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Probabilistic analysis of suction in homogeneously vegetated soils

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ABSTRACT

It is unlikely that natural vegetation growth induced soil suction can be predicted deterministically. Probabilistic approach may be an ideal tool to analyse effects of evapotranspiration (ET) induced suction by vegetation, which are commonly found on slopes. Most of the previous deterministic studies quantifying suction are carried out on natural slopes, which are *heterogeneous* in nature. The main objective of this study is to conduct *probabilistic* analysis of measured soil suction in *homogeneously* vegetated slopes. In the present work, a probabilistic model is developed for the measured values of suction, since the measurement process itself is very uncertain and is subjected to a wide range of climatic fluctuations owing to a wide monitoring interval. Expected values of soil suction are found to be significantly higher in treed slope as compared to grassed and bare slope. In contrast to this, the coefficient of variation of soil suction is found to be similar for all slopes irrespective of vegetation types. The probability distribution is found to be dynamically changing with time and also significantly different between bare slope (Weibull distribution) and the vegetated slopes (mostly Normal distribution). Using the estimated probability distributions of suction, the probability of failure is estimated using a simple limit state function using 1000 trials of Monte-Carlo simulation. It is observed that the distribution of suction alters significantly for bare soils during wetting events as compared to the grassed and treed soils. The probability of failure of the bare slopes increases significantly under wetting events.

1. Introduction

Probabilistic approach is often adopted in the analysis and design of various geotechnical infrastructures (D'Andrea and Sangrey, 1982; Chowdhury et al., 1987; Li and Lumb, 1987; Christian et al., 1994; Lacasse, 1994; Duncan, 2000; Hassan and Wolff, 2000; Whitman, 2000; Malkawi et al., 2000; Gui et al., 2000; El-Ramly et al., 2002; Griffiths and Fenton, 2004; Jiang et al., 2014; Li et al., 2014). Natural vegetation evapotranspiration (ET) induced matric potential (i.e., soil suction) (Hemmati et al., 2012; Ng et al., 2013; Garg and Ng, 2015; Garg et al., 2015a, 2015b, 2015c) can affect the analysis and design (Barker, 1995; Pollen-Bankhead and Simon, 2010) of slope, as it significantly affects the soil shear strength (Gan and Fredlund, 1988). Most of the studies related to analysis of soil suction induced by natural vegetation growth are conducted using deterministic approach. It is well known that natural vegetation growth induced suction will have many uncertainties owing to variations in climate and soil conditions (Allen et al., 1998; Garg et al., 2015a). Fig. 1 shows the variability in soil suction in bare and vegetated slopes as demonstrated in field study by Garg et al. (2015a). It is clear from the Fig. 1, that the variation of suction induced in bare and vegetated soils is quite uncertain, which is attributed changes in precipitation and evapotranspiration with time. Thus, probabilistic analysis of measured suction is important, considering the fact that there are considerable uncertainties associated with any of the parameters affecting ET induced soil suction. This is further important while quantifying the reliability of unsaturated slopes (Bergado and Anderson, 1985; Malkawi et al., 2000; Gui et al., 2000; Griffiths and Fenton, 2004; Zhu and Zhang, 2015).

Numerous field studies have been conducted by geotechnical researchers to quantify suction on vegetated slopes. These studies mainly encompassed residual soils (Ishak et al., 2012), silty sand soils (Leung et al., 2015a; Leung et al., 2015b; Garg et al., 2015a, 2015b, 2015c; Garg and Ng, 2015; Bordoloi et al., 2015; Gadi et al., 2016; Vardhan et al., 2016) and non-expansive clay (Heppell et al., 2014). However, in most of these studies, the ground considered is natural with heterogeneous vegetation and soil parameters. Moreover, probabilistic analysis of measured suction has been sparingly reported in vegetated soil mechanics literature. Recently, Zhu and Zhang (2015) evaluated suction profiles considering uncertainties of transpiration. However, in the aforementioned work, the soil suction is quantified using numerical probabilistic models, involving many assumptions in root water uptake model (Feddes et al., 1978) and input parameters (Garg and Ng, 2015), having no connection with the actual field data.

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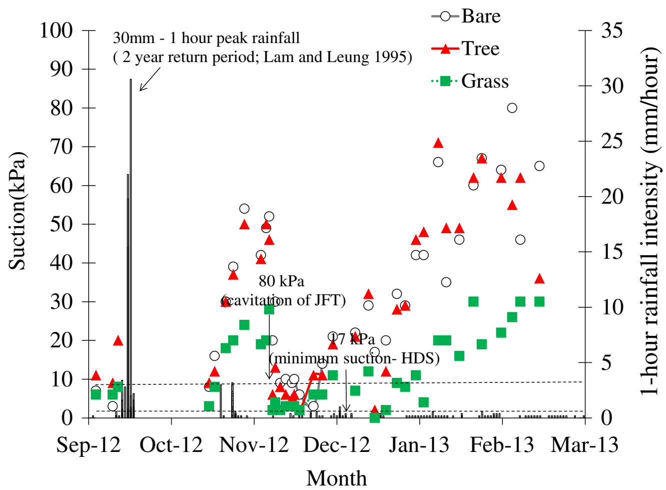

Fig. 1. Variability of soil suction in bare, grassed and treed slope (after Garg et al., 2015a).

This study aims to: (1) undertake a simplified probabilistic analysis of measured soil suction in bare and vegetated soils and fit a suitable probability distribution, and to (2) demonstrate the importance of probabilistic models of measured suction and the other quantities related to suction towards the probability of failure of bare unsaturated slopes. Two different species with contrasting root systems i.e. *Schefflera heptaphylla* (tree) and *Cynodon dactylon* (grass) are selected as vegetation species. Bare slope is used as a control. Field monitoring was conducted first for a period of around 10 months during which suction and root biomass were measured. The measured values of suction are then processed though probabilistic analysis for each slope under natural drying and wetting (different rainfall events). Probabilistic analysis includes identifying the probability distributions along with their standard parameters (mean, standard deviation) of measured soil suction considering temporal variation. This is followed by a reliability analysis (determining the probability of failure) of bare slope with uncertainties of soil suction as a controlling parameter.

2. Material and methods

2.1. Field monitoring of soil suction in bare and tree vegetated slope

The field-monitoring program for studying the effect of natural drying-wetting on suction response in grass and tree vegetated slope was conducted from 11th of September, 2012 to 11th of June, 2013. Bare slope was also monitored for comparison. *Schefflera heptaphylla* (Ivy tree) and *Cynodon Dactylon* (Bermuda grass) were selected as tree and grass species respectively based on its (i) prevalence in Asia and other sub-tropical regions of world (Hau and Corlett, 2003); and also (ii) their drought tolerant nature, which may be suitable for ecological restoration and rehabilitation at warm climate regions (Hau and Corlett, 2003). Fig. 2(a) and (b) shows the front view and side view of the embankment containing above mentioned three slopes (Bare, grassed and treed). Each slope is 2.5 m wide. Heat dissipation sensors (HDS) were installed at shallow depths (i.e., 0.1 m and 0.3 m) to measure suction beyond 90 kPa and up to 2500 kPa (Wong and Fredlund, 1989). Detailed calibration methods are reported in Wong and Fredlund (1989). For suction below 90 kPa, jet fill tensiometers (JFT), with an accuracy of ±1 kPa (Soil Moisture Equipment Corporation, Santa Barbara, USA) were also installed. Details of instrumentation are mentioned in Garg et al. (2015a). Soil suction sampling rate was kept higher to ensure sufficient measurements (at least 100 data points) for conducting an accurate probabilistic analysis during a certain selected period (drying or wetting).

JFT comprises of a negative pore water pressure measuring device (Fredlund and Rahardjo, 1993), and a water reservoir connected to a high air entry porous ceramic cup through a small tube. The ceramic cup is inserted at required depths in pre drilled holes (i.e., 0.1 m and 0.3 m). After insertion, the lower portion of pre drilled hole is back filled and compacted to in situ bulk density. This back fill prevents preferential flow through the clearance between wall of ceramic cup and its surrounding soil. Once the equilibrium between measuring system and surrounding soil is achieved, negative pore water pressure value (u_w) in soil is shown by pressure measuring device connected to ceramic cup. Occasional air bubbles developed within JFT due to cavitation may be removed by activating jet fill action from water reservoir. Suction (u_a-u_w) is estimated from the measured negative pore water pressure. On other hand, HDS (Fredlund and Rahardjo, 1993) contains a porous ceramic block consisting an element for sensing temperature and a miniature heater. Thermal conductivity of porous ceramic block varies with water content. However, water content of ceramic block depends upon the suction value of surrounding soil. Hence, ceramic block calibrated with respect to suction is considered for field measurements. A heater generates heat at the center of the block, some portion of which also dissipates through the block. Undissipated heat raises the temperature at the center of the block. This temperature rise is measured by sensing element in terms of voltage. Suction corresponding to the voltage output is found by calibration curve.

2.2. Statistical analysis methods

Previous works related to the field monitoring of vegetated slopes presented significant variability in the values of soil suction (Zhan et al., 2007; Rahardjo et al., 2014; Garg et al., 2015a; Leung et al., 2015a). The uncertainties associated with the soil suction behaviour can be best manifested by using probabilistic models. The first step towards a full-fledged statistical analysis is windowing the data into 5 day windows starting from the selected monitoring period. The rationale behind selecting the window length is that it should contain sufficient data points (at least 100) so that probability distributions can be fitted to the data. This provides a simple-minded way of looking at suction from a probabilistic viewpoint. However, it must be noted in general, field experiments undertaken on a highly uncertain quantity like suction records a sequence of data at different time instances, which necessitates the use of random process modelling rather than random variable modelling. With the presence of very limited measured data on suction in artificially compacted homogenous vegetated slopes in literature (Garg et al., 2015a), the present work intends to first develop a working knowledge, where the measured suction data (Garg et al., 2015a) is treated as a random variable rather than a random process. The focus is more towards arriving at worst case probability of failures for bare slopes due to suction, for which the present approach suffices the need.

For each of the data-windows probability distributions are fitted using probability paper plot (Ang and Tang, 1984). Five distributions are considered as candidates for fitting the data namely: Normal, Lognormal, Gumbell, Exponential and Weibull which are widely used in probabilistic geotechnical engineering literature (Phoon, 2008). Probability paper plot refers to a special graphical plot used for representing observed experimental data and their probabilities (or relative frequencies). The scale of the graph should be such that a linear relationship is produced between the random variable and their corresponding cumulative probabilities. The linearity or the lack of it thereof (expressed using R^2) can be used to decide whether the candidate distribution fits the data. The first step towards pp-plot is arranging the data in ascending order and then ranking the data according to the increasing order. The first value has rank 1, the second data value has rank 2 and the last data point has rank n (where n is the sample size of the data) and