MPC-447
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Project Title:
Post-Fire Ground Treatments for Protection of Critical Transportation Structures

University:
Colorado State University

Principal Investigators:
Christopher Bareither
Assistant Professor
christopher.bareither@colostate.edu
970-491-4669

Paul Heyliger
Professor
prh@engr.colostate.edu
970-491-6685

Research Needs:
Wildfires are a natural phenomenon in Colorado and the Western U.S., and the frequency of large, destructive wildfires has increased over the past decade and is forecasted to continually increase due to climate variability (Robichaud et al. 2010). Over 30 million acres of land have been burned by wildfires in the U.S. in the last five years alone. Potential damage to the human and built environments is not only associated with burned lands, homes, and infrastructure during a wildfire, but can extend for years following a wildfire in the form of increased runoff from precipitation, soil erosion, and debris flows. The frequency and magnitude of runoff, soil erosion, and debris flows increases following a wildfire due to burned surface vegetation that reduces soil cover, increased raindrop impact from loss of foliage, and/or soil hydrophobicity that can inhibit infiltration and water retention (e.g., Larsen et al. 2009; Santi et al. 2013).

The prevalence of increased runoff, erosion, and debris flows along transportation corridors can lead to damage of critical infrastructure (e.g., roads, bridges, culverts, etc.). Potential post-fire impacts include damage to the road system caused by increased run-off rates that overwhelm design limits for culverts and bridges, severe erosion of the road surface, and blocking of hydraulic structures by debris and sediment. Post-fire ground treatment that minimizes damage to transportation infrastructure is focused on emergency soil stabilization to mitigate erosion and runoff and generally is implemented within a 1-yr period following a fire. In addition to soil stabilization, post-fire ground treatment enhances burned area restoration to mitigate future land damage and facilitate repair of damaged infrastructure.

The state-of-practice in post-fire ground treatment primarily includes erosion barriers, mulching, chemical soil treatments, or a combination of these options (Robichaud et al. 2010). Erosion barriers include contour trenches, straw bales or wattles (straw-filled mesh tube), and felled logs that inhibit runoff and erosion while retaining moisture and sediment upslope to enhance regeneration of vegetation. Mulching refers to ground-cover treatments (e.g., agricultural straw or wood chips) that are surface applied to reduce raindrop impact and minimize erosion and overland flow (Bautista et al. 2009). This treatment can also increase infiltration and soil moisture content to enhance root uptake and vegetative regeneration. The predominant chemical soil treatment is hydromulching, which is a slurry-applied mixture of mulch, seeds, and nutrients designed for the advantages of mulching plus enhanced vegetative regeneration. Mulching and hydromulching are becoming the preferred ground treatment alternatives for emergency response required over large land areas and/or in short timeframes.

The estimated cost for post-fire emergency response actions following the 2012 High Park Fire in Larimer County was $24M (million USD). Included in this cost was $12.6M for mulching of post-burned slopes and $6.6M for increasing culvert size in anticipation of increased runoff and erosion (BAER 2012). Gorte (2011) report that federal funds expedited for post-fire rehabilitation is an increasing concern as expediting funds and corresponding rehabilitation actions can lead to inappropriate emergency actions in absence of a detailed feasibility study. This process can result in potentially greater future environmental damage. A similar argument can be made in regards to funds and actions expedited at the state level, and in general, post-fire ground treatment actions remain ad hoc with a need for knowledge of short-term and long-term benefits accompanying different treatment alternatives.

The main objective of this study is to assess the efficacy of post-fire ground treatments in mitigating soil erosion, runoff, and debris flows towards developing guidelines for conducting needs and feasibility assessments to enhance post-fire emergency response actions. A coupled laboratory and numerical research program will be used to determine a priori means for assessing post-fire ground treatments for soils near critical transportation infrastructure.

Research Objectives:
The following objectives will be completed as part of the proposed project:

1. Evaluate effects of fire on soil composition, soil shear strength, and moisture retention;
2. Evaluate the efficacy of post-fire ground treatments on mitigating erosion and runoff;
3. Evaluate the effects of percent ground cover, slope angle, and rainfall intensity on erosion and runoff; and
4. Develop preliminary guidelines for post-fire feasibility assessments focused on ground treatment applications to prevent loss of or damage to critical transportation components.

These research objectives will be completed via a coupled experimental and numerical research program. Objectives 1 and 2 will include laboratory experiments to understand the mechanisms of post-fire ground treatments that contribute to soil stabilization and obtain physical data necessary for calibration of numerical models. Objective 3 will be completed using discrete element models such that different combinations of variables affecting ground treatment performance can be evaluated (i.e., percent ground cover, slope angle, and rainfall intensity). The combined experimental and numerical research will be used to develop emergency stabilization recommendations in Objective 4.

Research Methods:
Experimental Research Program: The experimental research component of the proposed study will include (1) traditional soil mechanics testing and (2) slope-model experiments to assess erosion and runoff with and without ground-cover treatment. Soil samples for both laboratory components will be collected from land owned by the State of Colorado that is prone to wildfires. The ideal sample site will be located near critical transportation infrastructure such that research results will have direct application by the Colorado Department of Transportation (CDOT). The sample site shall be approximately 1.5-m long by 5-m wide to provide sufficient surface area to collect five 1.0-m-long by 0.30-m-wide block samples that represent in situ surface soil conditions. A photograph of a 0.30-m-diameter block-sample excavated from a soil layer is shown in Fig. 1. A similar procedure will be

Fig. 1. Photograph of block sampling method; 0.3-m-diameter sample.

used for block samples exhumed for this study, but include a modified mold design. Sampling molds will be constructed from 6.4-mm-thick steel sheet and extend 0.15-m below the soil surface.

Block samples will be transported to Colorado State University (CSU) and maintained in a safe, outdoor environment such that vibrant surface vegetation is maintained. Soil contained with the block samples will be used for both traditional soil mechanics testing and slope model experiments. One block sample will evaluated as collected to represent unburned conditions; the other four block samples will be burned under controlled conditions. Burning the block samples will be conducted with assistance of the Poudre Fire Authority (Fort Collins, CO) and input from the U.S. Forest Service, Rock Mountain Research Station (Fort Collins, CO). Critical aspects related to burning the block samples will be safety and application of a prescribed amount of heat that approximates high-burn severity in wildfires. The four burned block samples will be used to assess the following ground treatment conditions: (i) no treatment, (ii) straw mulch, (ii) wood chips, and (iv) hydromulching. The percent ground cover of each treatment alternative will be based on the current state-of-practice (e.g., Robichaud et al. 2010).

A schematic of the proposed slope-model experiment is shown in Fig. 2. The total length of the slope-model soil specimen will be 0.76 m. The slope model will include rigid sidewalls to contain the specimen and a geotextile end-drain to allow free drainage from the soil specimen. A 0.15-m length of the original block sample will be removed to assess initial soil characteristics. Final soil characteristic will be evaluated on soil exhumed from the slope-model soil specimen following testing. Final soil specimens will be exhumed from the down-slope end where less erosion and soil disturbance is anticipated due to proximity to the geotextile end drain. A catchment platform will be attached to the sidewalls at the down-slope end of the specimen to divert surface water flow and sediment to quantify runoff and erosion. An overhead sprinkler system will apply liquid to the soil surface that mimics actual precipitation events in Colorado. Diversion swales around the perimeter of the soil specimen (detail not shown) will divert precipitation not falling directly onto the specimen such that the quantity of precipitation falling on the soil surface can be determined.

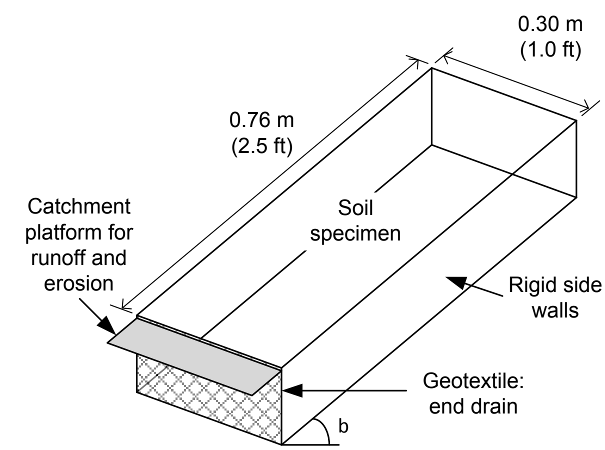

Fig. 2. Schematic of the laboratory-scale slope model to evaluate ground treatments.

An overhead high-resolution digital camera will be used to capture images during the applied precipitation events to quantify particle movement. Digital images will be processed in MATLAB and particle movement will be used in the numerical model calibration. The quantification of hydraulic forces on sloped particle beds generated by both direct rainfall and resulting runoff will build on DEM slope simulations from related studies (e.g., Liu and Koyi 2013). Determination of the levels in slope erosion caused by these actions is critical to design alternatives for existing post-fire treatments such that treatments reduce the propensity of runoff and erosion as well as subsequent infrastructure damage.

Traditional soil mechanics testing will be conducted on initial and final soil specimens exhumed from the block samples to evaluate soil composition, stress-strain and shear strength behavior, and moisture retention capacity. Particle size distribution and Atterberg limit tests will be used to classify the soils. Stress-strain and shear strength behavior will be evaluated in consolidated-undrained triaxial compression (TC) tests at low confining stresses representative of surface soil conditions. These experiments will be conducted on saturated soil specimens to represent a limiting strength condition for the soil. Moisture retention will be measured in a hanging column apparatus to determine the soil water characteristics curve (i.e., relationship between soil suction and volumetric water content). Data from the TC and moisture retention experiments will be used to assess effects of fire on shear strength and wetting-drying behavior, which are critical characteristics for understanding and assessing mechanisms of erosion and runoff.

Numerical Research Program: The onset of slope erosion is a relatively complex problem that combines features of fluid and solid mechanics. Simulating the behavior of fire-damaged soils will benefit from numerical models that can assist in predicting critical variables that influence the onset of soil erosion and surface flows in regions of roadbeds, bridges, and culverts. To this end, discrete element models (DEMs) will be used to quantify the interactions between hydraulic forces from rainfall and resulting erosion of soil slopes. In general, these models have a sound theoretical basis and excellent record of agreement with experimental results (e.g., Cundall and Strack 1979; Luding 2008).

In the proposed study, results from the experimental research program will be coupled with the numerical study to refine the DEMs such that the models mimic measured particle movement and mechanics. Through this process a mechanics-based modeling tool will be developed that is grounded in experimental results (i.e. rate of flow/rainfall that causes initial particle destabilization from equilibrium on a slope) and can be modified to reflect added protection of surface (dispersed straw, for example) and subsurface treatments (soil additives). Thus, this phase of the research is meant to be symbiotic in the sense that fundamental measurements tasked in the experimental program will guide development of mechanics models that can then be used to complete more comprehensive parametric studies. For instance, modeling particle fiber reinforcement (from roots and other organic materials) prior to a fire would incorporate structural parameters that have not yet been measured. Post fire, these networks are damaged or destroyed. The ability to simulate these stability and instability mechanisms for specific soil types will be of direct benefit in modeling an entire larger soil slope under duress.

Expected Outcomes:

The primary deliverable of the proposed research will be post-fire ground treatment recommendations to improve emergency stabilization efforts based on protection of critical transportation resources. Performance-based assessments from the research program will yield ground treatment recommendations that are both economical and sustainable. The developed recommendations will integrate treatment method, slope angle, and climate conditions and also address susceptibility of transportation infrastructure to damage with and without ground treatment application. Practitioners within public and private sector will have the ability to make judicious post-fire soil stabilization decisions and focus initial efforts in critical infrastructure areas. This timely response will decrease the potential for infrastructure damage from runoff, soil erosion, or debris flows.

The coupled experimental and numerical research program will yield innovative tools to assess the efficacy of varying ground treatment alternatives. Successful implementation of the research program will provide an assessment strategy for future site evaluations and design alternatives. Thus, future innovative ground treatments that are promising alternatives to current approaches can be evaluated according to a mechanistic-based approach that yields results targeted towards field implementation. Additionally, the systematic evaluation of soil characteristics, laboratory-scale behavior, and numerical modeling will generate data necessary to support a mechanistic-based field-scale ground treatment evaluation. This type of mechanistic evaluation of post-fire soil stabilization will aid in establishing proof-of-concept for the proposed research and enhance subsequent adoption of developed tools into practice.

Relevance to Strategic Goals:

This study will enhance the abilities of transportation personnel to respond to extreme wildfire conditions that pose an ever-present threat to the Western United States. The threat of severe wildfires is expected to increase with continued climate variability. Findings from the proposed study will increase the effectiveness and efficiency of post-fire emergency response and soil stabilization treatment techniques to reduce the vulnerability of transportation infrastructure to runoff, erosion, debris flow, and sedimentation that accompany wildfires. An enhanced understanding of hydraulic and geotechnical infrastructure aspects will improve the resiliency and adaptation of transportation infrastructure to wildfires and aim to generate improved tools for transportation management practices.

Completion of standard maintenance, repair, rehabilitation, and renewal of existing transportation infrastructure requires dedicated resources to maintain a state of good repair. In an era of post-fire threats, a critical question is how to direct resources such that small financial investments in maintenance can preclude massive expenditures in repair. During Fall 2013, there have been a minimum of three construction crews, composed of approximately 10 workers including traffic safety personnel, working 40-hour weeks on Highway 14 in the Poudre Canyon outside Fort Collins, Colorado. These workers are repairing damage caused by the large flows of mud and rock onto, over, and through pavement and culverts adjacent to the highway. The potential to identify critical regions of burned areas adjacent the highway that had higher risk, based on phenomenological performance of untreated and treated soils post fire, would considerably benefit resource allocation to stabilize soil prior to precipitation events to minimize or inhibit subsequent debris flows that caused infrastructure damage, transportation disruption, and monetary cost. An idealized end result of the proposed research is to develop recommendations to assist in these types of events, and the stated objectives provide the initial basis in creating such a mechanism.

Educational Benefits:

The proposed study will support two graduate students; one student will lead experimental research efforts and the other student will lead numerical research efforts. The students and Principal Investigators (PIs) will create a synergistic collaboration such that all personnel understand the integration of the proposed research tasks to further the state-of-practice of post-fire ground treatments and improve protection of transportation infrastructure. Experience gained by the PIs will be blended into undergraduate and graduate courses taught by the PIs to provide students tangible connections to a relevant civil engineering problem that we as a society will face for the foreseeable future. The laboratory and numerical tools will be invaluable teaching aids to demonstrate how coupling laboratory experiments and numerical modeling can enhance our ability to solve challenging, multi-disciplinary engineering problems.

Work Plan:

A timeline for the proposed project is shown in Fig. 3. Tasks outlined in Fig. 3 correspond to the three research objectives described previously. The project is proposed for a 2-yr duration, where Phase 1 corresponds to Year 1 and Phase 2 corresponds to Year 2. After graduate students are identified and hired, the first six months of Phase 1 will be devoted to background review and training to bring the students up-to-speed. During this time the PIs will connect with CDOT and the U.S. Forest Service to identify potential soil sampling locations. Soil samples will be collected during the summer of Phase 1 such that vegetation is established. Laboratory equipment for the proposed project is available at CSU with the exception of the slope-model apparatus. This apparatus will be designed, constructed, and evaluated during Phase 1 to facilitate slope-model testing throughout Phase 2. Preliminary DEM evaluations will be conducted in Phase 1 to simulate case studies to evaluate sensitivity of model parameters on post-fire behavior and eventually link with experimental models and results.

The PIs anticipate that the bulk of the laboratory and numerical work will be conducted during Phase 2 of the proposed project. To facilitate completion of the proposed laboratory work, an undergraduate student will be hired to assist the graduate student leading the experimental research efforts. Each slope-model experiment is anticipated to require approximately two months for setup, testing, and evaluation. The student leading Task 3 will use Year 2 to reduce digital image data, simulate slope-model experiments, and evaluate post-fire soil stabilization variables on ground cover treatment effectiveness. Throughout the duration of the project the PIs and students will collaborate on integrating findings from the proposed research with the state-of-practice to develop recommendations for post-fire emergency response actions.

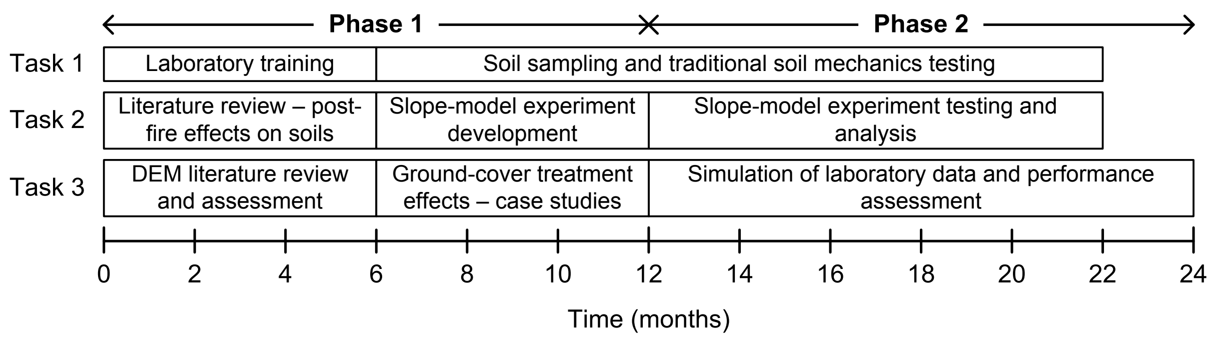

Fig. 3. Tentative timeline for the proposed project. Tasks correspond to research objectives.

Project Cost:
Total Project Costs: **Phase 1 = $196,800**, Phase 2 = $192,000, Total = $378,000
MPC Funds Requested: **$96,000** (half of Phase 1 project costs)
Matching Funds: **$100,800**
Source of Matching Funds: 1.5 month salary for Bareither (~ $27,400 salary + fringe + facilities and administration), 1.5 month salary for Heyliger (~ $38,800 salary + fringe + facilities and administration), CSU Borland laboratory upgrade proposal via Bareither ($6,000), and CSU start-up funds via Bareither (~ $20,800).

Note: the PIs are applying for MPC funding to support Phase 1 of the proposed project and will reapply for funding for Phase 2.

TRB Keywords:
Geotechnology, hydraulics, erosion, transportation infrastructure

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