UTC Project Information

Project Title	MPC-482 – Coupled Numerical Simulation of Debris Flow-Soil-Structure Interactions for Flexible Barrier Mitigation Systems
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Brief Description of Research Project	In 2010, landslides in Colorado cost the state $9 million U.S. dollars in direct costs (Highland2012). Additional indirect costs, associated with loss of agricultural productivity, interruption of transportation systems, or post-failure damage mitigation, can considerably increase the overall economic burden of landslides. Debris flows, a particular type of landslide prevalent throughout the Western United States, present an inherent risk to human health, infrastructure, and the environment due to their rapid development and downslope movement (e.g., Iverson 1997; Santi 2012; Hungr et al. 2014). Debris flows primarily develop on steep slopes (>10-20°) and can mobilize directly from a landslide mass, grow from a small failure with subsequent entrainment of sediment from bed-slope erosion, or initiate from surface water runoff with subsequent erosion and particle entrainment (e.g., Varnes 1978; Hungr et al. 2005; Hungr et al. 2014). Thus, the total mass of a debris flow depends predominantly on characteristics of channel and bed sediments. The recent Oso Landslide in Washington State (Keaton et al. 2014), was a traditional circular-arc slope failure that mobilized into a large debris flow and inundated an entire community, claiming 43 lives. This recent and catastrophic event documents the real threat debris flows

present and indicates additional research is needed to understand debris flow mobility and improve geo-hazard warning and mitigation systems.

The size, extent, and frequency of debris flows vary considerably with respect to surface material composition, geologic setting, and amount of water present (Jakob 2005). Detailed assessments of debris flows in the Western United States have been conducted for both unburned and burned areas following wildfires (e.g., Santi et al. 2013). The prevalence of wildfires in the Western United States and the removal of ground cover and root reinforcement in surficial soils considerably increase the likelihood of debris flows as well as the volume of sediment within a given debris flow. The frequency and magnitude of wildfires in the Western United States has increased over the past decade and is anticipated to further increase due to climate variability (Robichaud et al. 2010). Furthermore, landslides, and in particular debris flows, often occur along transportation corridors in the Western United States due to the presence of disturbed soil and rock involved in roadway construction combined with steep slopes associated with mountainous terrain (Highland 2012). Thus, debris flows remain an ever present and growing risk for transportation corridors in the Western United States. The ability to understand practical hazard mitigation possibilities prior to the occurrence of a debris flow will provide transportation personnel and consulting engineers vital tools to enhance protection of human life, infrastructure, and the environment.

Debris flow mitigation structures most commonly are deployed in the vicinity of infrastructure, and include flexible barriers, levees and dams, and/or baffles (Mizuyama 2008; Wendeler et al. 2008; Santi 2012; Ng. et al. 2014; Choi et al. 2015). The most successful mitigation strategies involve entrapping debris as the material moves down a channel to prevent an increase in overall volume of the debris flow due to subsequent channel erosion and entrainment (e.g., Iverson 1997; Santi 2012). Thus, mitigation strategies are designed with the same fundamental purpose: prevent development and downslope movement of debris flows. Rigid mitigation structures (e.g., dams, levees, and baffles) primarily function to impede flow, such that impact forces on downslope structures and overall run-out distance of the flow are reduced. These structures are often expensive and labor intensive to build, and present difficulties with construction and maintenance when needed in remote areas. Retention-type systems, such as silt fences and basins, quickly fill with sediment and water and easily overflow. Due to these construction challenges and performance limitations with current mitigation strategies, recent research has focused on the efficacy of flexible barriers as a debris flow mitigation strategy.

Pictures of flexible barrier systems for mitigation of debris flow hazards and a rigid, debris rack structure are shown in Fig. 1. In general, flexible barrier systems include (i) a steel mesh- or ring-type structure that spans the width of a channel (Fig. 1a) and (ii) a connection system that attaches the steel structure to the earth. The structure is designed to retain material and is constructed of loosely connected high tensile-strength steel wire rings or mesh that is supported by steel wire ropes anchored to the ground (DeNatale et al 1999; Roth et al. 2010; Canelli et al 2012; Brighenti et al

2013; Volkein et al. 2011; Volkein et al. 2015). The open, freely-draining properties of the steel rings or mesh allow water and small debris to pass through the barrier, increasing the material retention capacity and reducing build-up of pore water pressure behind the barrier. Flexible barriers are light-weight and require minimal space for installation, creating an ideal structure for installation in remote locations (Sasiharan et al. 2006) and along transportation corridors where right-of-way and zoning issues constrain design possibilities for hazard mitigation structures (Wendeler et al. 2008). Roth et al. (2010) report that flexible barrier systems were effective in mitigating large erosion events and that retention capacity of the barrier system can be restored by removing accumulated debris (e.g., Fig. 1c).

Current design methods for flexible barrier mitigation systems rely on empirical methods, engineering judgment, and experience (e.g., Sasiharan et al. 2006; Volkein et al. 2015). However, application of one barrier design to a different site often results in over and under design of structural strength or debris retention capacity, as each site requires unique barrier heights, capacities, and earth retention infrastructure (Volkein et al. 2011). Recent experimental and numerical studies have documented that key aspects to avoid barrier failure include a strong anchorage system, strong lateral wires and up-slope support connections, energy absorption capabilities, protection against abrasion, and suitable retention volumes (Roth et al. 2010; Canelli et al 2012; Brighenti et al 2013; Volkein et al. 2011; Volkein et al. 2015). However, this collection of research does not provide guidance on model parameterization for design of a flexible barrier system or develop practical tools such that transportation personnel and other relevant practitioners can readily design flexible barrier systems for site-specific conditions.

Various efforts have been put forth for developing terrain models for shallow landslide predictions. The models initially utilized steady-state conditions and were further extended to include dynamic and hydrologic conditions to estimate local pore water pressure driving instability (Montgomery and Dietrich 1994; Pack et al. 1998; Wu and Sidle 1995; Casadei et al. 2003; Iverson 2000; Rosso et al. 2006). High level of accuracy was achieved in these models for three-dimensional variably saturated flow calculations. However, for landslide modeling over a large area, approximate solutions have been used to capture the increased complexity associated with spatial pore water pressure dynamics. The most advanced approximate modeling enables treatment of both the lateral subsurface flow and the dynamic passage of vertical flux on pore water pressure development (Iverson 2000). For modeling the behavior of structural systems, various software packages exist; e.g., ABAQUS, ANSYS, SAP2000, etc. These software packages have been well-verified against benchmark studies and have been extensively used for the assessment of complex phenomena characterized by geometric and material nonlinearities.

Merging of structural and soil-fluid modeling capabilities can prove very effective in studying problems concerned with fluid-structure interaction.

	Recent development of such capabilities includes Coupled Eulerian-Lagrangian (CEL) analysis in ABAQUS software. The Eulerian capability included in ABAQUS can be coupled with traditional Lagrangian capabilities to model interactions between highly deformable materials and relatively stiff bodies, such as in fluid-structure interaction. The availability of this formulation significantly reduces the analysis time for fluid-structure interaction problems in comparison to traditional computational fluid dynamics. This modeling technique, although relatively new, has been verified and used for simulating tsunami debris impact load on structural walls (Como and Mahmoud 2013). The primary objective of the proposed research is to develop and assess numerical modeling techniques capable of simulating coupled behavior of debris flows and flexible barrier mitigation structures.
Describe Implementation of Research Outcomes (or why not implemented) Place Any Photos Here	To further investigate the response of flexible ring-net barriers to debris flow loading, FEMs should be developed with a simplified barrier system and more complex modeling of the debris flow to represent interactions are the particle level within the flow. Ultimately, coupled FEM simulations with more complex debris flows and the ring-net barrier FEM developed herein can be used to assess the level of model complexity needed for engineering design versus research-based investigations.
Impacts/Benefits of Implementation (actual, not anticipated)	This research provides an alternative approach to using FEM to simulate the complex interactions between a debris flow and flexible steel, ring-net barrier.
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