MPC-447 (Year 2)

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Project Title:
Post-Fire Ground Treatments for Protection of Critical Transportation Structures (continuation)

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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.

Development of Research Methods:

Experimental Research Program: Development of a slope experiment was proposed in Phase 1 of the original project. A schematic of the initial proposed slope-model experiment is shown in Fig. 1a and a photograph of the existing slope-model experiment is shown in Fig. 1b. The actual slope-model experiment was constructed to the proposed length of 0.76 m and width of 0.30 m. A wooden frame sealed with a polyurethane coating was constructed to hold the test box with a series of vertical holes drilled in the frame to allow changes in slope angle of the soil (Fig. 1b). The test box was constructed of stainless steel and includes a geosynthetic drainage layer at the bottom. A catchment platform is attached to the sidewalls at the down-slope end of the specimen to divert surface water flow and sediment to quantify runoff and erosion.

Modifications were made to the rainfall generation system as the research team determined that measuring the exact quantity of water falling on the specimen would be impractical. A rainfall generation system is being developed to generate controlled rates of rainfall such that the rate of precipitation can be controlled. Thus, in future experiments, the magnitude of erosion and runoff will be correlated to rainfall intensity as opposed to the volume of liquid falling on the surface of the soil. Rainfall intensity is a more common parameter used to correlate runoff and erosion in post-burned soils and will be used in this study.

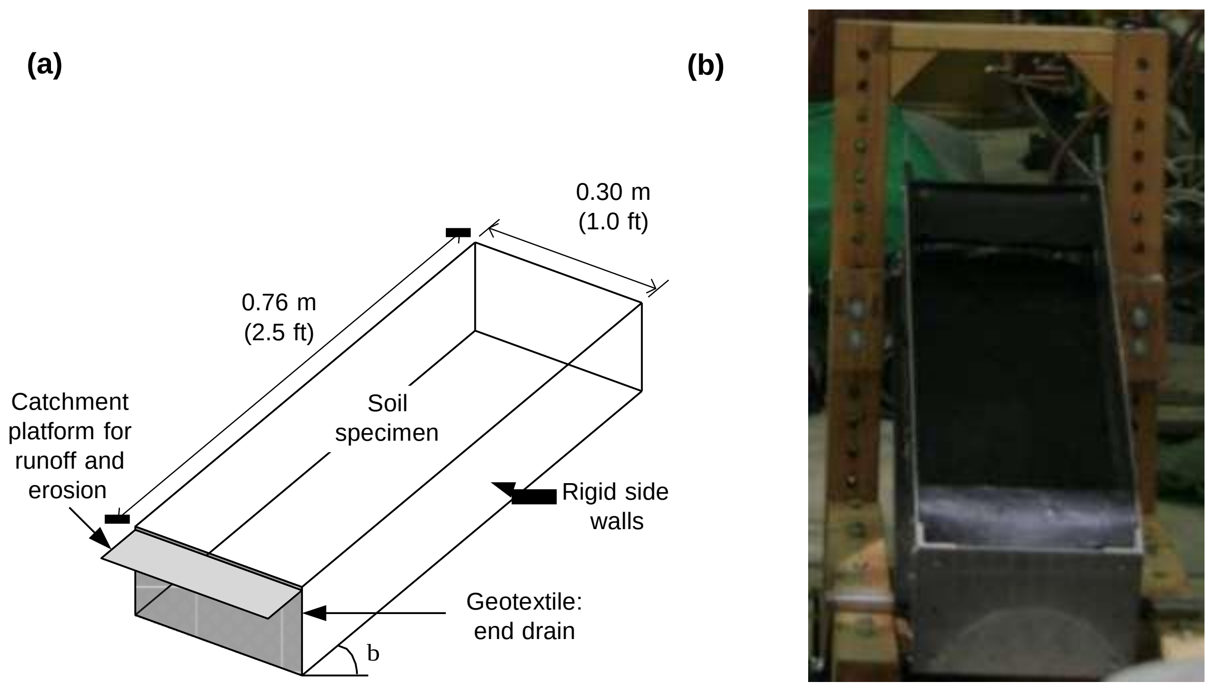

Fig. 1. (a) Schematic of the laboratory-scale slope model to evaluate ground treatments from the original proposal and (b) photograph of the current version of the slope-model experiment.

A schematic of a rainfall simulation system developed by Regmi and Thompson (2000) is shown in Fig. 2a and a photograph of the current rainfall generation system being developed is shown in Fig. 2b. The design developed by Regmi and Thompson (2000) was based on three objectives: (i) provide control of raindrop application in time and space, (ii) reproduce distributions of drop sizes similar to nature across a range of intensities, and (iii) generate approximate terminal velocity of drops at impact. These objectives correspond with objectives of the slope-model experiment, and thus, the design in Regmi and Thompson (2000) was selected for the rainfall generation method in this study. This rainfall generation system has added additional materials and manufacturing needs to the project, but will be worthwhile as the system has been shown to permit control on rainfall intensities between 0.25 and 160 mm/h and also allow raindrops to achieve 95% of terminal velocity. These rainfall controls are ideal for laboratory experimentation and will allow for more accurate representation of actual storms that lead to increased runoff and erosion following wildfires.

Numerical Research Program: The numerical research component of this project will focus on the development of a discrete element model (DEM) to simulate particle-to-particle and fluid-to-particle forces. The model is being developed in-house at Colorado State University (CSU) using FORTRAN to more precisely evaluate soil behavior at the particle level. Once the DEM is fully developed, the numerical code will be used to (i) simulate existing case studies on particle mechanics and (ii) simulate a series of preliminary experiments in the slope-model experiment using a clean, well-rounded, poorly-graded (i.e., uniform) sand.

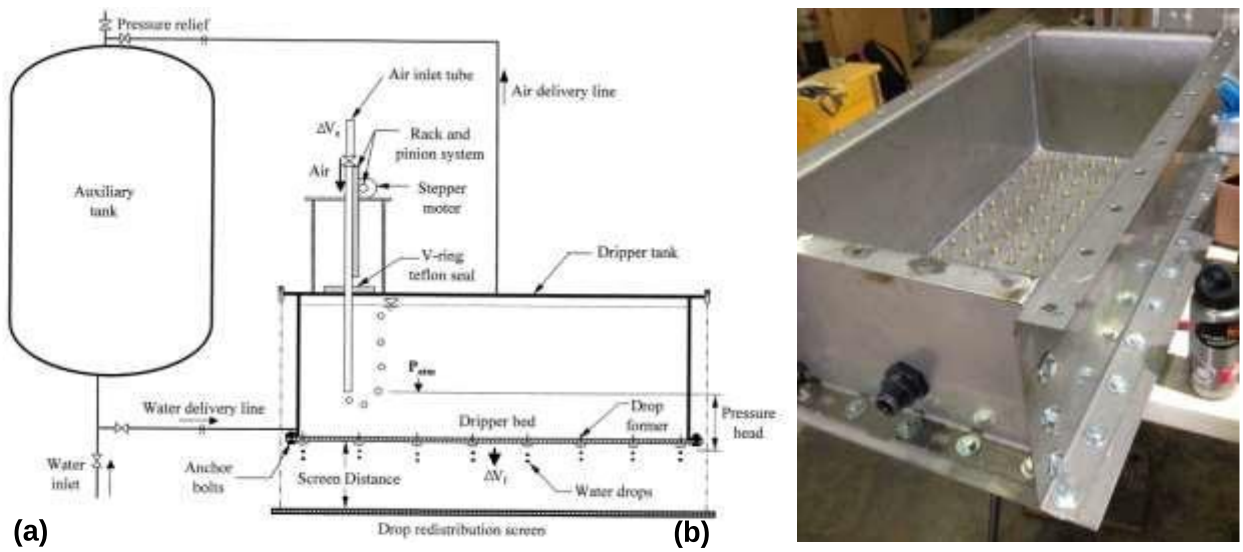

Fig. 2. (a) Schematic of a laboratory-scale rainfall generation system from Regmi and Thompson (2000) and (b) photograph of the current rainfall generation system.

The use of uniform sand for preliminary testing is a new addition to the proposed research and is believed essential to assess behavior in the physical experiment and validate the numerical model. Simulating a uniform material is the most straight-forward application of DEM and is necessary to assess functionality of the numerical code for subsequent iteration towards final development. In addition to commonly-used boundary conditions in DEM, such as rigid and periodic boundaries (e.g., O'Sullivan 2011), a novel boundary condition called "save mass" has been developed for this study. In brief, the save mass boundary condition allows for summation of particles the exit the save mass boundary in the numerical simulation. The save mass boundary condition will be used on the lower slope boundary to compute the total mass of simulated particles that have been eroded and removed from the problem domain. This boundary condition will be used to assess total erosion and compare with physical measurements of the slope-model experiment.

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 and Supplement Support Justification:
An updated timeline for the project is in Fig. 3. Tasks outlined in Fig. 3 correspond to the three research objectives described in the original proposal. The project has been revised from the proposed 2-yr duration to a 3-yr duration, where Phase 1 corresponds to the first 1.5 yr and Phase 2 corresponds to the second 1.5 yr. As of this time (i.e., December 2015) literature reviews corresponding to post-fire ground treatments and post-fire effects on soils as well as on DEM have been completed. These literature reviews were used to support development of the slope-model experiment (Fig. 1), rainfall generation system (Fig. 2), and DEM numerical code.

The current project team consists of Principal Investigators (PIs) Dr. Bareither and Dr. Heyliger, a PhD student Kirsten Peterson, an MS student Taylor Ray, and an undergraduate student Kayla Moden. Kirsten is leading development of the DEM, Taylor is leading development of the slope-model experiment, and Kayla is assisting with the slope-model experiment and other laboratory experiments as needed (e.g., soil characterization). The supplemental funding requested will be used as follows: (i) salary support for students to complete Phase 1 of the project; (ii) materials and manufacturing support to complete the rainfall generation system; (iii) purchase of water content sensors and data loggers to monitor infiltration and moisture movement within the soil specimen of the slope-model experiment; and (iv) final equipment modifications needed to finalized development of the slope-model experiment.

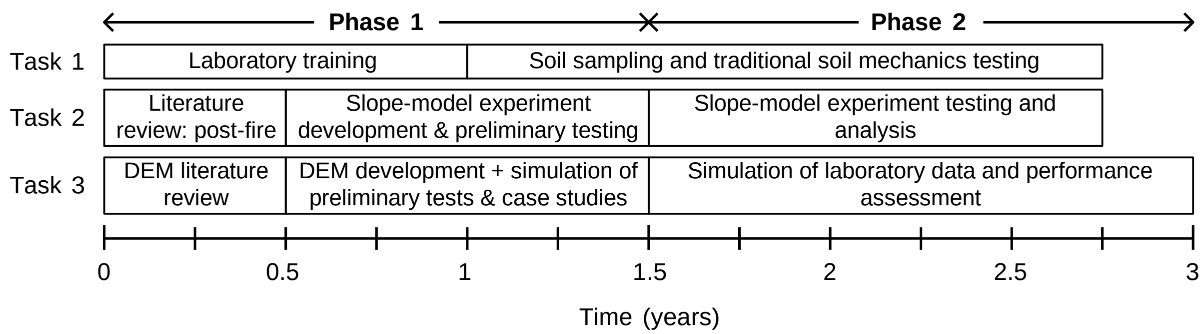

Fig. 3. Revised project timeline. Tasks correspond to research objectives outlined in the original proposal.

Project Cost:
Total Project Costs: Phase 1 = $196,800, Phase 2 = $30,000 Total = $223,800
MPC Funds Requested: $30,000 (supplemental to Phase 1)
Matching Funds: $30,000
Source of Matching Funds: In-kind contribution via salary support.

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

TRB Keywords:
Geotechnology, hydraulics, erosion, transportation infrastructure

References:
O'Sullivan, C. (2011). Particle-based discrete element modeling: geomechanics perspective, *International Journal of Geomechanics*, 11(6) 449-464.

Regmi, T. P. and Thompson, A. L. (2000). Rainfall simulator for laboratory studies, *Applied Engineering in Agriculture*, American Society of Agriculture Engineering, 16(6), 641-647.