Post-Wildfire Stability and Improvement of Hillslopes Near Pacific Northwest Transportation Infrastructure to Increase Mobility

FINAL PROJECT REPORT

by

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16. Abstract

An increased incidence of wildfires followed by a wet season in the Pacific Northwest of the United States has resulted in surficial stability issues (erosion, shallow landslides). If a wetting-induced shallow landslide occurs on a highway embankment or on a natural hillslope near Pacific Northwest infrastructure, in addition to human life and property loss, there are significant economic consequences when hillslope material blocks the highway, damages the transportation infrastructure, and thus reduces mobility. This study updated an existing slope stability model (level one stability analysis, LISA) by incorporating suction stress and then tested the model performance by estimating the landslide susceptibility of a past landslide. In addition, the study tested the effect of surficial application of a soil stabilizer (xanthan gum) on the shear strength of subsurface soil. The results showed that 2.8 g of xanthan gum applied on the soil surface (68.5 cm x 68.5 cm) reduced erosion by 2.9 times and increased runoff only by ~12 percent, while also increasing the normal stress-shear stress behavior of the subsurface soil at the end of three wetting events.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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EXECUTIVE SUMMARY

An increased incidence of wildfires followed by a wet season in the Pacific Northwest of the United States has resulted in surficial stability issues (erosion, shallow landslides). If a wetting-induced shallow landslide occurs on a highway embankment or on a natural hillslope near Pacific Northwest infrastructure, in addition to human life and property loss, there are significant economic consequences when hillslope material blocks the highway, damages the transportation infrastructure, and thus reduces mobility. To effectively estimate the probability of wetting-induced landslides, slope stability models should consider the contribution of matric suction on the shear strength of soils (i.e., suction stress). Level one stability analysis (LISA) is one of the first distributed physically-based probabilistic models that uses Monte Carlo simulation to calculate landslide probability by using infinite slope stability analysis. LISA is an attractive model because of its simple form; however, it does not consider suction stress in its slope stability routine. This study incorporated suction stress into the LISA and used the updated model (i.e., suction-based LISA) to calculate the probability of landslides for a past landslide at Edmonds, Washington. The suction-based LISA estimated the likelihood of landslide as 50 percent at the location of the real field landslide. For comparison, the probability of failure was calculated as 15 percent at a 1-m depth, which remained stable in the field.

After the landslide susceptibility of burned hillslopes have been identified with a reliable method, critical slopes can be stabilized. Currently, post-wildfire hillslope treatment alternatives focus on erosion reduction on critical slopes. This study evaluated the contribution of a biopolymer (xanthan gum) that is surficially applied for erosion control on the shear strength of subsurface soil. Laboratory rainfall simulation experiments showed that 2.8 g of xanthan gum applied on the soil surface (68.5 cm x 68.5 cm) reduced erosion by 2.9 times while increasing runoff by only ~12 percent at the end of three wet-dry cycles. Samples cored after the third

wetting event were tested with a direct shear test and showed an increase in normal stress-shear stress behavior. Loss on ignition tests on the cored samples showed increased organic content for the xanthan gum-treated. The results indicated vertical movement of xanthan gum into the soil, resulting in increased strength.

CHAPTER 1. INTRODUCTION

1.1. The Post-Wildfire Wetting-Induced Shallow Landslide Problem

An increased incidence of wildfires followed by a wet season in the Pacific Northwest of the United States has resulted in shallow landslides. The depth of shallow landslides is typically 3 to 10 ft, and the major cause is heavy rainfall or snowmelt (e.g., Lu and Godt 2013). When rainfall or snowmelt is combined with other factors that change the soil moisture content, such as timber harvesting or wildfires, landslide susceptibility increases (e.g., Montgomery et al. 1998, Simon and Collison 2002, Dhakal and Sidle 2003). If a wetting-induced shallow landslide occurs on a highway embankment or on a natural hillslope near Pacific Northwest infrastructure, in addition to human life and property loss, there are significant economic consequences when hillslope material blocks the highway, damages the transportation infrastructure, and thus reduces mobility. When hillslope material moves into stream channels, culverts are blocked and highways are washed out, which can lead to long-term road closures and thus to significantly reduced system mobility. The identification of slopes susceptible to wetting-induced shallow landslides and stabilization of critical slopes that could damage infrastructure, block corridors, and reduce mobility are crucial to maintaining transportation system performance. Especially after a natural hazard such as a wildfire, keeping corridors open is critical to maintaining access to the hazard area.

Wetting-induced shallow landslides are a common problem in the Pacific Northwest. For example, in a recent survey, the Washington State Department of Transportation (WSDOT) reported over 100 wetting-induced shallow landslides along its roadways in the last five years, and the Oregon and Alaska DOTs reported between 31 and 100 such landslides (Wayllace et al. 2017). Each landslide on a critical hillslope results in a decrease in mobility until the landslide debris has beeb cleared from the roadways. In addition to road vehicles, other transportation modes are also vulnerable to shallow landslides, and costs associated with mitigation and immobility can be significant. For example, between 2008 and 2014, WSDOT spent $16.1 million of federal funds and $304,000 of state funds on landslide mitigation along Burlington Northern and Santa Fe (BNSF) railway corridors alone (Smelser 2014). Seaport operations can also be disrupted by landslides. For example, the Port of Everett had problems with access to terminal and cargo staging areas after a shallow landslide in 2012, and it spent a significant amount of money to clean the landslide debris from access points as well as from stormwater treatment facilities (Smelser 2014). In addition to mitigation costs, there are indirect costs associated with immobility. For example, from October 2009 to June 2013, Amtrak Cascades trains faced 164 annulments and 243 disruptions, which caused various losses to both passengers and Amtrak. Passengers with existing tickets lost time, and future passengers decided to avoid taking the train, so Amtrak lost ridership and revenue.

The incidence of such wetting-induced shallow landslides is expected to increase with increases in the frequency, duration, and intensity of extreme temperature and precipitation events, including heat wave, drought, flood, and wildfire phenomena. Pacific Northwest slopes are especially susceptible to wetting-induced shallow landslides after intense wildfires. After summer wildfires, wetting-induced landslides can be caused by rain in the fall, rain or snow in the winter or spring, or snowmelt in the spring; therefore, the infrastructure is prone to immobility issues the entire year.

1.2. Post-Wildfire Slope Stability Models and Unsaturated Slope Failures

Efforts have been made to develop models to calculate post-wildfire slope stability. For example, researchers at the Rocky Mountain Research Station in Moscow, Idaho, developed a versatile model for slope stability analysis called level-one stability analysis, or LISA

(Hammond et al. 1992). LISA is one of the first distributed physically-based probabilistic models that uses Monte Carlo simulation to calculate landslide probability by using an infinite slope stability analysis. Other current GIS-based slope stability models such as SINMAP (Pack et al. 1998) and DHSVM (Doten et al. 2006) use the slope stability routine defined in LISA. The current models that analyze slope stability do not take into account slope failures above the groundwater table, and they assume that increases in positive pore water pressures and rises of the groundwater table are the only triggers for landslides. However, in many shallow landslide cases, a rise in the water table did not increase positive pore water pressures sufficient to trigger the landslide (Fourie et al. 1999); instead, a decrease in negative pore water pressures after a wetting event was the trigger (Muntohar and Liao 2008, Godt et al. 2009, Lee et al. 2009). Many of these slopes remain stable at angles much steeper than the angle of repose largely because of the contribution to shear strength provided by matric suction (i.e., suction stress). Increased cohesion due to cementation and root strength also contributes to an increase in the stability of such slopes. Loss of trees after wildfires, coupled with prolonged rainfall and the advancing wetting front, decrease suction enough to trigger failures (Rahardjo et al. 1994, Barik et al. 2017).

1.3. Post-Wildfire Hillslopes Treatment

Currently, post-wildfire hillslope treatment alternatives focus on erosion reduction on critical slopes and include mulch treatment and seeding for vegetation regrowth (Robichaud et al. 2013). Although mulching is an effective way to reduce surface erosion, it does not contribute to shear strength and therefore does not reduce landslide susceptibility. Vegetation regrowth is effective at reducing landslide susceptibility; however, vegetation takes time to regrow and contribute to soil strength. Chemical soil stabilizers can reduce erosion and promote vegetation growth, but they are short-lived and can create concerns related to water quality and aquatic habitat in nearby streams and rivers. For example, the Pacific Northwest is specifically concerned about salmon and trout life in streams and rivers (e.g., Smith and Caldwell 2001, Newcombe and MacDonald 2001). Soil stabilizer applied on a hillslope will be washed into streams and rivers over time; therefore, it should be prevented from being a threat to aquatic species. Researchers have recently started testing an environmentally friendly alternative, xanthan gum biopolymer, for strength improvement (e.g., Chang et al. 2015, Qureshi et al. 2014). Laboratory tests have been promising, showing an increase of up to ~2500 kPa in the unconfined compressive strength of sand when xanthan gum has been mixed with sand and compacted to form cylindrical specimens.

1.4. Project Goals

The goals of this research were to (1) modify the slope stability routine used in LISA with a suction-based model, (2) use a data-driven approach to run the suction-based LISA to estimate post-wildfire landslide susceptibility due to changes in infiltration rate and corresponding saturation, and (3) evaluate the application of surficial xanthan gum to improve post-wildfire slope stability.

1.5. Organization of Report

Chapter 2 presents the suction-based LISA for wetting-induced shallow landslides. Chapter 3 presents a laboratory study on surficial xanthan gum application to improve post-wildfire slope stability. Chapter 4 presents the conclusions, and Chapter 5 is the list of references.

CHAPTER 2. SUCTION-BASED SLOPE STABILITY ANALYSIS

2.1. Level One Stability Analysis (LISA)

Various models can be used to perform slope stability analysis. Among all the models, LISA was selected for this research because of its simple form. LISA is a probabilistic model that uses a general form of the infinite slope stability equation (Eqn. 1) in Monte Carlo simulation to calculate the probability of slope failure in a basin (Hammond et al. 1992). Slope failure is defined as a factor of safety (FS) less than or equal to 1. The FS equation used in LISA was developed by using the Mohr-Coulomb failure criterion and applying the equilibrium of forces for an infinite slope. It has the general form:

$$FS = \frac{\tau_f}{\tau_m} = \frac{c + c_r + \cos^2\beta\left[q_0 + \gamma H_{wt} + (\gamma_{sat} - \gamma_w)z_w\right]\tan\phi'}{\sin\beta\cos\beta\left[q_0 + \gamma H_{wt} + \gamma_{sat} z_w\right]} \tag{1}$$

where c is the soil cohesion, c_r is the root cohesion, β is the slope angle, q_0 is the vegetation surcharge, H_{wt} is the vertical depth of the groundwater table from the ground surface, z_w is the vertical depth to the failure surface from the groundwater table, ϕ' is the effective friction angle, γ is the total unit weight, γ_{sat} is the saturated unit weight, and γ_w is the unit weight of water. The equation was designed for landslides that occur below the groundwater table and cannot detect wetting-induced landslides (Koler 1998).

2.2. Suction-Based LISA

2.2.1. Factor of Safety Equation

The original factor-of-safety equation used in LISA (Eqn. 1) does not take into account the changes in effective stress due to changes in saturation and therefore cannot capture the influence of saturation and suction on slope stability or capture landslides that occur above the groundwater table. Slope stability models developed with the original equation assume that landslides can only occur when the soil is fully saturated.

That assumption simplifies the slope stability and factor of safety equations by reducing the soil to a two-phase medium (either water or air, and solids) but prevents representation of either the true stress state of soil or changes in stress state due to fluctuations in soil saturation. When soil is partially saturated (i.e., unsaturated), the stresses that arise because of the air-water interphase (i.e., interparticle capillary stress) contribute to the strength and stiffness of the soil (e.g., Akin and Likos 2017, 2020; Zhou et al. 2016). The contribution of interparticle stresses in effective stress is a non-monotonic function of saturation (or suction), which is represented by the suction stress characteristic curve (i.e., SSCC). The traditional effective stress formula of Terzahgi (1943) can therefore be modified as follows (Lu and Likos 2006):

$$\sigma' = (\sigma - u_a) - \sigma^s \tag{2}$$

where σ is total stress, u_a is pore air pressure, and σ^s is the suction stress characteristic curve (SSCC). The SSCC is a function of saturation, S (or matric suction, ψ):

$$\sigma^s = -f\left(S\right) \tag{3}$$

where f is a scaling function that quantifies the relationship between suction stress and saturation (or matric suction).

Suction stress is an isotropic tensile stress and is therefore a negative value. Thus, suction stress contributes to the effective stress of soil. For precipitation-induced landslides, the primary trigger mechanism is reduction in suction stress (and, therefore, reduction in effective stress) with an increase in saturation. This reduction can take place at saturations as low as 40 percent or as high as 95 percent, depending on the soil type (Akin and Likos 2020).

The original factor of safety equation used in LISA can be modified for landslides above the groundwater table, following the suction stress concept (e.g., Lu and Likos 2006, Lu and Godt 2008), as:

$$FS(z_u) = \frac{\tan\phi'}{\tan\beta} + \frac{2(c+c_r)}{\gamma(H_{wt}-z_u)\sin 2\beta} - \frac{\sigma^s}{\gamma(H_{wt}-z_u)}(\tan\beta + \cot\beta)\tan\phi' \qquad (4)$$

where z_u is the depth from the groundwater table in the unsaturated zone. The value of σ^s is linked with the soil water retention curve, SWRC, with the following equation (Lu et al. 2010):

$$\sigma^s = -(\psi) \qquad \psi \le 0 \qquad (5a)$$

$$\sigma^s = \frac{1}{\alpha}\frac{\ln[(1+q/k_s)e^{-\gamma_w \alpha z} - q/k_s]}{(1+\{-\ln[(1+q/k_s)e^{-\gamma_w \alpha z} - q/k_s]\}^n)^{(n-1)/n}} \qquad \psi > 0 \qquad (5b)$$

where ψ is the matric suction, k_s is the saturated hydraulic conductivity, α and n are the Van Genuchten (1980) parameters from the best fit to SWRC, and q is the infiltration rate (-m/s). It is defined as:

$$q = -k(\psi)\frac{\partial h_t}{\partial z} \qquad (6)$$

where $k(\psi)$ is the hydraulic conductivity function (HCF) and h_t is the total head. Suction stress is expressed as negative pressure; therefore, it is a contributor to resisting forces. A larger (more negative) suction stress results in an increased factor of safety.

2.2.2. Monte Carlo Simulation

With the suction-based LISA, a Monte Carlo simulation was run to estimate the soil shear strength and the corresponding FS for each localized depth by generating 1,000 values for each random variable (i.e., c, φ, α, and n) in MATLAB. The random variables were generated by using the mean, standard deviation, maximum, and minimum values of each random variable. A probability density function (PDF) (truncated normal distribution for c, φ, α, and lognormal distribution for n) was used to represent each random variable. The probability of failure was calculated for each localized depth as the ratio of the number of FS less than 1 to the total number of passes.

2.2.3. Data Sources

The suction-based LISA was evaluated for an historic landslide, the Edmonds Field landslide on Puget Sound, near Seattle, Washington, in 2006. A wetting-induced shallow landslide occurred at the site while the site was being monitored with field sensors; therefore, site, material, groundwater, and surface moisture flux data are available. The soil and site properties were obtained from Godt et al. (2009) and are shown in figure 2.1. The measured experimental value for each parameter was input into suction-based LISA as the mean of the PDF. The minimum and maximum values of silty sand were considered to be the lower and upper bounds of the PDF to account for potential variability in the field. To observe the effect of the intense precipitation event on the probability of failure of landslides, an infiltration flux rate of 1 x 10-7 m/s was chosen, and it was calculated from the cumulative infiltration rate between 29 December 2005 and 14 January 2006, to which was attributed landslide initiation.

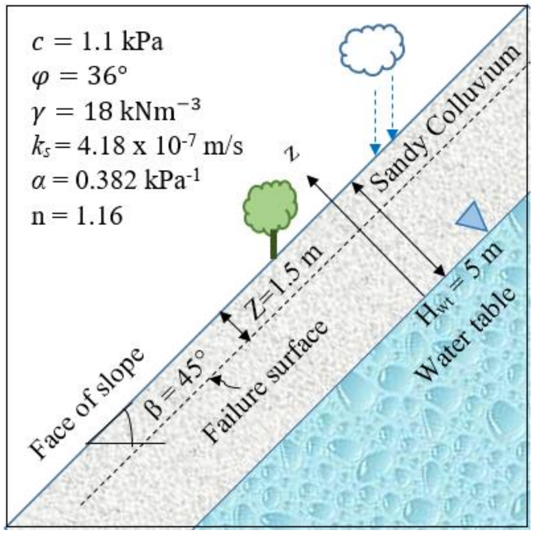

Figure 2.1: Cross-section of the Edmonds site

2.3. Model Evaluation

The probability of failure for each localized depth was estimated by using the suction-based LISA. The probability of failure profile (figure 2.2) showed a gradual increase with soil depth. The suction-based LISA assessed that the likelihood of a landslide was 50 percent at the location of the real field landslide (i.e., at a 1.5-m depth below the ground surface). For this site, slope failure happened at a 1.5-m depth in the field, and the inserted instrument remained stable up to a 1-m depth. The results from the modified LISA showed that at a 1-m depth the probability of failure was 15 percent and at a 1.5-m depth the value changed to 50 percent, which reflected the field scenario.

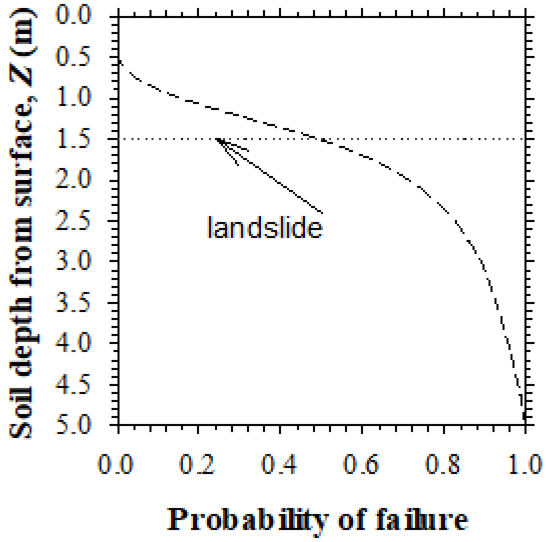

Figure 2.2: Probability of failure profile

CHAPTER 3. SURFICIAL XANTHAM GUM APPLICATION POST-WILDFIRE

3.1. Overview of the Use of Xanthan Gum in Geotechnical Applications

Xanthan gum is a polysaccharide with numerous industrial uses, in particular as a food additive and a rheology modifier. It is produced, via the fermentation of glucose or sucrose, by the *Xanthomonas campestris* bacterium (Davidson 1978, Rosalam and England 2006). Pseudoplasticity (i.e., viscosity degradation depending on increase of the shear rate) is the most distinguishing property of xanthan gum (Casas et al. 2000). Therefore, it is used as a stabilizer and thickening agent for various purposes. Xanthan gum structure consists of repeated units formed by five sugar residues: two glucose, two mannose, and one glucuronic acid (Jansson et al. 1975, Melton et al. 1976). $C_{35}H_{49}O_{29}$ is the fundamental chemical structure of xanthan gum.

In geotechnical engineering, xanthan gum is referred to as a biopolymer. A number of studies have evaluated xanthan gum as a stabilizer for improving mechanical and hydraulic soil behavior. Various concentrations of xanthan gum have been found to increase cohesion by 90 percent for sand (Wiszniewski et al. 2017), 100 percent for bentonite, and 200 percent for kaolinite (Latifi et al. 2016). Xanthan gum has also been found to increase the shear strength of sand by 533 percent (Cabalar and Canakci 2005), increase the unconfined compressive strength of bentonite by 40 percent and of kaolinite by 60% (Latifi et al. 2016), reduce the soil loss of a silty sand by 32 percent (Kavazanjian et al. 2009), and improve the erosion resistance of a natural loose soil by 30 percent (Chang et al. 2015).

3.2. Xanthan Gum for Post-Wildfire Slope Stabilization

3.2.1. Study Site and Sample Collection

Soil samples were collected from a high burn severity location of a site that was burned by the Mesa Fire in the Payette National Forest, Idaho. Bulk and intact soil core samples were collected as described by Akin et al. (2021). Bulk soil was collected from the surface (0- to ~10-

cm depth) of a 200-m^2 area. The soil was passed through a custom sieve (1.27-cm opening diameter) in the field to remove gravel and large roots and brought to the laboratory. It was then sieved again (0.63-cm opening diameter) and used for soil classification and rainfall simulation experiments. Soil was classified according to the Unified Soil Classification System following ASTM D2487 as MH (table 3.1).

Table 3.1: Properties of the 2018 Mesa Fire-burned soil

Property	**Value**
Gravel	3%
Sand	34%
Silt	48%
Clay	15%
Liquid Limit	53
Plasticity Index	11
Specific Gravity	2.6
USCS Classification	MH

3.2.2. Erosion Experiments

The erosion experiments were conducted in custom-made 68.5-cm x 68.5-cm plots with a front end depth of 7 cm and a rear end depth of 15 cm (Pannkuk and Robichaud 2003). The soil was compacted to an *in-situ* void ratio of 2.1 and a water content of 10 percent. The plots were inclined at a 30° angle during wetting and were placed horizontally during drying, as described by Akin et al. (2021). Wetting and drying events were alternately applied by using a modified Purdue-type rainfall simulator (Meyer 1995) and two 5,700-watt ultraviolet (UV) light sources, respectively. To each plot, 2.8 g of powdered xanthan gum (Sigma-Aldrich, CAS 11138-66-2, St. Louis, Mo.) were uniformly sprinkled on the compacted soil surface. At the end of each wetting and drying event, disc-shaped samples were extracted from three different locations in the rainfall plots—upslope, midslope, and downslope—to run direct shear experiments.

3.2.3. Direct Shear Experiments

Direct shear tests were performed to evaluate the potential downward movement of the soil additives during wet-dry cycles, which would alter soil strength. Soil samples with a 6.35-cm diameter and 2.55-cm height were cored from the plots from three locations (upslope, midslope, downslope) at the end of the third drying event. The normal stress was maintained as 25 kPa, 50 kPa, and 100 kPa for the upslope, midslope, and downslope samples, respectively. A displacement rate of 0.5 mm/min was used during the direct shear tests. High stresses were used to observe the effect of xanthan gum on soil strength more clearly.

3.2.4. Loss on Ignition Tests

Loss on ignition (LOI) tests were run in addition to direct shear tests to determine the additive concentration in the soil after the third wetting event. The soil samples were first dried at 105°C for 12 to 16 hours to remove water. They were then weighed, placed in a high temperature furnace (550°C) for 4 hours, and weighed again. The mass difference gave the organic content, which included the soil organic matter and xanthan gum.

3.2.5. Results

For the untreated soil, runoff started at ~20 min and increased thereafter, whereas runoff started after ~5 min of rainfall for the xanthan gum-treated soil (figure 3.1). As a result, soil loss started after ~20 min for the untreated soil and after ~5 min for the xanthan gum-treated soil. At the end of the three wetting events, xanthan gum had increased the total runoff by ~4 percent in comparison to the untreated soil, while reducing the soil loss by 2.9 times. The total soil loss due to the three wetting events combined was 2,365 g for untreated soil and 850 g for xanthan gum-treated soil.

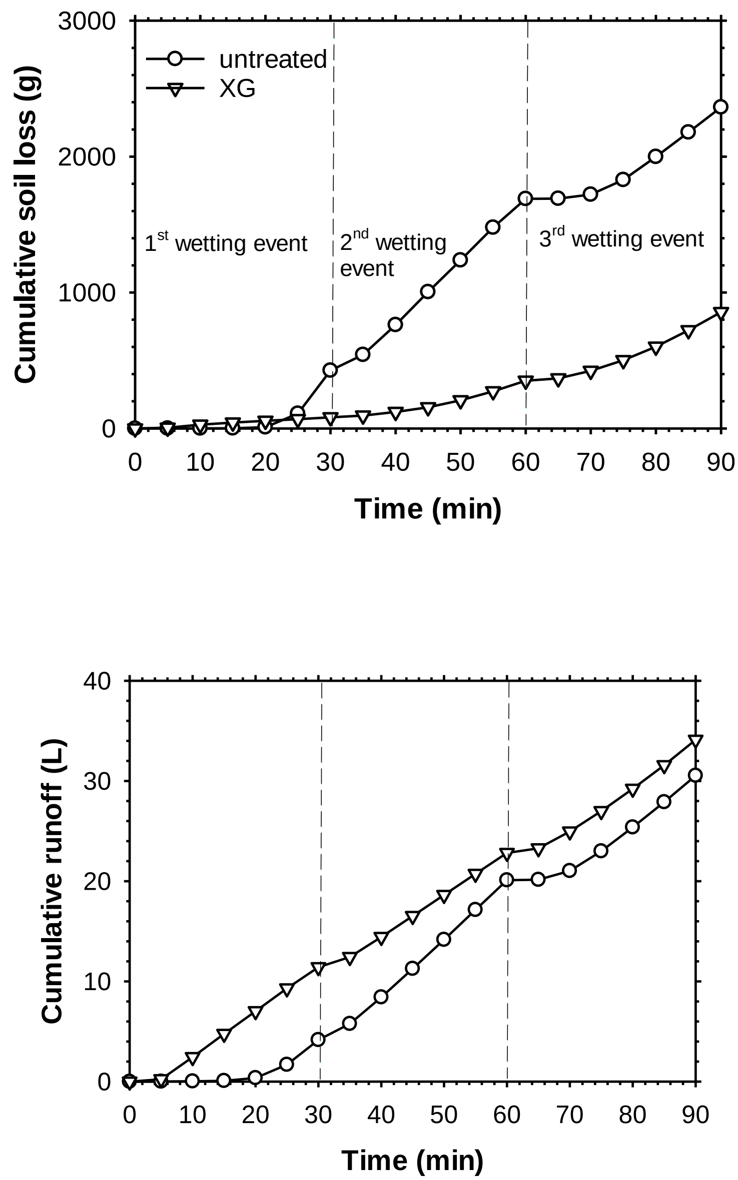

Figure 3.1: (a) Cumulative soil loss and (b) cumulative runoff for untreated and xanthan gum-treated soil over time. XG: xanthan gum.

A linear Mohr-Coulomb failure envelope was obtained for the untreated samples, with cohesion and friction angle determined, respectively, as 13.8 kPa and 32.1°, whereas the xanthan gum-treated samples showed a non-linear failure envelope (figure 3.2). The non-linearity was attributed to reflect the effect of the xanthan gum on the shear stress-normal stress relationship. At all three normal stress levels, the shear strength of the xanthan gum-treated samples was higher than that of the untreated samples. This indicated that the xanthan gum was mobile and could migrate vertically into the soil with rainfall, contributing to the shear strength of the soil and thus hillslope stability. The vertical movement of the xanthan gum was also indicated by the LOI results (shown in parentheses in figure 3.2). The LOI for untreated soil ranged from 11.7 percent to 12.3 percent, whereas for the xanthan gum-treated soil it ranged from 13.2 percent to 15.0 percent. The LOI for the treated soil was greater than that of the untreated soil, indicating a presence of additional organic material in the treated soil. No trend was observed between the LOI and sample locations (i.e., downslope, midslope, upslope).

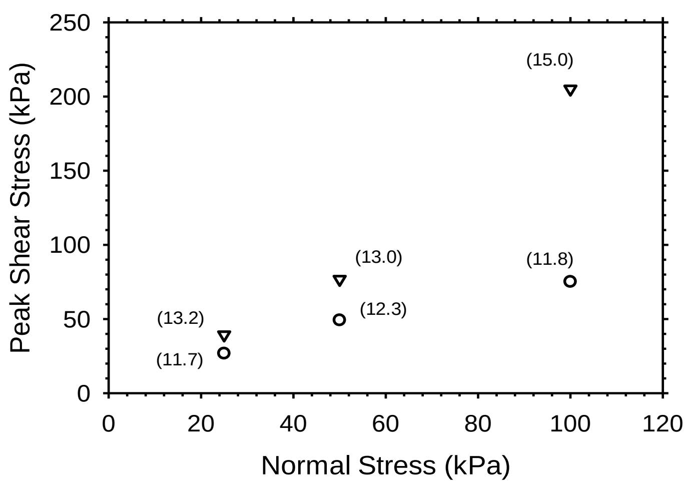

Figure 3.2: Direct shear results of untreated (circles) and XG-treated (triangles) soil after the third wetting event. LOI values are shown in parentheses.

CHAPTER 4. CONCLUSIONS

A probabilistic slope stability model, LISA, was modified to incorporate the effects of matric suction on slope stability. The model was used to estimate the probability of landslide at Edmonds Field, where an actual landslide took place in 2006. The suction-based LISA estimated the likelihood of landslide as 50 percent at the location of the real field landslide. For comparison, the probability of failure was calculated as 15 percent at a 1-m depth, which remained stable in the field.

Surficial application of xanthan gum to stabilize wildfire-burned soils was evaluated. Stabilization against erosion was assessed through rainfall simulation experiments run in the laboratory. The contribution of xanthan gum to the shear strength of subsurface soil was evaluated with direct shear tests. The results showed that at the end of three wet-dry cycles, 2.8 g of xanthan gum applied on the soil surface (68.5 cm x 68.5 cm) reduced erosion by 2.9 times without sealing the soil surface completely (a 12 percent increase in runoff). Xanthan gum resulted in an increase in normal stress–shear stress behavior in the subsurface soil, indicating that the surficial stabilization could be effective for subsurface soil, too. The organic content measured with loss on ignition also showed an increase, infivsyinh yhr improved strength of the subsurface soil.

CHAPTER 5. REFERENCES

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