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Stochastic hydro-mechanical stability of vegetated slopes: An integrated copula based framework

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ABSTRACT

Vegetation induces considerable uncertainties in the hydrological (suction, ψ) and mechanical (cohesion, c and frictional angle, ϕ) parameters of soil, due to which, it is essential that the stability of vegetated slope is evaluated in a probabilistic framework. Moreover, from previous studies, it has been found that the mechanical parameters of soil share inherent correlation, which has a profound effect on slope stability. The combined effect of stochastic hydro-mechanical parameters is not well studied, more so in vegetated slopes. This study demonstrates a probabilistic approach to analyse the stability of vegetated slopes, under the combined effect of univariate suction and bivariate $c-\phi$. Data corresponding to suction and the mechanical parameters, are obtained from a field monitoring programme, conducted on a homogeneously compacted vegetated slope (adopted from previous literature). The suction responses are probabilistically evaluated by estimating their probability distribution functions, and the dependence structure of c and ϕ is established via copula theory. Treed slopes are found to be more stable than grassed and bare (i.e. sparsely vegetated) slopes, since suction induced in treed soil is relatively higher. The probability of failure for vegetated slopes decreases substantially with increase in magnitude of $c-\phi$ correlation, thereby yielding more conservative estimates than the uncorrelated case.

1. Introduction

Vegetation plays a significant role in the stability of natural slopes, as it not only contributes to strength enhancement through mechanical reinforcement by roots, but also induces suction via evapotranspiration (Indraratna et al., 2006; Fatahi et al., 2010; Garg et al., 2012; Ng et al., 2013). Moreover, due to changing weather conditions, the uncertainties associated with suction significantly affect the shear strength of soil (Ishak et al., 2016; Gadi et al., 2016), which in turn affect the stability of vegetated slopes. Unsaturated shear strength of soil is dependent on suction. Fredlund et al. (1978) defined the unsaturated shear strength of soil as,

$$\tau_s = c + \sigma' \times \tan(\phi) + \psi \times \tan(\phi_b) \tag{1}$$

where, σ' is the net normal stress, and ϕ_b is the angle indicating the rate of increase in shear strength relative to suction (ψ), and $[\psi \times \tan(\phi_b)]$ is the cohesion intercept, which is a function of suction.

The above equation shows that the any presence of vegetation induced soil suction could be crucial in enhancing soil strength by varying the cohesion intercept.

In order to conduct a realistic analysis on the reliability of vegetated slopes, it is essential to address the uncertainties induced by vegetation on the mechanical (c, ϕ) as well as hydrological (ψ) parameters of soil (Chen et al., 2007; Fatahi et al., 2009; Ng et al., 2016c). Moreover, c and ϕ parameters share an inherent statistical correlation, which when combined with their stochastic behaviour, pose significant challenges in the assessment of slope reliability (Tang et al., 2013a; Wu, 2013, 2015; Li et al., 2015). In order to address the variability in the aforementioned soil parameters, several probabilistic techniques for estimating slope stability (Griffiths and Fenton, 2004; Phoon, 2008; Zhang et al., 2014; Liu et al., 2016; Zhang et al., 2016) have been proposed. However, most of these studies deal with bare soils without considering the influence of vegetation (Zhu and Zhang, 2015; Hazra et al., 2017). Vegetation induced suction significantly affects the shear strength of soil, which in turn, has a profound influence on the stability of vegetated slopes (Simon and Collison, 2002; Pollen et al., 2004; Fatahi et al., 2007; Chirico et al., 2013). Recently, studies have been conducted to quantify suction in vegetated soil (Garg et al., 2015b; Fatahi et al., 2014; Ni et al., 2016). However, these studies employed deterministic methods and hence, did not cater to the heterogeneity in the soil parameters

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owing to presence of vegetation. Some studies have made attempts to incorporate the randomness associated with suction of vegetated soil, in an extensive numerical framework (Zhu and Zhang, 2015). Recently, Hazra et al. (2017) provided a probabilistic analysis of univariate suction in vegetated soil, but did not consider the effect of correlated $c - \phi$ on slope stability. Studies on slope reliability, considering the bivariate association between the mechanical parameters (c,ϕ) only are more common place (Li et al., 2012; Wu, 2013, 2015; Li et al., 2015). These studies also deduced a negative correlation between c and ϕ (Phoon, 2008; Tang et al., 2013a, 2013b, 2015). Tang et al. (2013b) reported the importance of copula selection (dependence structure) on geotechnical reliability. However, most of the aforementioned precluded the effect of bare soil suction or vegetation induced suction. Das et al. (2017) evaluated the dependence structures of both mechanical and hydrological parameters of vegetated soil, but did not address their implications on slope stability. The present work attempts to integrate both the effects of random ψ and $c - \phi$ on the stability of vegetated slopes, considering a bivariate association between c and ϕ.

The main objective of this study is to provide a reliability analysis of homogeneously compacted vegetated slopes, considering univariate probabilistic models of suction (ψ) obtained from measured data, and the bivariate probabilistic model of mechanical parameters (c,ϕ). The study first establishes a probabilistic model of field suction segregated into 5-day window periods (refer Table 1) to address its stochastic behaviour owing to weather changes. In addition to this, vegetation induces significant uncertainties on the mechanical parameters (c,ϕ) of soil, whose impact on the reliability of vegetated slopes is also considered. Previous literatures have recognised the fact that cohesion and frictional angle are negatively and non-linearly correlated (Tang et al., 2013b; Wu, 2013; Li et al., 2015). Thus, a copula based model of c and ϕ is utilised while analysing slope stability. The data processed in this study, have been recorded from a field monitoring programme, conducted on homogeneously compacted slope having non-crop species (*Cynodon dactylon* and *Schefflera heptaphylla*) under atmospheric conditions (Garg et al., 2015a), which are referred to as *grassed* slope and *treed* slope. The slope which rarely consists of any vegetation is referred to as *sparsely vegetated* slope (i.e. almost bare slope).

2. Overall plan

In this study, suction (ψ) and the mechanical parameters (cohesion (c) and angle of internal friction (ϕ)) of vegetated soil, measured from the field monitoring programme (Garg et al., 2015a), are treated as random variables. The suction induced in bare and vegetated soils are modelled probabilistically by estimating their univariate probability distribution functions (PDFs), on the basis of Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values. The dependence structure between c and ϕ is established by estimating their joint distribution functions via copula theory. Copula is used to establish a non-linear correlation structure, and also to map the multivariate distribution function to its correlated marginals, in this case being, c and ϕ. The aforementioned reliability analysis is then carried out in the framework of *three scenarios*. ***Scenario 1*** studies the impact of suction, subjected to time varying weather conditions (during the monitoring period), on the reliability of vegetated slopes, considering the dependence structure of c and ϕ. ***Scenario 2*** captures the impact of various suction ranges (*low, high*) and *overall* suction on the probability of failure of vegetated slopes, considering the bivariate association of c and ϕ. *Low* and *high* suctions refer to the suction responses during the wetting and prolonged drying periods respectively. *Overall* suction is the suction when treated as a random sequence by appending all the individual windows of estimated random variables of field suction. ***Scenario 3*** addresses the impact of varying correlations between c and ϕ on the stability of vegetated slopes for *overall* suction. The correlation value is estimated from measured bivariate (c, ϕ) data, using Kendall's tau (τ). The stability of slopes is then estimated with respect to varying magnitudes of correlation, without altering the estimated copula function.

2.1. Experimental database

2.1.1. Measurement of mechanical parameters for vegetated soils

The shear strength parameters of soil were obtained using conventional direct shear test apparatus (Khan and Lateh, 2015; Das et al., 2017). Undisturbed samples for rooted soils of both grass and tree were removed (at 30 cm soil depth) by manually pushing the cylinder with a known volume (63.4 mm diameter × 20 mm height). Strain-controlled direct shear tests were carried out using a standard shear testing procedure. A ring cutter was used to take three samples from each profile at 30 cm soil depth, and then a knife was used to take undisturbed soil samples and transferred to the shear box. The undisturbed unsaturated soil samples were placed in a shear testing device under three different normal loads 10 kg, 20 kg and 40 kg. A lateral displacement was applied at 0.25 mm/min until failure occurred and the peak shear force was noted. Based on the study by Das et al. (2017), the diameter of root ranges from 0.2 mm to 6 mm (Lateh et al., 2015), which is around

Table 1
Probability distribution parameters of measured suction at 0.1 m depth for bare, grassed and treed soils.

Window (5 days)	Bare soil			Grassed soil			Treed soil		
	AIC	BIC	Distribution parameters	AIC	BIC	Distribution parameters	AIC	BIC	Distribution parameters
Sept 9–14, 2012	819.4	824.5	N(85,14.4)	650.3	665.3	LN(3.78,0.35)	1036.9	1042.1	N(219.5, 46.83)
Sept 15–19, 2012	1093.8	1099	W(100,1.2)	1054.6	1060.2	W(13,6.87)	978	983.2	N(335.1,34.23)
Sept 20–24, 2012	984	952.9	N(64.9,35.5)	1023.5	1028.7	N(105,37.8)	1216.6	1221.8	N(251,110)
Oct 1–5, 2012	1003.1	1008.7	N(107.8,16)	898.7	903.9	N(58.3,21.89)	1133.7	1138.9	N(209.1,69.75)
Oct 6–10, 2012	1035.6	1041.2	N(157.4,18.3)	1145.4	1151	N(140,29)	1295	1300.6	W(410,8.60)
Oct 11–15, 2012	781.5	787.7	W(195,17.57)	1127.9	1133.4	N(222,26.8)	1215.1	1220.7	W(523,6.20)
Oct 16–20, 2012	1068.5	1074.1	LN(5.37,0.09)	1216	1221.5	LN(5.71,0.12)	1250.1	1255.7	LN(6.4,0.07)
Oct 21–25, 2012	878	883.2	W(245,13.02)	1036.4	1041.6	W(394,11)	1215.7	1221	W(600,6.34)
Nov 5–9, 2012	1062.8	1068.4	W(73,3.35)	807.8	812.9	N(30.26,13.08)	997.1	1002.3	N(86.3,38.02)
Nov 10–14, 2012	1011.9	1017.5	W(116,7.4)	1067.2	1072.8	W(90,4.58)	1253	1258.6	W(233,5.45)
Nov 15–19, 2012	914.6	919.8	N(135.45,23)	826.1	831.3	N(101.27,14.8)	1291.7	1297.2	W(222,5.40)
Jan 24–28, 2012	988.6	994.2	W(150,12.3)	827.4	832.6	N(92.54,14.87)	998.9	1004.1	N(190.4,36.51)
Jan 29–2, 2012	942.5	948.1	N(160.2,12.3)	1001.2	1006.8	W(113,7.911)	1055	1060.2	N(212,46.93)
Feb 3–7, 2013	950.6	956.2	LN(5.04,0.08)	818.7	824.3	W(131,20.49)	1003.4	1009	W(276,6.18)
Feb 8–12, 2013	819.7	824.9	N(181.7,16.6)	831.5	836.7	N(142.6,15.49)	947.4	952.6	LN(5.58,0.10)
Feb 13–17, 2013	895.1	900.7	W(227,25.8)	927.6	933.2	W(246,24.57)	1213.7	1219.3	LN(5.83,0.1)

Note: AIC – Akaike Information Criterion, BIC – Bayesian Information Criterion (explained in Section 2.2.1).
N – normal distribution, W – Weibull distribution, LN – lognormal distribution (explained in Section 2.2.1).