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Project Title

Probabilistic Modeling of Landslide Hazards to Improve the Resilience of Transportation Infrastructure

University

Colorado State University

Principal Investigators

Peter A. Nelson
Associate Professor
Colorado State University
Phone: (970) 491-5247
Email: peter.nelson@colostate.edu
ORCID: 0000-0002-8679-3982

Research Needs

In steep or mountainous terrain, natural disasters such as wildfire, or severe weather and flooding, are often followed by landslides and debris flows. The intersection of landslide processes with human development creates risks of property damage, disruption of infrastructure, injury, and loss of life. Roads and highways, which traverse a wide range of potential landslide hazards, are particularly susceptible to damage from mass wasting events. There is a pressing need to improve our ability to quantify risks to transportation infrastructure from landslides and debris flows given the increasing frequency of wildfires and severe storms associated with a changing climate (e.g., Westerling et al., 2006).

Prediction of landslide hazard to roads and highways is an important, but challenging, problem. Scoring systems relying on qualitative assessment of a variety of potential risk factors have been developed to assess relative landslide hazard and risk to roadways (e.g., Pratt, 2014 and references therein). Process-based landslide initiation models, which capture the essential physics of the underlying stability problem, are potentially capable of making quantitative predictions of landslide hazard over a broad range of landscapes and environmental conditions. Models of varying level of complexity have been developed to try to predict conditions under which landslide instability may occur, but data uncertainty in hydroclimatic variables and soil and hillslope properties makes deterministic, quantitative prediction of landslide initiation at large spatial scales uncertain. A modeling framework that captures this underlying variability, however, has the potential to quantify this uncertainty and provide probabilistic estimates of landslide hazard to infrastructure.

This project proposes to explicitly connect predictions from a probabilistic, process-based model of landslide initiation to spatial data on transportation infrastructure. The model will use Monte Carlo simulation to incorporate spatial and temporal variability in landscape properties and forcing variables, and model-derived probabilities of landslide initiation will be mapped downslope onto the road network. The resulting maps of landslide hazard may be a useful tool for risk planning and management.

Research Objectives

The objectives of this study are to (1) use Monte Carlo simulations of a process-based model of landslide initiation to calculate probability of landslide occurrence, (2) develop a methodology to connect outcomes from this model to the transportation network, and (3) use the results to generate continuous estimates of landslide hazard throughout the road network.

The methodology to spatially map landslide initiation probabilities to the road network will likely rely on a number of physical or geographic parameters, such as the distance between the road and the landslide initiation cell, the distribution of slopes between the road and the landslide source, land use and vegetation characteristics adjacent to the road and on the hillslopes, and potentially other criteria.

Research Methods

This project will use the Landlab earth surface modeling toolkit (Hobley et al., 2017) to implement a probabilistic model of regional shallow landslide initiation. Transportation infrastructure, in the form of GIS data, will be draped onto model-generated hazard maps, and the probabilistic likelihood of failure upslope of any cells in the model domain collocated with transportation infrastructure will be determined. In this way, probabilities of landslide hazard can be determined continuously throughout the transportation network.

The model will build upon recent efforts by Strauch et al. (2018), who used Landlab – an open-source, Python-based earth surface modeling framework that provides flexible model customization and coupling – to develop a process-based model for shallow landslide initiation. The model evaluates the infinite-slope stability equation to calculate a factor of safety for every grid cell in a digital elevation model (DEM). This calculation relies on estimates of soil and hillslope properties such as cohesion, soil depth, bulk density, internal friction angle, relative wetness, and hydraulic conductivity. These parameters are inherently spatially and temporally heterogeneous, making deterministic predictions of landslide instability over broad regions uncertain; however, in this project we will treat these parameters as random variables represented by probability distributions and use them to perform Monte Carlo simulations, producing probabilistic maps of landslide susceptibility across the landscape. These landslide probabilities will then be projected downslope onto the road network, producing continuous maps of landslide risk along each road in the model domain.

This method should be applicable at any location where sufficient elevation data, transportation network data, and estimates of soil and hydrologic properties exist. In this project, we will use the Colorado Front Range as a test example. In September 2013, a highly unusual multi-day rainstorm triggered at least 1,138 debris flows in the Colorado Front Range (Coe et al., 2014), including the High Park Fire burn area where the PI has had ongoing research since 2012 (e.g., Brogan et al., 2017). Due to the historic and highly damaging nature of this storm, the topography, rainfall, and locations of debris flows resulting from it have been well documented, and consequently it is an excellent test case for the proposed modeling and risk assessment framework.

Expected Outcomes

The expected outcomes of this work are (1) development of new methodology connecting probabilistic predictions of landslide initiation computed over large spatial scales to transportation infrastructure data to quantify the probability of landslide hazard along a road network, and (2) evaluation of the modeling methodology and framework with a recent extreme event (the 2013 Colorado Front Range floods). We anticipate that this work will lead to at least 1-2 scientific publications, and it may provide initial results that will aid the development of a longer-term proposal to be sent to federal or state funding agencies.

Relevance to Strategic Goals

The primary USDOT strategic goal addressed by this project is Safety. Landslides pose a major threat to our nation's roadways, and developing quantitative, probabilistic, process-based estimates of landslide hazard along roads and highways will be an important step toward ensuring the safety of our nation's motorists.

Educational Benefits

This project will support a graduate student in their pursuit of a Master of Science in Civil and Environmental Engineering at Colorado State University. The student will be primarily responsible for working with and modifying the landslide initiation model, acquiring data, running the model, analyzing results and developing landslide hazard maps, and presenting research through written reports, papers, and oral presentations.

Additionally, this project will be used as an example study in a course taught by the PI, CIVE 513: Morphodynamic Modeling. The curriculum for this course will be adapted to include material on models of landslide initiation, and the data and model used in the 2013 Colorado test case will provide material for a class project or assignment.

Technology Transfer

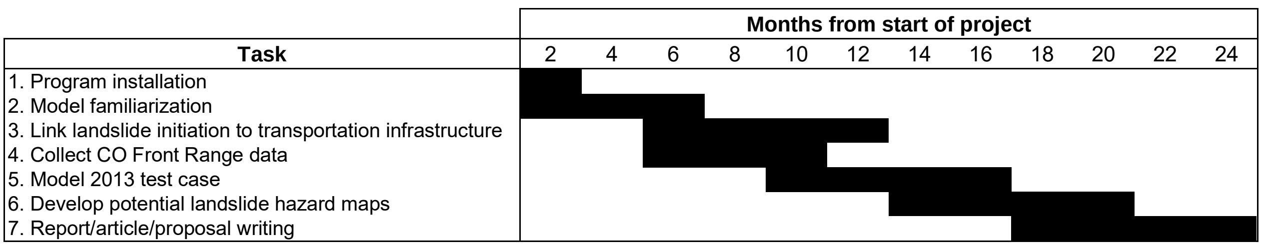
Findings from this research will be disseminated through conference presentations, project reports, and journal articles. Revisions and adaptations of the Strauch et al. (2018) probabilistic landslide initiation model, including integration with transportation GIS data, will be freely provided via HydroShare (www.hydroshare.org). HydroShare is a system operated by The Consortium of Universities for the Advancement of Hydrologic Science Inc. (CUAHSI) that enables users to share and publish data and models in a variety of flexible formats, and to make this information available in a citable, shareable and discoverable manner. HydroShare includes a repository for data and models, and tools (web apps) that can act on content in HydroShare providing users with a gateway to high performance computing and computing in the cloud.

Work Plan

The major tasks associated with this research are as follows:

1) Acquire and install onto a high-performance workstation the existing Landlab-based Python model of landslide initiation described in Strauch et al. (2018).
2) Become familiar with the model's underlying assumptions, data requirements, operation, and analysis of results.
3) Develop a methodology to link model-derived landslide initiation probability to spatial information on transportation infrastructure.
4) Acquire input data for the model for test application in the Colorado Front Range.
5) Run the model test case and compare predicted landslide initiation to those observed during the 2013 flood.
6) Use the validated model to develop probabilistic maps of potential landslide hazard on the road network.
7) Complete draft report and possible journal article(s) and additional proposals based on initial work.

A chart with expected time completion dates is shown below.



Project Cost

Total Project Costs:	$112,000
MPC Funds Requested:	$56,000
Matching Funds:	$56,000
Source of Matching Funds:	Faculty time and effort

References

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