Debris Flows

This module provides guidance for investigating debris flows (potential or recent events); analyzing impacts of debris flows; and selecting and designing countermeasures to mitigate impacts. Debris flow investigations may be required in response to storm damage and wildfire response at the request of the District Major Damage Coordinator or Maintenance Engineering but should also be considered for any project occurring in regions susceptible to debris flows. The Geoprofessional (GP) is responsible for investigating debris flow potential as well as evaluating recent or anticipated debris flow impacts. The GP should include recommendations to mitigate impacts in their reports and must collaborate with other functional units, e.g., Hydraulics, Maintenance Engineering, Construction, Environmental, etc., to select, design, and construct the appropriate countermeasures.

Debris flows are high-velocity landslides typically generated by high intensity rainstorm events that saturate steep mountain slopes and watersheds, leading to the rapid movement of soil and rock entrained in water within drainage channels downstream towards valleys. Debris flows that intersect the State Highway System cause debris accumulation, inundation of drainage systems, severe erosion and scour at culverts and structures, and overtopping and failure of roadway embankments (Kirk, 2021; Zekkos and Stark, 2024; Figure 1).

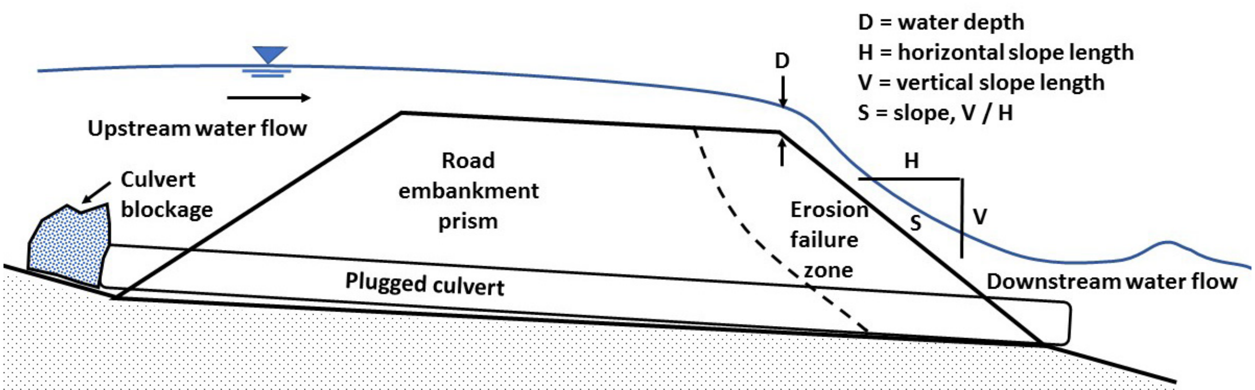

Figure 1: Diagram of embankment overtopping during debris flow and flooding conditions (Kirk, 2021).

The threat of debris flows is exacerbated by aging infrastructure and increased frequency of wildfires. Recently burned areas generate increased runoff, sediment, and debris during storm events and are a common source of debris flows in California that can threaten California's highway system (Fraser et al., 2022; Li and Chester, 2023; Zekkos and Stark, 2024). Various federal and state agencies are tasked with providing rapid debris flow prediction information to help prevent damage including the Burned Area Emergency Response Team (BAER), Watershed Emergency Response Team (WERT), and the United States Geological Survey (USGS), see the Caltrans Office of Vegetation and Wildfire Management BAER-WERT Procedural Guide for details on the BAER-WERT teams (OVWM, 2023). The modern expansion of the post-wildfire debris flow interagency response has greatly improved Caltrans' ability to anticipate post-fire debris flows and implement mitigation within the highest risk timeframe, typically 1-3 years post-fire. This module will focus primarily on debris flows associated with post-fire conditions, but the guidance can generally be applied to other debris flow scenarios.

Investigations

Perform debris flow investigations upon request and under the following conditions:

1. Emergency post-fire in steep mountainous terrain
2. Emergency debris flow event
3. Improvement project located in debris flow prone area

The Highway Design Manual Chapter 810 (HDM 810) describes Debris Hazard Areas as locations:

(a) At or near the toe of slope 2:1 or steeper
(b) At or near the intersections of ravines and canyons
(c) Near or within alluvial fans
(d) At soil slips

The goal of a debris flow investigation is to determine the location, size, and probability of debris flows to impact the highway, and to inventory and inspect all State assets that may be, or have been, impacted by debris flows (i.e., Values-At-Risk, VAR). In post-fire conditions in debris hazards areas, the risk of other geohazards such as flooding, landslide, rockfall, etc., increases. Branch Chiefs and Emergency Response Specialists must coordinate with Caltrans Major Damage Coordinators and District Maintenance Engineering to ensure that debris flow investigations, if implemented, are performed by Geotechnical Services. This module addresses flooding hazards as it relates to debris flow investigations, but landslide and rockfall investigations should be performed according to the respective module.

<u>BAER-WERT</u>

The BAER-WERT teams are assembled to rapidly identify and assess post-fire risks to life and property, i.e., VAR. The teams are interdisciplinary and include environmental scientists, hydrologists, soil scientists, geologists, foresters, biologists, and other specialists. The BAER-WERT teams implement a systematic process beginning with detailed soil burn severity mapping and watershed topographic data collection and compilation. These data are typically used by the USGS to model potential debris flow hazards within the burned area according to typical local rainstorm intensities (Staley et al., 2016, 2017). Using the debris flow modeling data from the USGS combined with their own calculations, the BAER-WERT teams will perform site assessments to inventory VAR that may be impacted by potential debris flows. A summary of BAER-WERT procedures is outlined in the Caltrans Office of Vegetation and Wildfire Management BAER-WERT Procedural Guide (OVWM, 2023). Although BAER-WERT teams may identify major Caltrans VAR, e.g., bridges, they do not perform a detailed inventory of all Caltrans specific VAR. BAER-WERT reports should be reviewed in detail by the GP performing the post-fire debris flow investigation, and the GP should discuss the details of the report with BAER-WERT personnel. Ultimately, the GP must perform their own comprehensive identification and assessment of Caltrans VAR.

USGS Debris Flow Models

To determine Caltrans VAR, first determine the location, probability, and size of potential debris flows. The best available data are provided by the USGS. The USGS utilizes the BAER team's soil burn severity mapping to model potential debris flow hazards within the burned area (Staley et al., 2016, 2017). The data estimates debris flow likelihood, volume, combined hazard, and rainfall thresholds. The combined relative hazard metric (Table 1) is a combination of the likelihood of debris flow (in %) and potential volume of debris (in cubic meters). The data are published in map form, but increasingly the data are becoming available in digital web-based databases such as GIS web apps such as the USGS Post Wildfire Debris Flow Hazard Assessment (PWDFHA) Viewer (USGS, 2024).

The PWDFHA viewer allows the GP to see limited data based on a single design recurrence interval storm (typically 24 mm/hr for 15-minute duration); however, the default data shown in the viewer are insufficient to assess impacts to Caltrans VAR. For instance, the GP should assess debris flows hazards according to 1- and 2-year recurrence interval rainstorm intensities (15-minute duration) determined for, or measured from within, the burn area or as close as possible. The 1- and 2-year recurrence interval storm rainfall intensities are prioritized due to the probability of them occurring within the first three years after a recent fire when the watershed is particularly susceptible to debris flow initiation (Kirk, 2021). In fact, the majority (77%) of debris flows in the southwestern United States are triggered by rainfall intensities with a recurrence interval of 2-years or less (Staley et al., 2020). The 1- and 2-year storm intensities for a given site can be obtained from the closest weather station recorded on the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 Precipitation Frequency Data Server available online (NOAA, 2024). The GP compiles and reports the USGS debris flow model data generated for 15-minute duration rainstorm intensities closest to the 15-minute duration 1- and 2-year storm intensities reported for the site on NOAA Atlas 14. Note that the data are reported as millimeters of rain for 15-minute duration and that USGS debris flow data are published based on mm/hr. Multiply the NOAA rainstorm data by four to convert to mm/hr.

Appendix 1 provides instructions on how to view, export, and compile the necessary USGS debris flow data using ArcGIS Pro. Compile and report the following USGS debris flow segment data where they intersect or are near Caltrans facilities (i.e., roadway-channel intersection data; Figure 2):

- Upstream Watershed Area
- Percent Watershed Burned
- Percent Watershed Moderately-Severely Burned and >23 degrees

- Debris flow data for 1- and 2-year rainfall intensity specific to the burn area, data includes:
  - Probability
  - Volume (including min and max)
  - Combined Hazard Ranking (Score and Low/Medium/High; Table 1)

These data can be accessed by downloading the USGS debris flow GIS geodatabases for the fire in question. The GP can upload the data to ArcGIS, ArcMap or other GIS software and collect and compile the object or segment IDs for select debris flow segments intersecting Caltrans facilities (or the closest) using the instructions provided in Appendix 1. These segment IDs can be used to filter the tabulated raw debris flow data exported from GIS for the segments of interest and, thereby, allow the GP to compile all the roadway specific debris flow data. This data must be critically reviewed alongside the adjacent Caltrans facilities at each location and used in decision making and mitigation design. The GP may request assistance from District GIS support or the Office of Vegetation and Wildfire Management GIS Branch to extract roadway specific debris flow data. The USGS data does not determine debris flow runout and, therefore, the GP must use professional judgement to determine if Caltrans facilities are close enough to mapped USGS debris flow hazards to warrant further investigation and mitigation.

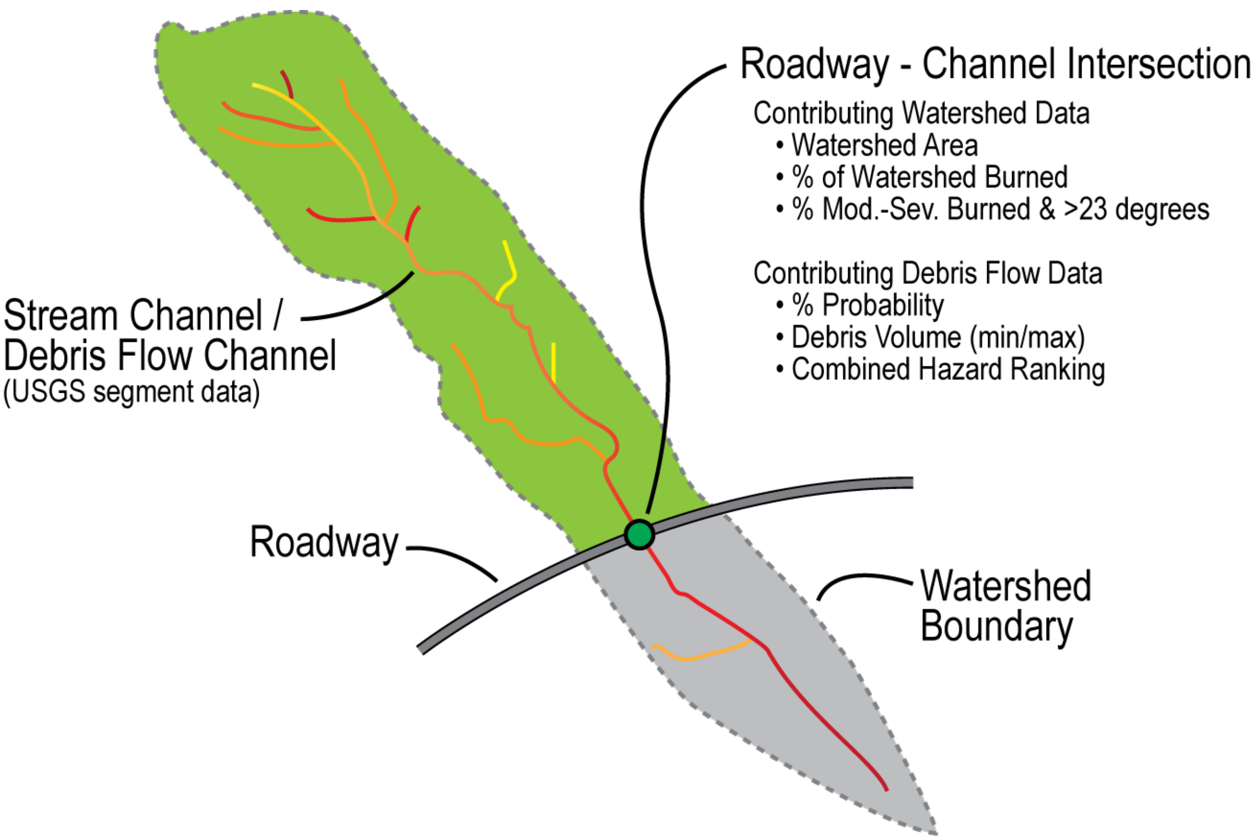

Figure 2: Diagram illustrating pertinent USGS debris flow and watershed data.

Table 1: Combined Debris Flow Hazard Criteria

Probability of Debris Flow	Debris Volume (m^3): <1,000	Debris Volume (m^3): 1,000 - 10,000	Debris Volume (m^3): 10,000-100,000	Debris Volume (m^3): >100,000
0-20%	Low	Low	Moderate	Moderate
20-40%	Low	Moderate	Moderate	Moderate
40-60%	Moderate	Moderate	Moderate	High
60-80%	Moderate	Moderate	High	High
80-100%	Moderate	High	High	High

<u>Estimating Debris Flow Volumes</u>

BAER soil burn severity mapping and USGS debris flow modelling may not be performed for wildfires that do not occur on state or federal land. Also, projects may require debris flow mitigation recommendations in areas that have not recently experienced fire and new USGS debris flow data will not be generated. Therefore, it may be difficult or impossible to accurately determine the probability and volume of debris flows. In many wildfire prone areas, however, there are historical USGS debris flow data available on the USGS PWDFHA Viewer. Determine if historical debris flow data are available for the site and use data whenever available.

If no USGS data are available, estimate the volume of a debris flow by evaluating the length and condition of the watershed drainage channel. Debris flows are primarily caused by scour and erosion of the drainage channel. Therefore, the accumulation of soil and debris within the channel, i.e., “load” of the channel, directly correlates to the potential debris flow volume. The length of the drainage channel and tributary channels can be approximately measured using Google Earth and the width and depth of debris within the channel can be measured or approximated in the field. The width and depth of the debris channel refers to the narrow channel of accumulated surficial soil, rock, and woody debris. Steep mountainous debris flows will typically only scour a 5 to 10-foot-wide drainage channel to a depth of 2-5 feet. The debris volume can be estimated from a simple calculation using these measurements as shown in the equation below:

Debris Volume = Length of Drainage Channel x Width of Debris Channel x Depth of Debris Channel

This calculation does not account for many important variables that contribute to debris volume and potential, e.g., rainstorm intensity, drainage and watershed slope angle, non-uniform loading of the debris channel, etc. Furthermore, the calculation provides no probability data to assess the likelihood of debris flows occurring within the watershed. The estimate does, however, make a first-order approximation of the scale of the debris flow hazard at a site and design conservative mitigation measures.

Caltrans Values-At-Risk

Debris flows inundate retention basins leading to overtopping flows and roadway embankment washouts. Debris flows and flooding also lead to bank erosion and scour if flows occur at the bottom of embankments or adjacent to structures. These damages can result in long closures and costly repairs. Mitigative measures can often minimize impacts from debris flows if implemented as soon as possible in post-fire conditions (1-2 years) or during reconstruction or repair following recent debris flows. In many cases, existing facilities may be in poor condition and subject to increased vulnerability due to post-fire debris flows and flooding. When determining Caltrans VAR, the GP must photograph, inventory, and inspect the condition of the following facilities within the vicinity of each potential debris flow location or within the entire burn area:

- Postmile of debris flow location/intersection
- Culvert (PM, system number, size, material)
- Retention basin (estimated volume, capacity - clear/full)
- Debris control structure (size, material)
- Downslope embankment (enforcement present, AC dike, berm, etc.)
- Overside drain conditions (size)
- Structure support locations (scour protection present)
- Upstream watershed channel (cleared or loaded with soil/debris)
- Channel debris material (fine, coarse, boulders, woody)

By combining Caltrans facility and USGS debris flow data the GP can assess and report on Caltrans VAR. These data points are critical in decision making, prioritizing, and mitigative design. Special attention should be given to areas with high combined hazard ranking within the 1- and 2-year storm intervals. Aggressive mitigation strategies should be employed if these systems have small culverts, vulnerable embankments, or small retention basins.

Preliminary Post-Fire Response (prior to BAER-WERT and USGS data)

District Major Damage Coordinators and Maintenance Engineering may request assistance from Geotechnical Services before BAER-WERT reports and USGS debris flow data are available. The USGS debris flow data relies on soil burn severity data that is reportedly available one to seven days after fire containment. Ultimately, USGS debris flow data are typically available within 1-2 months after the start of a wildfire. Any post-fire response prior to the release of USGS debris flow data should be limited to mitigation of post-fire rockfall hazards, notifying the District that debris flow prone watersheds above the highway have been severely burned and are at an elevated risk of debris flow pending further review and data from the USGS, and preliminary debris flow mitigation. Notify the District that a detailed debris flow investigation and debris flow mitigation are required and recommend that District Hydraulics be requested to assess drainage facilities within the burned area and provide debris flow mitigation recommendations. Preliminary debris flow mitigation recommendations prior to the release of USGS debris flow data may include:

- Clearing of culvert inlet retention basins
- Replacing/repairing/upgrading existing debris control structures
- Repairing/upgrading AC dike and earthen berm protecting roadway embankments
- Recommending inspection of all drainage systems within the burned area (including downdrains/overside drains)
- Recommend a hydraulics analysis at culvert locations within the burned area utilizing a debris flow bulking factor of 1.67 to 2.00, according to HDM 810
- Recommending a detailed debris flow investigation following the release of USGS debris flow data

It is critical that GPs emphasize that post-fire debris flows pose an imminent threat to state facilities up to approximately three years after recent wildfire. Debris flow mitigation projects should occur as quickly as possible following wildfire but may be delayed by environmental permitting, Director's Order approval, mitigation design decision-making, and contractor readiness. For these reasons, post-fire debris flow mitigation projects may be protracted, and the GP should ensure their assessment and mitigation recommendations are not finalized until USGS debris flow data are released, reviewed, and summarized in the GP's report.

Recent Debris Flow

Recent debris flows most commonly occur in California due to post-fire conditions or high intensity rainstorms. In these cases, the GP is typically requested to assess impacts and provide repair recommendations. If a debris flow has occurred, it's likely several sites within the vicinity have experienced debris accumulation and flooding conditions. Photograph, inventory, and inspect Caltrans VAR as described in the previous section within the vicinity of the debris flow location. All damages must be documented and reported to the District to reestablish the drainage and improve resiliency of the facilities. All debris flow material must be removed to reestablish the original retention basin dimensions.

Coordination with District Hydraulics

District Hydraulics should be involved in all potential or recent debris flow hazard investigations. Post-fire debris flow hazards and recent debris flows are often associated with flooding. Therefore, debris flow mitigation and response should consider drainage system improvements and protections. Request that District Hydraulics inspect the condition of drainage systems within recent burn areas and assess whether their condition, size, and any rigid barrier systems are adequate for increased sediment load and runoff. District Hydraulics is ultimately responsible for drainage redesigns and rigid debris control structures. Any Caltrans VAR documented by the GP should be reported to District Hydraulics along with a request for their assessment.

Coordination with Structure Maintenance and Investigations

Structure Maintenance and Investigations (SM&I) should be involved whenever anticipated post-fire flooding and debris flows have the potential to impact bridges or bridges have been recently impacted by flooding and debris flows. Identify bridges within the USGS debris flow pathway, or downstream from the USGS debris flow pathway, that may be impacted by debris flow runout. The GP should recommend the district request an investigation and design recommendations from SM&I. Mitigation and repair investigations and designs are the responsibility of various SM&I units, which may include Hydraulics, Bridge Investigations, and Bridge Maintenance Design branches. The Area Bridge Maintenance Engineer should be contacted to help coordinate with SM&I.

Design

Debris flow mitigation strategies are divided into four categories: management, stabilization, protection, and avoidance. Each strategy is weighed against the debris flow risk, purpose of the project, and potential costs. For the purposes of this module, it is assumed the project is mitigating anticipated debris flows due to post-fire conditions. The GP has completed their investigation and has compiled USGS debris flow data and Caltrans VAR information. The strategies are presented below in order of increasing cost:

1. Management includes warning signs; weather and roadway monitoring; establishing rain intensity thresholds for evacuation, warnings, and road closures. Management is generally implemented for all major fires with anticipated debris flow hazards. Management is generally coordinated by an interdisciplinary and interagency team with limited contribution from Geotechnical Services.

2. Stabilization measures include various forms of erosion control applied to the watershed or drainage channel, e.g., mulching, seeding, and erosion fencing. For these measures to be affective they generally need to be implemented beyond Caltrans right-of-way.

3. Protection techniques include increasing debris retention basin size, constructing rigid or flexible barriers, earthen berms, upsizing culverts, upsizing/adding overside drains, AC dike/berms, and embankment reinforcement/armoring. See Tables 2 and 3 for summaries of protection measures.

4. Avoidance measures rely on relocation or realignment of the road away from the anticipated debris flow path. Generally, this involves elevating the roadway above the path via a bridge. The cost and time involved often preclude this mitigation approach from being selected.

Management

Debris flow management is a typical countermeasure implemented in post-fire conditions. Management begins with WERT establishing a rainfall intensity threshold that is anticipated to trigger debris flows. These triggers are communicated to various agencies, including Caltrans, and a burn area monitoring plan is developed. Rainfall thresholds are used to determine when public warnings and mandatory evacuations will be implemented. For Caltrans, these thresholds may be used to implement preemptive road closures or increased maintenance monitoring of the roadway. Signage may be posted communicating potential debris flow hazards within burn areas. The GP should recommend that the District engage in debris flow management following recent fires and implement preemptive road closure and monitoring when USGS debris flow data indicate multiple high combined hazard rating debris flow models intersect the highway. Management, however, is often implemented with limited involvement of Geotechnical Services.

Stabilization

Stabilization includes erosion control countermeasures installed in the watershed or drainage channel to minimize runoff and control soil and debris mobility. Examples of stabilization measures include seeding, mulch, log erosion barriers, silt fences, etc. Studies have shown that the bulk of debris flow material is sourced from the watershed channel and not from side slopes (Santi et al., 2007). Therefore, mulching and seeding side slopes has only a slight but measurable reduction in debris flow volume. Mulching and seeding need to be applied to large areas, generally outside of Caltrans right of way. The GP should recommend consulting the Office of Vegetation and Wildfire Management (OVWM) and District Landscape Architecture to determine if seeding and mulching is warranted and necessary for designs. The District may decide to partner with external agencies or request permits to perform seeding and mulching outside of Caltrans right of way; however, the associated costs are generally prohibitive and should be limited to high value/risk VAR.

Drainage channel stabilization methods include silt fences, check dams, and debris racks. Silt fencing has been shown to be ineffective in debris flow mitigation and should not be recommended (Santi et al., 2007). Check dams and debris racks installed in sequence within the upper reaches of debris channels, if constructed properly and in < 2 km^2 watersheds with channel gradients less than 25 degrees, have some potential for reducing debris flow volume. Constructing and maintaining check dams and debris racks often requires working outside of Caltrans right of way and in areas with very difficult access to be most effective. Therefore, implementing these countermeasures are rare and generally left to the responsibility of the property owner, e.g., federal and state forest services. The GP should consult the WERT and OVWM to determine if check dams and debris racks within the upper reaches of drainage channels should be considered for high value/risk VAR. District Hydraulics is responsible for designing debris racks and dams according to the FHWA Debris Control Structures, Hydraulic Engineering Circular (HEC) 9 (FHWA, 2005).

Protection

Debris flow protection measures can either occur upstream or downstream. Upstream protection measures are intended to stop debris and water from overtopping the roadway or impacting a facility, typically by increasing debris retention and keeping drainage systems operational. Downstream protection measures are intended to protect the downstream embankment from erosion by diverting runoff water and debris to controlled drainage systems or armoring the embankment. A summary of upstream and downstream protection measures is provided in Tables 2 and 3, respectively. The use and effectiveness of protection measures have been documented in numerous studies (e.g., Foltz et al., 2009; Papaioannou, 2023; Santi et al., 2007). Post-fire and recent debris flow mitigation must consider a combination of protection measures best appropriate for the site conditions, debris flow risks, and project scope.

Retention Basin Modifications

Culvert inlet retention basins should be restored to maximum available capacity following recent fires or recent debris flows to minimize the likelihood of debris and water overtopping the roadway embankment. Generally, the GP should assess the condition of each retention basin within the burned area and recommend debris removal volumes to re-establish capacity. Clearing should be done to the maximum extent possible, in many cases right-of-way may limit the extent of clearing. Access roads may need to be re-established or constructed if the basin is in a deep canyon. Access road construction prior to post-fire debris flows provides valuable access to rapidly clear debris flows from drainage systems following debris flow events. Deflection or retention berms may be constructed within large retention basins to divert debris towards alternative sub-basins, towards drainage systems, or to confine debris to a particular area within the basin. Retention basin modifications are a cheap, first-line protection measure for debris flow mitigation.

Table 2: Upstream Protection Measures

Protection Measure	Description / Purpose	Limitations	Design Unit Responsible
Retention basin modifications	Removal of debris from retention basin to increase capacity. Constructing deflection berms to reduce flow energy or divert flow.	Small retention basins are easily overtopped. Debris may still block culvert inlet and water will not drain, which may lead to overtopping the embankment.	GS & Hydraulics
Rigid Barriers	Rigid debris deflectors, inlet debris racks, or rigid debris racks to keep woody and coarse debris from clogging culvert inlet and allow water to pass through.	Limits maintenance access to inlet basin for clearing. Foundations constructed in waterway may be considered an environmental impact.	Hydraulics (FHWA HEC 9), GS may recommend
Flexible Barriers	Flexible debris flow barriers keep woody, coarse, and fine debris from clogging culvert inlet and allow water to pass through.	Requires repair/replacement after impact and loading. May still be overtopped and lead to blocked culvert if barrier is undersized. Installation is expensive and requires specialty contractor.	GS, Hydraulics may recommend
Culvert upsizing, redesign, and replacement	Increasing culvert capacity or replacing poor condition culverts to account for increased runoff and high bulking factors. Culvert upsizing reduces likelihood of becoming blocked and embankment overtopping.	Large woody debris can still block upsized culverts. Site conditions may limit culvert upsizing. Expensive and not quickly deployed.	Hydraulics, GS may recommend
Redundant culvert inlets (i.e., risers)	Extensions of the culvert to cause deposition of flowing debris before it reaches the culvert inlet.	Vertical risers may be damaged by large debris flows. Redundant inlets anchored to basin slopes are easily damaged by debris flows.	Hydraulics, GS may recommend
Relief drainage systems (i.e., culvert near roadway grade)	Additional culverts near the roadway grade as relief systems if the lower culvert becomes blocked and water pools upstream of the roadway embankment. Should be considered for all moderate to high combined hazard rating debris flow locations and locations with large watersheds.	May only be feasible in larger/deeper inlet retention basins.	Hydraulics, GS may recommend

Table 3: Downstream Protection Measures

Protection Measure	Description / Purpose	Limitations	Design Unit Responsible
AC Dike/Berm	New/replacement AC dike or berm installed along roadway at top of downstream embankment to redirect overtopping water to controlled drainage system and armored embankment.	May be ineffective if significant debris accumulates on roadway.	Hydraulics, GS may recommend
Earthen Berm	Earthen berm behind AC dike to further protect the embankment from overtopping water and debris.	Site may be a narrow roadway without space for a berm.	Hydraulics, GS may recommend
Overside drains and downdrain upsizing	Repairing or increasing size of overside drain or downdrain systems to account for increased flows.	Not quickly deployed.	Hydraulics, GS may recommend
Embankment Armoring - Rip Rap	Placing rip rap on downslope embankment as energy dissipator and erosion control against overtopping flows.	Steep large embankments may be difficult and expensive to place rip rap on. Mitigative rip rap may be considered an environmental impact.	Hydraulics, GS may recommend
Embankment Armoring - Turf Reinforcement Mat	Placing turf reinforcement mat on downslope embankment as energy dissipator and erosion control against overtopping flows.	Steep surrounding terrain with large circumference trees and large boulders are not appropriate for TRM. Limited case studies, evidence, and Caltrans experience.	Hydraulics, GS may recommend
Embankment Armoring - Articulated Concrete Blocks	Placing articulated concrete blocks on downslope embankment as energy dissipator and erosion control against overtopping flows.	Steep large embankments that exceed manufacturer recommendations may exclude this option. Limited successful case studies, evidence, and Caltrans experience for overtopping debris flow mitigation. Expensive construction and potential environmental impacts.	Hydraulics, GS may recommend
Embankment Armoring - shotcrete/reinforced concrete	Placing shotcrete or reinforced concrete aprons on downslope embankment to protect against overtopping flows.	Shotcrete is best on small embankments or erosion features for quick mitigation. Reinforced concrete aprons are rarely used compared to rip rap for debris flow mitigation. Similar limitations to rip rap.	Hydraulics, GS may recommend

Debris Barriers

Debris barriers include a variety of steel and timber structures installed within the drainage channel or at the culvert inlet to keep woody and coarse debris from blocking the culvert. Ultimately, the goal of debris barriers is to preserve the capacity of the drainage system so that water and fine debris can pass under the roadway rather than overtopping the roadway. Debris barriers have historically been rigid, i.e., constructed from steel or timber beams, that have concrete foundations or are attached to a culvert inlet structure. Alternatively, flexible debris flow barriers, constructed out of cable rings, support cables, and steel posts, have become popular due to their versatility and retention capacity. Assess whether a debris barrier is warranted for the potential debris flow site and if rigid or flexible designs are appropriate.

I. Rigid Debris Flow Barriers: Includes debris deflectors, inlet and channel debris racks, and rigid debris check dams. The District Hydraulics Engineering Branch is responsible for recommending and designing rigid debris flow barriers according to FHWA HEC 9 (FHWA, 2005). Identify drainage channels and/or inlets that may be good candidates for rigid debris barriers based on basin geometry or due to high VAR and risk of overtopping. Rigid barriers are best suited when basin retention volume is close to or greater than anticipated debris volume and basin geometry allows for equipment access and debris clearing around and behind the rigid barrier. Timber debris deflectors should be replaced with steel debris deflectors to increase fire resiliency. In many cases, rigid debris barriers may require lengthy environmental permitting due to the construction of concrete foundations within waterways. Rigid debris barriers are a cost effective and standard approach to debris flow mitigation.

II. Flexible Debris Flow Barriers: Includes ring net and cable support systems installed with cable anchors within the drainage channel. Channels wider than approximately 60 feet typically require the use of steel posts to support and elevate the ring net system. Flexible debris flow barriers have become increasingly popular due to their ability to retain large debris flow volumes in almost any site condition (Berger et al., 2021). Furthermore, the system can be temporarily removed or partially disassembled (usually requires a specialty contractor and new funding) to allow access behind the barrier for clearing. Individual components of the system can be repaired, e.g., re-tensioning cable clips and support ropes, or replaced, e.g., brake rings and patching ring net. Maintenance and repairs, however, can be challenging with flexible barriers as the materials are proprietary and the work generally requires a specialty contractor. For instance, flexible barrier impacts often result in sagging systems due to brake ring elongation, which requires brake ring replacement. If frequent flexible barrier repairs are needed or anticipated, the GP should consider if a rigid structure could be constructed while maintaining access.

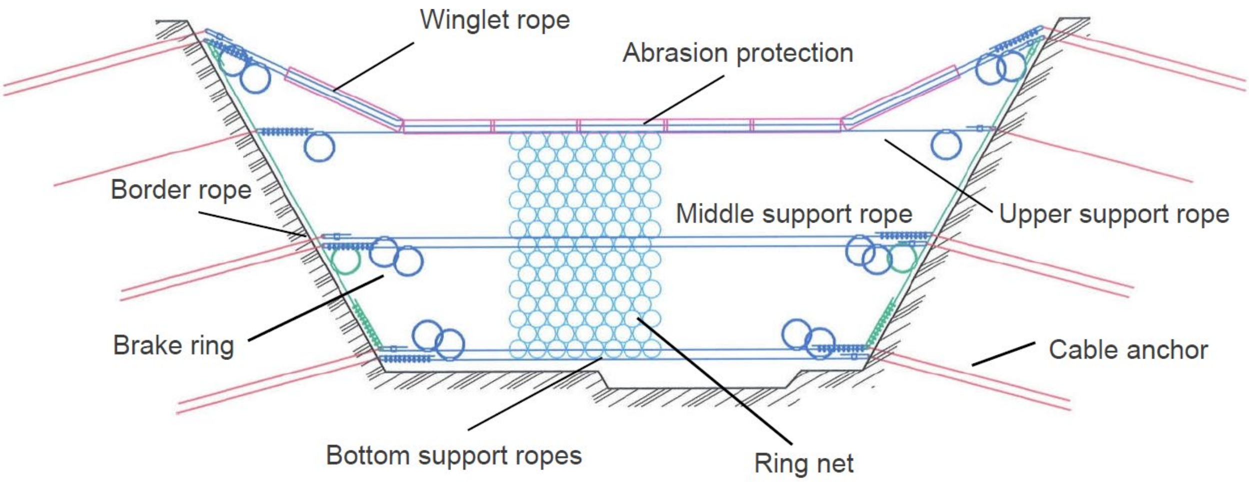

Figure 3: Typical diagram of a flexible debris flow barrier.
(Source: Geobrugg VX System; Geobrugg, 2016)

Flexible barrier systems are best suited for small/shallow inlet retention basins and/or steep channels with vulnerable downslope roadway embankments, i.e., unreinforced/armored slopes. Flexible barriers may also be suitable in narrow drainage channels and inlet basins where rigid debris barriers and deflectors would make access difficult for equipment. Flexible barriers should be considered in cases where there are environmental restrictions or delays caused by constructing rigid barrier foundations within the channel/water way. Flexible barrier anchors are typically installed in the walls of the drainage channel and, therefore, may avoid environmental impacts to the water way.

The recommendation and design of flexible barriers is typically the responsibility of Geotechnical Services. Most flexible barriers are constructed in emergency project situations and designed by the GP assigned or designed by the material manufacturer, specialty contractor, or a consultant to the manufacturer or contractor. Flexible barrier manufacturers offer a variety of standard design sizes based on the drainage channel dimensions, required retention volume (i.e., system height), and anticipated loads. Flexible barrier guides and manuals are increasingly available to assist in barrier dimensioning and design. These resources include user-friendly web-based flexible barrier dimensioning and design tools (e.g., DEBFLOW; Geobrugg, 2021, 2024). Dimension and design calculation methods and practical advice regarding barrier type and location are also readily available (e.g., Berger et al., 2021). See Appendix 2, and the manufacturer's manual (Geobrugg, 2021), for detailed instructions on how to use a web-based flexible barrier dimensioning tool to dimension and design flexible debris flow barriers.

Flexible barrier locations within the drainage channel should be selected to maximize anchor capacity and retention volume. The required anchor forces for flexible barriers are exceptionally high and comparable to anchor forces required for high impact energy rockfall fences. Anchor locations, therefore, should be constructed where anchors can be embedded in rock while maximizing volume retention if possible. Anchors have a typical hole diameter of three to six inches and have a minimum factor of safety of 2 for foundation anchor pullout resistance.

When designing flexible barriers, keep in mind that the total anticipated debris volume may not be retained by the barrier, but remaining material may be fine enough to pass through the drainage system and preserve the embankment. More than one flexible barrier in a single drainage system is rare due to right-of-way limitations; however, multiple barriers in succession should be considered if there is sufficient right-of-way and particularly vulnerable VAR downstream. The GP should consider an additional rigid barrier at the culvert inlet or other protection systems if a flexible barrier system cannot be reasonably designed to retain the entire anticipated volume.

Flexible barrier construction should be performed according to the manufacturer's installation manual. Inspect the constructed barrier prior to acceptance to ensure compliance with the system's plans and manufacturer's manual. Inspect the following components of all flexible debris flow barriers during and after construction to ensure compliance with the contract plans and specifications; manufacturer's manual; manufacturer's typical plans; or otherwise agreed upon project plans and specifications:

- Anchor materials, centralizer spacing, layout, hole diameter and depth
- Verification and/or production anchor testing
- Cable clip layout, spacing, and torque
- Ring net shackle attachment at support cables and seams
- Abrasion plate shackle attachment
- Post materials, foundation layout, and foundation and post construction
- Brake ring layout and spacing

Culvert Upgrades

All drainage systems vulnerable to anticipated debris flows, post-fire flooding, or impacted by recent debris flows should be thoroughly inspected and assessed by culvert inspection team members and District Hydraulics. The GP should also perform a preliminary investigation of these systems, either in coordination with the team members or independently. Detailed inspections should identify poor condition systems particularly vulnerable to flooding conditions. Furthermore, culvert capacity should be re-evaluated based on increased bulking factors. According to the Caltrans HDM 810, bulking factors for culvert sizing calculations within debris flow prone areas should vary from 1.67 to 2.00. The GP should recommend District Hydraulics perform an investigation of existing drainage systems within the burned area or area susceptible to debris flows using elevated bulking factors of 1.67 to 2.00, per the HDM. The results of these assessments may identify culverts that are undersized or in poor condition and in need of replacement/upsizing. Assist District Hydraulics to ensure all drainage system discharge onto bedrock or engineered energy dissipators, e.g., riprap.

Culvert replacement may be difficult due to site conditions, and, in these cases, redundant culvert inlets or relief culverts may be necessary. Redundant inlets refer to riser inlets installed on existing culverts, or an additional culvert installed near roadway grade, i.e., relief culverts. In many cases, relief culverts may be the most appropriate countermeasure, instead of culvert replacement or upsizing, to retaining full drainage capacity during flooding conditions. District Hydraulics is responsible for recommending and designing redundant inlets and relief culverts; however, GPs should recommend District Hydraulics consider relief culverts at all moderate and high combined hazard rating debris flow locations and all recent debris flow locations where overtopping has occurred. Site conditions may preclude sufficient culvert upgrades and require additional upstream and/or downstream protection measures.

AC Dike and Earthen Berm

Many debris flow prone areas have no AC dike installed on the downslope embankment or the existing dike is in poor condition. An AC dike should be installed on vulnerable embankments to divert water away from the embankment and towards controlled drainage systems, e.g., overside drains. Large AC dike designs have been installed on some flood and debris flow prone mountainous highways to address large surface water flows. The addition of an earthen berm behind the dike provides enhanced protection against debris overtopping. Typical earthen berm heights are three to four feet. District Hydraulics is responsible for recommending and designing AC dike and earthen berm; however, the GP should identify locations where these measures may be beneficial or where the existing dike and berm are distressed.

Overside Drain and Downdrain Upgrades

Overside drains and downdrains ensure that runoff water is discharged at the bottom of the embankment or at armored locations. In many flood and debris flow prone areas overside drains and downdrains are underutilized, undersized, or in poor condition. These systems are focal points of concentrated water flow and can easily become sites of embankment failure if they are missing, undersized, or poorly maintained. District Hydraulics is responsible for the design and recommendation of overside drains and downdrains. District Hydraulics should investigate the condition and sizing of all overside drains and downdrains in anticipation of post-fire debris flows and flooding, or in response to recent debris flows and flooding. Inspect these systems and alert the district and District Hydraulics to locations needing new drains or drain repairs. In many cases, large flume designs are preferred as they allow for easy inspection and clearing.

Embankment Armoring

Embankment armoring and protection measures include rock slope protection (RSP), precast articulated concrete blocks, shotcrete/concrete slope protection, and other less common measures such as turf reinforcement mats (Kirk, 2021). Embankment armoring recommendations and design are the responsibility of District Hydraulics. Identify locations at a high risk of overtopping, based on USGS debris flow data and site conditions, and determine the presence and condition of existing embankment armoring. Furthermore, the GP must identify locations of current embankment erosion and distress that will be exacerbated by post-fire flooding conditions and debris flows. District Hydraulics should inspect localities identified by the GP to determine if embankment armoring is needed and, if feasible, provide recommended designs. Embankment armoring can be difficult to install rapidly due to potential environmental impacts, although emergency conditions can significantly reduce the environmental restrictions. Also, embankments are often large and steep, making placement of protection measures difficult. Armoring methods such as articulated concrete blocks, turf reinforcement mats, etc., are currently underutilized statewide but may provide preemptive solutions when debris flows are anticipated or repair solutions when large and steep embankments are being rebuilt (Kirk, 2021). Embankment armoring should be considered whenever repairing or rebuilding an embankment after a recent debris flow and flooding related washout.

Avoidance

Avoidance requires relocation or realignment of the highway or facility away from the anticipated debris flow path, i.e., drainage channel/ravine. Typically, this requires elevating the highway over the debris flow path via a structure or tunnelling under the debris flow path. Avoidance costs are very high and implementation can take years; therefore, avoidance is rarely considered in rapid post-fire debris flow mitigation projects. However, avoidance may be considered for new highway projects or recent debris flow projects where the roadway has been completely washed away. In these cases, a conservative approach to debris flow mitigation is recommended and avoidance should be considered.

Reporting

Debris flow investigations and recommendations are reported in accordance with the *Geotechnical Design Report* module or in a Maintenance Support Memo. For emergency response the report may be abbreviated to meet project deadlines (see *Emergency Response* module). The level of information provided should be commensurate with the project scope. Reports should include the following information for each debris flow location:

- Postmile of debris flow location/intersection
- Upstream Watershed Area
- Percent Watershed Burned
- Percent Watershed Moderately-Severely Burned and >23 degrees
- Debris flow data for 1- and 2-year rainfall intensity specific to the burn area, data includes:
    - Probability
    - Volume (inc. min and max)
    - Combined Hazard Ranking (Score and Low/Medium/High)
- Culvert (PM, system number, size, material)
- Retention basin (estimated volume, capacity - clear/full)
- Debris control structure (size, material)
- Downslope embankment condition (enforcement present, AC dike, berm, etc.)
- Overside drain conditions (size)
- Structure support conditions (scour protection present)
- Watershed channel (completely cleared or loaded with soil/debris)

Include the following in the *Recommendations* section of the Preliminary Geotechnical Design Report and Geotechnical Design Report (as appropriate):

- Inlet retention basin clearing and modifications
- Upgrading timber debris racks to steel
- Flexible barrier locations, materials, and dimensions (See Appendix 2)
- Recommendations for clearing and inspecting all drainage systems within the burned area
- Recommendations to consult District Hydraulics to investigate all moderate and high combined hazard risk debris flow locations and determine the need and designs for the following mitigative measures:
    - Rigid barriers
    - Culvert repair, replacement, upsizing, redundancy, relief
    - AC dike and earthen berm
    - Downdrain and overside drain repairs and upgrades
    - Embankment armoring
- Recommendations to consult SM&I to investigate all structures within known or anticipated pathways of debris flows and provide mitigative measures.

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APPENDIX 1: ArcGIS Pro Procedure

Exporting USGS Post Wildfire Debris Flow Assessment Data

1. **Ensure ArcGIS Pro is installed on your computer**

2. **Download GIS Data (see Figure 1)**

   a. Visit the USGS Post Wildfire Debris Flow Hazard Assessment Dashboard and navigate to area/fire of interest in the map space. Data from older fires is available.

   b. Click on the fire location dot in the center of the fire of interest, and a pop-up menu should appear with links and fire summary information.

   c. In the Hazard Assessment Data section of the pop-up menu, in the "Geodatabase Download Link" row, click "View" to download the USGS data to your computer. The downloaded USGS data should be in a .zip file titled ***PostFireDebrisFlowEstimates.zip*** but may have a different name if USGS implements data structure changes in the future.

3. **GIS Data Management**

   a. Create a dedicated GIS project folder on your computer and move the downloaded data to this folder.

   b. Unzip/extract the data in your designated project folder by moving the .zip file into the folder, right clicking the file to select ***Extract All…***, and then follow the prompts to extract the data.

      - The newly unzipped/extracted folder will contain the data organized in various folder structures. You may need to continue unzipping/extracting additional files in the USGS data's folder structure. For example, the PostFireDebrisFlowEstimates master folder may subsequently contain additional .zip files. If this is the case, make sure to unzip/extract the data in the file that ends in ***_dfestimates_utm.zip***. This will be the case for many pre-2024 fires.

4. **Open and Export Data**

   a. Open ArcGIS Pro (see Figures 2 & 3). In the start menu that appears, select ***Map*** in the ***New/Blank Templates*** section in the middle of the menu to open a blank map. The ***Create a New Project*** menu will appear. Specify a project name, navigate to or specify your designated project folder, and de-select ***Create a new folder for this project***. Then select ***OK***.

b. If the ***Catalog*** pane is not visible when opening ArcGIS Pro, go to the ***View*** tab in the toolbar ribbon and select ***Catalog Pane*** (see Figure 4). In the ArcGIS Pro ***Catalog*** pane, ensure the data you downloaded is in the project folder you created. To check you can expand the following folders in the ***Catalog*** pane: ***Folders*** → ***Your designated project folder*** → ***PostFireDebrisFlowEstimates***. The downloaded data will be in the PostFireDebrisFlowEstimates folder as a geodatabase with .gdb file type (see Figure 5).

- If exporting data from a 2023 or earlier fire, the geodatabase filename will often end in ***_dfestimates_utm.gdb*** (e.g., the 2020 El Dorado/Apple Fire geodatabase is named ***aed2020_dfestimates_utm.gdb***).

- If exporting data from a 2024 fire (or later) the geodatabase containing the data of interest will be named with a 3-letter abbreviation of the fire name and the year (e.g., the 2024 Lake Fire geodatabase is named ***lak2024.gdb***).

- If necessary, you can right click on ***Folders*** in the ***Catalog*** pane and select ***Refresh*** if the folder is not populated or if uploaded data does not appear once you move the data into the folder.

c. Export the segment data from the downloaded geodatabase.

Drag the segments feature class to the ***Map*** (see Figure 6).

- For 2023 or earlier fires, there are multiple segment feature classes, but the feature class appended by ***_AllIntensities*** can be used (e.g., the 2020 El Dorado/Apple Fire segments feature class is named ***aed2020_Segment_DFPredictions_15min_AllIntensities***).

- For 2024 fires (or later) the segment feature class will be named with the geodatabase name and year preceding ***_segments*** (e.g., the 2024 Lake Fire segments feature class is named ***lak2024_segments***)

The GP may also want to add up-to-date Caltrans roadway data or aerial imagery to the ***Map*** space to aid in the analysis, but default ArcGIS Pro basemap datasets can also be used.

Identify the debris flow segments that intersect Caltrans facilities within the burn area or within the area of analysis using one of the two following methods:

- ***Explore*** tool (see Figure 7): Ensure the ***Explore*** Tool is selected in the ***Map*** tab of the toolbar. Using the cursor (which should look like a hand pointing), identify and select segments of interest that intersect Caltrans assets.

  When selecting a feature such as a segment with the Explore tool, the click location will temporarily glow green and if selected correctly, the feature will be highlighted in blue. If the feature is not highlighted in blue, try the following:

  - Be more precise when selecting the feature. The mouse click must be directly on the feature.

  - Check the ***Explore*** tool dropdown menu and ensure ***Topmost Layer*** or ***Visible Layers*** is selected.

  A ***Pop-up*** menu that displays the feature's data will also appear. In the ***Pop-up*** menu that appears, note the ***OBJECTID*** (or ***Segment_ID*** for older datasets) for the segment of interest that was selected. Continue to select and note ***OBJECTIDs*** for every segment of interest that crosses a Caltrans asset to compile a list of ***OBJECTIDs*** that will be used in the analysis. Every segment feature will have a unique ***OBJECTID*** (or ***Segment_ID***).

- ***Selection*** tool (see Figure 8): Ensure the Select tool is selected in the Map tab of the toolbar. Using the cursor (which should look like a normal cursor with a subtraction sign appended to it), identify and select segments of interest that intersect Caltrans assets. Hold the Shift key while clicking on each individual segment that intersects a Caltrans asset. While holding shift, when a segment is selected it should be highlighted in blue and remain highlighted. Continue to select segments until all segments of interest, or all segments that cross Caltrans assets are selected and highlighted. Once all segments of interest are selected, you may release the shift key. Do not click anywhere else in the ***Map*** space at this point.

Next, use the ***Table to Excel*** tool to export the data.

In the ***Command Search*** in the upper right of the ArcGIS Pro interface enter "Table to Excel" and select ***Table to Excel (Conversion Tools)*** from the results to open the tool (see Figure 9).

Use the ***Input Table*** dropdown to select the segments feature class that you moved to the ***Map***. Use the ***Output Excel File*** field to specify an output location and filename. Click ***Run*** in the bottom right (see Figure 10). Your data should now be exported in .XLS or .XLSX format.

- If you used the ***Explore*** tool to compile a list of ***OBJECTIDs*** (or ***Segment_IDs***) for the segments that cross Caltrans assets, you can now filter for those OBJECTIDs in the output excel file.

- If you used the ***Selection*** tool to select and highlight the segments that cross Caltrans assets, the output excel file will contain only data for those segments.

5. **Perform data analysis**.

Open the exported data for more user-friendly data review in Excel. The GP can analyze the data of interest based on the 1- and 2-year recurrence interval rainstorm intensities for the fire area. See the module for additional information related to selecting appropriate intensities.

Additionally, the downloaded ***PostFireDebrisFlowEstimates*** data package that was downloaded at the beginning of the procedure should contain a .TXT file that contains descriptions of the segments data fields (e.g., the 2024 Borel Fire data package contains a .TXT file titled ***bor2024-field-descriptions.txt***).

APPENDIX 2: DEBFLOW Dimensioning Tool

Using the DEBFLOW Dimensioning Tool to design debris flow barriers

1. **Creating a DEBFLOW Project**
    a. Create a myGeobrugg account on the Geobrugg website, or login to an existing account, and navigate to the DEBFLOW Dimensioning Tool. Make sure to review the DEBFLOW manual in detail prior to using the tool.
    b. Add a Project Number, Project Name, and Date/Author.

2. **Adjust the following debris flow input parameters:**
    a. Granular or mud flow material type.
    b. Debris flow material density (see DEBLOW manual Table 1 for common values)
    c. Anticipated debris flow volume (Recommended to use ~95% of the low volume estimate from USGS debris flow data).
    d. Number of surges anticipated (typically 1-3 surges)
    e. Volume of the first surge (use DEBFLOW recommended value).
    f. Peak discharge rate (use DEBFLOW recommended value).
    g. Global safety factor (SF = 1.15 to 1.25 is recommended)

3. **Adjust the following barrier dimensions under Summary of Results tab:**
    a. Check box for a new barrier location and name the barrier location.
    b. Adjust the following inputs under Geometry of Barrier Location section:
        - System height and top and bottom channel width to match the site conditions at the anticipated proposed barrier location. Modify the dimensions as needed to increase retention volume so long as site conditions permit.
        - Distance to next barrier upstream (Input 500 m if no additional barriers are proposed).
    c. Adjust the following inputs under Torrent Inclination and Retention Volume section:
        - Average torrent inclination upstream of the barrier. Use a value that best represents the channel inclination within the anticipated debris retention area behind the barrier. This will typically be the channel inclination measured from the proposed barrier location to a location within the channel upstream of the barrier where the channel elevation has increased by approximately 1.5 times the anticipated barrier height.

- Deposition inclination of filled barrier (Use DEBFLOW recommended value).

d. Under the Retention Volume Section, ensure the total retention volume exceeds or is within 95% of the required retention volume. If not, attempt to adjust the dimensions of the barrier, as site conditions permit, to increase retention volume and consider additional mitigative measures, e.g., rigid barriers, relief culverts, etc.

4. Selecting suitable flexible barrier system designs

a. Under the Front Velocity and Flow Height Section, input an impact velocity at barrier location (Use DEBFLOW recommended values).
b. Under Flexible, Permeable Debris Flow Protection System, select a system type from the drop-down menu. Ensure that the following criteria are reported as fulfilled:
    - Proof of system height and system width
    - Proof of max. dynamic loading
    - Proof of max. static loading
c. Keep in mind that proof of system height and system width may not be fulfilled because site conditions and barrier dimensions are outside of the manufacturer’s reported size range for a given system. Engineering judgement should be used to select systems that may not fulfill the reported system height and width requirements. Systems have been used with success that are slightly larger or smaller than the reported system size limits.

5. Saving and finalizing system design

a. Save the DEBFLOW project and create a pdf using the buttons at the top of the screen.
b. Once a system has been selected, download the typical design detail from myGeobrugg for the selected system and record the system dimensions.
c. Other manufacturers can supply comparable systems and dimensions to Geobrugg systems output using DEBFLOW.