

## **Project Title**

Coupled Numerical Simulation of Debris Flow-Soil-Structure Interactions for Flexible Barrier Mitigation Systems

## **University**

Colorado State University

## **Principal Investigators**

Christopher Bareither  
Assistant Professor  
Colorado State University  
Email: christopher.bareither@colostate.edu  
Phone: (970) 491-4669

Hussam Mahmoud  
Assistant Professor  
Colorado State University  
Email: hussam.mahmoud@colostate.edu  
Phone: (970) 491-6605

## **Research Needs**

In 2010, landslides in Colorado cost the state \$9 million U.S. dollars in direct costs (Highland 2012). 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 ( $>10\text{-}20^\circ$ ) 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).

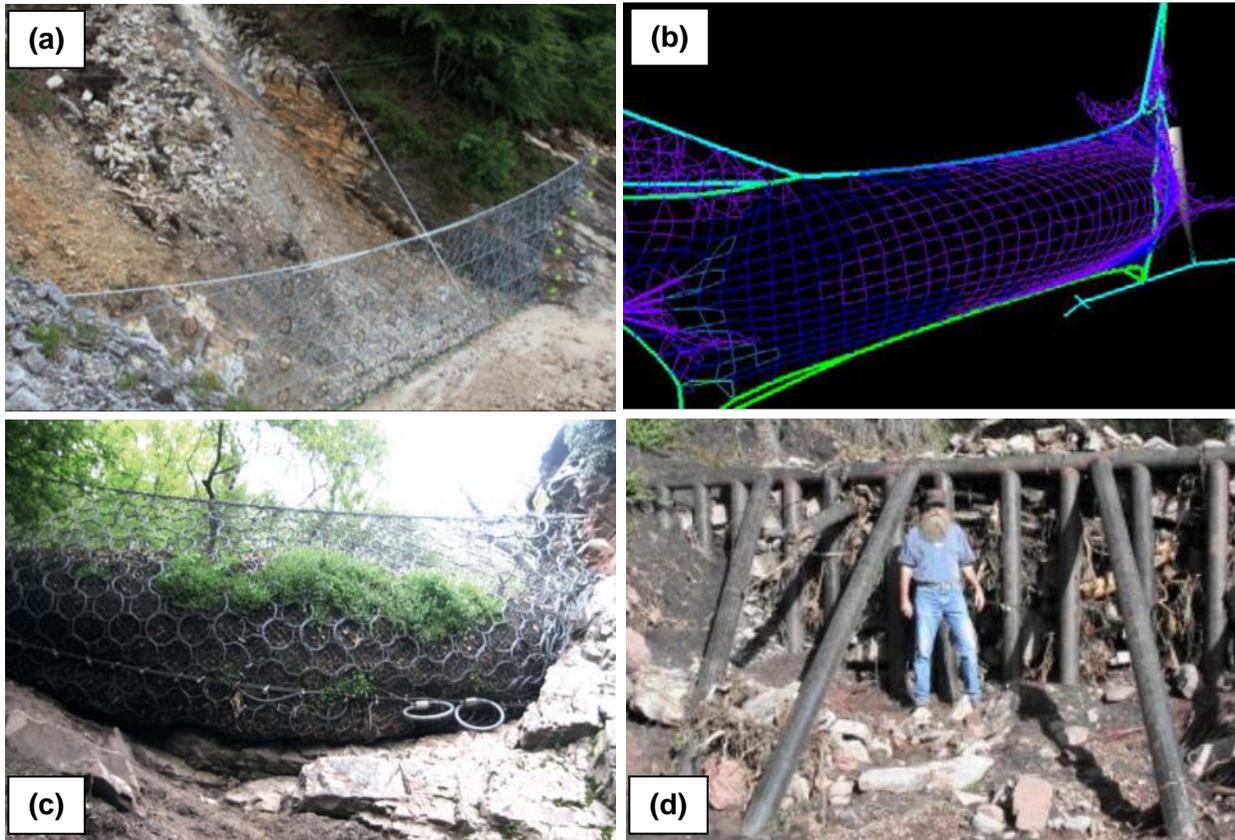


Fig. 1. (a) Photograph of a flexible debris flow barrier prior to loading (Brighenti et al. 2013), (b) numerical simulation of a flexible debris flow barrier (Wendeler et al. 2008), (c) partially-filled debris flow barrier (GeoBrugg 2012), and (d) rigid debris rack structure (Santi 2012).

### Research Objectives

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. The following research tasks will be completed to achieve this objective:

1. Conduct a literature review to compile relevant data and information on debris flow characteristics and triggering mechanisms, debris flow mitigation structures, modeling techniques to couple debris flow-soil-structure (DFSS) interactions, and case studies;
2. Assess numerical modeling capabilities for relevancy and practical implementation to develop design and assessment tools for transportation personnel;
3. Simulate available laboratory- and field-scale experimental data to evaluate and refine modeling capabilities; and
4. Conduct a numerical modeling exercise to assess potential flexible barrier system designs for site-specific, debris flow scenarios in Colorado.

Task 1 will expand on current knowledge of debris flows and mitigation strategies (e.g., Santi et al. 2006) to develop a state-of-practice review of design, performance, and prevalence of flexible mitigation structures for debris flows in the Western United States. This task will also yield a compilation of modeling techniques that have been applied to debris flows, soil / rock behavior,

and structures individually as well as coupled strategies. Task 2 will lead directly from background information compiled on modeling strategies and build on current knowledge of the Principal Investigators (PIs) (e.g., Como and Mahmoud 2013) to identify a modeling strategy capable of simulating DFSS interactions applicable to the conceptual problem outlined herein. The objective of Task 3 will be to apply the developed DFSS interaction modeling strategy to case studies (e.g., DeNatale et al. 1997; Canelli et al. 2012; Brighenti et al 2013; Huang et al. 2014) to assess viability of the numerical modeling technique and physical significance of the modeling parameters. Finally, Task 4 will be conducted via integrating site-specific conditions of Colorado debris flows compiled from Task 1 with the developed modeling strategy from Task 2 and 3 to assess the feasibility of flexible barrier systems for mitigation of debris flow hazards.

## **Research Methods**

Research efforts needed to complete the proposed study will include (i) design of flexible barrier systems for debris flow mitigation and (ii) numerical simulation of a given design subjected to different debris flow loading considerations. The first research effort will be executed to generate practical designs for a range of mitigation structures relevant to Colorado case studies. These designs initially will be developed from static analyses that consider earth and pore water pressure from debris flow material, loads and deformations within the flexible barrier system, and dissipation of loads through soil-structure interactions (e.g., rock bolts, soil anchors, retaining structures, etc.). Three-dimensional, finite element method (FEM) models will be developed for designs that have satisfactory structural and geotechnical performance (e.g., adequate factors of safety). An example of an FEM debris flow structure is shown in Fig. 1b. A range of debris flow events that represent different size and frequency will be applied to a given mitigation structure to assess the structural and geotechnical response to loading and evaluate potential effectiveness in short- and long-term debris flow hazard mitigation.

*Static Loading Analysis:* Considerations in the design of flexible barrier mitigation structures will include the following: (i) foundation and tie-back/reinforcement elements, (ii) steel structural members and components of the barrier system, (iii) structure height, and (iv) earth and pore water pressures transferred to the barrier structure. Structure designs will also account for debris flow conditions specific to Colorado to identify (i) areas that are most susceptible to large and/or frequent debris flows, (ii) site conditions (e.g., surface geology, channel slope, channel shape, etc.), and (iii) debris flow characteristics (e.g., particle size gradation, water content, etc.). Characterizing site geology and topography will be particularly important to design potential structures with dimensions representing site-specific conditions and earth retention devices that comprise the barrier system.

The PIs propose to develop at least five relevant designs for flexible debris flow mitigation structures that represent the following scenarios: (i) largest volume debris flow, (ii) highest frequency debris flow area, (iii) site with highest potential risk to human health, (iv) site with highest potential risk to critical transportation infrastructure, and (v) site that represents challenging conditions for implementation of a structure (e.g., broad lateral extent, steep valley, weak soil or rock that would serve as foundation material, etc.). Each potential evaluation may include considerations of a single, large structure near the bottom of a slope channel that provides easy access for construction and structure maintenance following a debris flow event or multiple, smaller up-slope structures. A series of up-slope structures would require smaller

structural members that could simplify installation, but also need to provide comparable total debris flow volume retention relative to a single, large debris flow mitigation structure.

*Dynamic Loading Analysis:* Both Lagrangian and Eulerian formulations will be used in the FEM model to allow for small and large deformations, as needed. The soil will be modeled as an Eulerian part for soil with very low shear strength, beginning with initial assumptions that soil flow behaves as a nearly incompressible, frictionless, Newtonian fluid. The Navier-Stokes equation will be used in the analysis as shown below:

$$\rho \frac{Dv}{Dt} + \nabla \rho - \eta \nabla^2 \mathbf{v} - \frac{\eta}{3} \nabla (\nabla \cdot \mathbf{v}) = \rho \mathbf{b} \quad (1)$$

where  $\rho$  = fluid/soil density,  $v$  = fluid/soil velocity,  $\eta$  = fluid/soil viscosity, and  $b$  = body forces. For soil with measurable levels of shear strength, the soil will be modeled using Lagrangian elements (i.e., Lagrangian-Lagrangian model). Alterations to these proposed simulations will depend on the debris flow modeled and will be based on recommendations of simulating debris flow mobility (e.g., Iverson 1997).

The Eulerian-Lagrangian general contact formulation is based on an enhanced immersed boundary method. In this method the Lagrangian structure occupies void regions inside the Eulerian mesh. The general contact algorithm automatically computes and tracks the interface between the Lagrangian structure and the Eulerian materials, while penalty methods are used to couple the Eulerian and Lagrangian parts.

### **Expected Outcomes**

The primary deliverable from the proposed project will be a modeling assessment of flexible, debris flow mitigation barriers. Emphasis will be placed on developing and evaluating numerical modeling strategies for DFSS interactions that can lead to practical tools for transportation personnel. Potential debris flow structures will be designed to incorporate state-of-the-practice and site-specific conditions in Colorado such that the modeling assessment has direct implications to debris flow hazard mitigation techniques in Colorado. This assessment also will have broader implications for similar site conditions throughout the Western United States.

The PIs anticipate that the project will lead to opportunities for technology transfer of state-of-the-art numerical modeling techniques into the state-of-the-practice. Dr. Mahmoud's recent research on the impact of tsunami loads on rigid structures (Como and Mahmoud 2013) provides a starting point for this development. The PIs see logical extension of this past work to dynamic loading of debris flow mitigation structures (as proposed in this project) as well as fluid and debris loads on infrastructure during flood events. The recent Colorado Front Range floods in the fall of 2013 indicate that considerable damage and loss of infrastructure can be anticipated during flash flood events. The proposed project will provide an excellent opportunity to expand on fluid-structure interaction modeling that can be used to assess current and future structural designs of transportation infrastructure subjected to dynamic loadings during extreme events. Developing new modeling capabilities and transferring the capabilities back into practice will provide transportation personnel with state-of-the-art predictive tools.

## **Relevance to Strategic Goals**

The proposed study is developed with the vision to provide transportation personnel with numerical tools to assess the practicality of flexible, debris flow mitigation barriers. Background information will provide a state-of-the-practice assessment of debris flow behavior, debris flow site conditions relevant to Colorado, and modeling strategies for coupled assessment of DFSS interactions. This knowledge and the proposed modeling tools to be developed directly relate to enhancing the safety of transportation corridors in mountain states, with particular emphasis on site-specific conditions in Colorado. Potential mitigation of debris flows and minimization of flow material intercepting and possibly damaging transportation infrastructure (e.g., roadways, bridges, culvers, etc.) will enhance the state-of-good-repair.

The PIs believe that implementation of effective debris flow hazard mitigation structures will provide long-term benefits via reducing damage of transportation infrastructure. Thus, broader impacts of the proposed research are assessments of economic competitiveness of debris flow hazard mitigation options as well as environmental sustainability of these different options. For example, a cost-benefit analysis could be conducted to compare up-front costs associated with installation of a flexible, debris flow mitigation barrier relative to direct and indirect costs associated with clean-up and rehabilitation of infrastructure following a debris flow. Additionally, flexible, debris flow mitigation barriers can be designed with capabilities to remove debris following a debris flow event (Roth et al. 2010) such that retention capacity is restored and minimal long-term geomorphological changes occur within the vicinity of the mitigation structure. Thus, the structures to be evaluated in this study have potential as a long-term option that provides both economic and environmental sustainability.

## **Educational Benefits**

The proposed project will support a Graduate Research Assistant (GRA) at Colorado State University (CSU) in pursuit of an MS degree in Civil Engineering. This GRA will lead the proposed research, and successful implementation of the project plan will allow the graduate student to prepare and defend an MS thesis. The GRA will gain invaluable knowledge and experience related to relevant and practical modeling tools for a future career as a Geotechnical / Structural Engineer. In particular, the GRA will have an understanding of current and future geo-hazards related to debris flows, assessment and mitigation strategies, and modeling capabilities to design and evaluate DFSS interactions. Thus, the GRA will be well-equipped to transition into an engineering consulting career with unique state-of-the-art tools.

The proposed project will provide an opportunity for the PIs to expand and enhance their understanding of debris flow hazards, mitigation structures, and modeling capabilities for coupled integration of DFSS interactions. This knowledge will be used in both undergraduate and graduate courses. Dr. Bareither will integrate an overview of debris flow hazards as well as modeling tools and findings from the proposed research into his graduate-level course, CIVE 553, entitled "Slope Stability and Retaining Structures". Currently, the topics of slope stability and retaining structures in CIVE 553 are predominantly addressed independently, with integration addressed during course lectures and discussions on slope stabilization techniques. The coupled modeling strategies to be developed as part of the proposed research will allow development of a unique module that couples slope stability considerations with earth retention assessments of hazard mitigation structures.

Dr. Mahmoud currently teaches the following structural engineering courses at CSU: CIVE 466 – Design and Behavior of Steel Structures and CIVE 664 – Mechanics of Fatigue and Fracture. Case studies, model development, and findings from the proposed research will be integrated into both courses. Specifically, in CIVE 466, the results of the study will be highlighted and conservative methods will be used to estimate actions and deformations in the wire mesh impacted by the debris. Comparisons will be made between hand calculations and the results obtained using the advanced FEM study. In CIVE 664, students will be given the ABAQUS files obtained from the study and will be required to determine the potential for fracture of the steel wire mesh as a result of different dynamic and static loadings. This will be realized through extracting data from the ABAQUS output file and numerically processing the results to arrive to the appropriate conclusion.

**Work Plan**

A timeline for the proposed project is included in Fig. 2. The proposed project will require 18 months for completion. Durations of specific research tasks (i.e., Tasks 1, 2, 3, and 4) are identified in Fig. 2 and correspond to each of the research objectives discussed previously. Project reports for the Mountain-Plains Consortium will be developed at 6, 12, and 18 months.

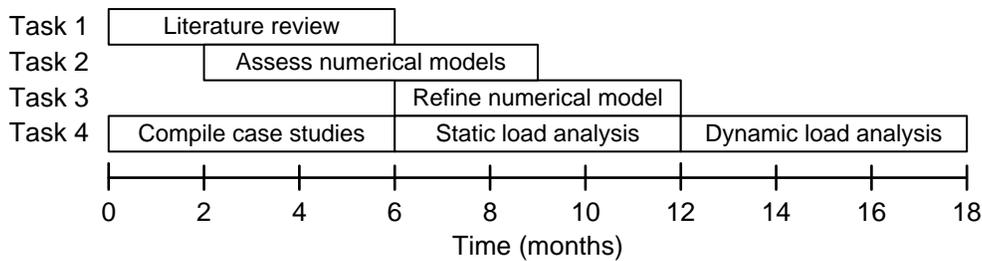


Fig. 2. Estimate timeline of the primary tasks for completing the proposed project.

**Project Cost**

Total Project Costs: \$99,956  
 MPC Funds Requested: \$49,000  
 Matching Funds: \$50,956  
 Source of Matching Funds: Colorado State University

**TRB Keywords**

debris flow, infrastructure, modeling, soil-structure

**References**

Brighenti, R., Segalini, A., and Ferrero, A.M. (2013). Debris flow hazard mitigation: a simplified analytical model for the design of flexible barriers, *Computers and Geotechnics*, 54, 1-15.

Canelli, L., Ferrero, A.M., Migliazza, M., and Segalini, A. (2012). Debris flow risk mitigation by the means of rigid and flexible barriers – experimental tests and impact analysis, *Natural Hazards and Earth System Sciences*, 12, 1693-1699.

- Casadei, M., Dietrich, W.E. and Miller, N.L. (2003). Testing a model for predicting the timing and location of shallow landslide initiation in soil mantled landscapes, *Earth Surface Processes and Landforms*, 28(9): 925-950.
- Choi, C. E., Ng, C. W. W., Law, R.P.H., Song, D., Kwan, J.S.H., and Ho, K.K.S. (2015). Computational investigation of baffle configuration on impedance of channelized debris flow, *Canadian Geotechnical Journal*, 52(2), 182-197.
- Como, A. and Mahmoud, H. (2013). Numerical evaluation of tsunami debris impact loading on wooden structural walls, *Engineering Structures*, 56, 1249-1261.
- DeNatale, J.S., Iverson, R.M., Major, J.J., LaHusen, R.G., Fiegel, G.L., and Duffy, J.D. (1999). *Experimental Testing of Flexible Barriers for Containment of Debris Flows*, Open-File Report 99-205, U.S., Geological Survey, Denver, CO, USA.
- GeoBrugg (2012). Debris Flow Barriers, Technical Documentation, Geohazard Solutions, Romanshorn, Switzerland.
- Highland, L.M. (2012). *Landslides in Colorado, USA: Impacts and Loss Estimation for Year 2010*, Open-File Report 2012-1204, U.S., Geological Survey, Denver, CO, USA.
- Huang, Y., Yiu, J., Pappin, J., and Strut, R. (2014). Numerical investigation of landslide mobility and debris-resistant flexible barrier with LS-DYNA®, *Proc. 13<sup>th</sup> Int. LS-DYNA® Users Conference*, Livermore Software Technology Corp., 1-12.
- Hungr O., McDougall, S., and Bovis, M. (2005). Entrainment of material by debris flows. In: *Debris Flow Hazards and Related Phenomena*, Jakob, M. and Hungr, O. (eds), Springer, Heidelberg, 135-158.
- Hungr, O., Leroueil, S., and Picarelli, L. (2014). The Varnes classification of landslide types, an update, *Landslides*, 11(2), 167-194.
- Iverson, R.M. (1997). The physics of debris flows, *Reviews of Geophysics*, 35(3), 245-296.
- Iverson, R.M. (2000). Landslide triggering by rain infiltration, *Water Resources Research*, 36, 1897-1910.
- Jakob, M. (2005). A size classification for debris flows, *Engineering Geology*, 79, 151-161.
- Keaton, J.R., Wartman, J., Anderson, S., Benoit, J., de LaChapelle, J., Gilbert, R., and Montgomery, D.R. (2014). *The 22 March 2014 Oso Landslide, Snohomish County, Washington*, Geotechnical Extreme Events Reconnaissance.
- Mizuyama, T. (2008). Structural countermeasures for debris flow disasters, *International Journal of Erosion Control Engineering*, 1(2), 38-43.
- Montgomery, D.R. and Dietrich, W.E. (1994). A physically-based model for topographic control on shallow landsliding, *Water Resources Research*, 30(4), 1153-1171.

- Ng, C.W.W., Choi, C.E., Song, D., Kwan, J.H.S., Koo, R.C.H., Shiu, H.Y.K., and Ho, K.K.S. (2014). Physical modeling of baffles influence on landslide debris mobility, *Landslides*, online Feb. 2014, 10.1007/s10346-014-0476-y, 1-18.
- Pack, R.T., Tarboton, D.G., and Goodwin, C.N. (1998). The SINMAP approach to terrain stability mapping. In D.P. Moore & O. Hungr (eds.), Proc., *Eighth International Congress of the International Association for Engineering Geology and the Environment*, Vancouver, Canada, 1157-1165.
- Robichaud, P.R., Ashmun, L.E., and Sims, B.D. (2010). *Post-fire treatment effectiveness for hillslope stabilization*, Gen. Tech. Rep. RMRS-GTR-240, U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA.
- Rosso, R., Rulli, M.C., and Vannucchi, G. (2006). A physically based model for hydrologic control on shallow landsliding, *Water Resources Research*, 42(6), 1-16.
- Roth, A., Wendeler, C., and Amend, F. (2010). Use of properly designed flexible barriers to mitigate debris flow natural hazards, *GeoFlorida 2010: Advances in Analysis, Modeling & Design*, GSP 199, ASCE, 3207-3216.
- Santi, P., Higgins, J., Cannon, S., and DeGraff, J. (2006). *Evaluation of Post-Wildfire Debris Flow Mitigation Methods and Development of Decision-Support Tools*, Joint Fire Science Program, USGS, Denver, CO.
- Santi, P. (2012). Challenges for debris-flow mitigation in Colorado: helpful ideas from recent research, *GeoChallenges: Rising to the Geotechnical Challenges of Colorado*, GPP 7, ASCE, 1-16.
- Santi, P. and Morandi, L. (2013). Comparison of debris-flow volumes from burned and unburned areas, *Landslides*, 10(6), 757-769.
- Sasiharan, N., Muhunthan, B., Badger, T.C., Shu, S., Carradine, D.M. (2006). Numerical analysis of the performance of wire mesh and cable net rockfall protection systems, *Engineering Geology*, 88, 121-132.
- Varnes D.J. (1978). Slope movement types and processes. In: Schuster, R.L., Krizek, R.J. (eds) *Landslides, Analysis and Control*, special report 176: Transportation Research Board, National Academy of Sciences, Washington, DC., pp. 11–33.
- Volkein, A., Wendeler, C., and Guasti, G. (2011). Design of flexible debris flow barriers, *5th International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment*, Casa Editrice Università La Sapienza, 1093-1100.
- Volkein, A., Baumann, R., Rickli, C., and Wendeler, C. (2015). Standardization for flexible debris retention barriers, G. Lollino et al. (eds.), *Engineering Geology for Society and Territory*, V. 2, Springer International Publishing, Switzerland, 193-196.

- Wendeler, C., Volkwein, A., Roth, A., Herzog, B., Hahlen, N., and Wenger, M. (2008). Hazard prevention using flexible multi-level debris flow barrier, *Interpraevent*, 1, 547-554.
- Wu, W. and Sidle, R.C. (1995). A distributed slope stability model for steep forested basins, *Water Resources Research*, 31, 2097–2110.