	bridge 40-ft	10,839-8,752	12.6-14.9	17.3-18.2	20.5-22.0	0.11	40	0	40.0
20000	ds channel	10,838-8,752	13.2-15.0	15.3-16.0	19.9-21.3	0.1	30	1	60.1
15000	us transition	8,530-6,994	11.8-13.3	18.6-19.3	22.8-24.4	0.19	20	1	46.5
15000	bridge 40-ft	8,530-6,994	10.7-12.4	16.4-17.2	19.0-20.3	0.11	40	0	40.0
15000	ds channel	8,530-6,994	11.5-13.0	14.6-15.2	18.5-19.7	0.1	30	1	56.0
9200	us transition	5,672-4,774	9.4-10.4	17.3-17.9	20.1-21.3	0.19	20	1	40.9
9200	bridge 40-ft	5,672-4,774	8.1-9.1	14.8-15.5	16.8-17.8	0.11	40	0	40.0
9200	ds channel	5,672-4,774	9.1-10.1	13.5-14.0	16.3-17.2	0.1	30	1	50.2
5000	us transition	3,412-2,967	7.0-7.7	15.6-16.1	17.2-18.0	0.19	20	1	35.3
5000	bridge 40-ft	3,412-2,967	5.7-6.3	12.9-13.5	14.4-15.0	0.11	40	0	40.0
5000	ds channel	3,412-2,967	6.7-7.3	12.1-12.5	13.9-14.6	0.1	30	1	44.7
Historic Events (2003-2017)	us channel	7,946-876	3.7-13.8	12.8-19.9	12.1-26.0	0.22	15	1	42.6