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Slope Stability Analysis Using the Unsaturated Stress Analysis. Case Study

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Abstract

Paper approaches the problem of considering the unsaturation of soils above water table in the slope stability analysis, condition for obtaining realistic results in both cases of rainfall infiltrating into the soil mass and drainage for improving soil stability. It presents in its first part a brief review methods related to unsaturated stress analysis applied for slope stability analysis, such as Unsaturated phi-b, Unsaturated Fredlund, Unsaturated Vanapalli, Unsaturated Khalili and Unsaturated Vilar model. These methods are estimating in different manners the shear strength depending on soil unsaturated conditions. These methods are applied in the second part of the paper in a case study, presenting a site affected by landslides located in Cluj-Napoca, Romania. For the slope stabilization a siphon drain system has been proposed and installed. An experimental program started and is ongoing on site, compromising site monitoring of suction using jet fill tensiometers and laboratory testing. Site measurement of suction in presence of drainage system was used for perform slope stability analysis using SVSlope software and the embedded methods for estimating the increase in soil shear strength when passing from saturated to unsaturated state.

Keywords: unsaturated soil, slope stability analysis, siphon drain system, tensiometer

1 Introduction

Slope stability is largely affected by water-related changes in the soil mass. Obvious, there are number of possible factors that can lead to the instability of a soil slope. In general, earthen slopes remain stable unless there are changes in the pore-water pressures in the soil comprising the slope. Changes in pore-water pressure are generally the result of water infiltration related to the climatic conditions. Often it is the reduction in negative pore-water pressures in the upper part of soil that triggers slope instability (Fredlund and Rahardjo, 2007).

Several other authors (Bittelli et al., 2012) emphasized that the most important cause for shallow landslides is the decrease of matric suction after a rainstorm and the development of positive pressures

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above the water table. As soil shear strength increases with increasing soil matric suction, when suction becomes less negative the soil is more susceptible to failure (Bittelli et al., 2012).

As several field measurements showed, suction has a key role in maintaining the stability of slopes (Gavin and Xue, 2008). Therefore, modeling in the slope stability analysis the suction effect becomes mandatory for obtaining realistic results. Traditional saturated soil mechanic approach cannot solve the problem. Especially when a drainage system is implemented for ensuring slope stability, the negative pore-water pressure is permanent and highly influencing the safety factor.

Paper presents in the first part some generalities about methods used for stability analysis in unsaturated slopes, methods which will be later used for a case study. Case study presents an instable slope which is in process to be consolidated using siphon drains, thus by reducing pore-water pressure. Site measurements were performed regarding the suction and its evolution during the time. Then, several methods for unsaturated slope stability analysis were applied.

2 Unsaturated Slope Stability Methods

Slope stability analysis is a common element in the designing process of civil engineering projects. There are several possibilities for performing a slope analysis, for example:

- limit equilibrium methods (LEM) based on slice discretization of the soil mass, assuming various geometrical forms for the slip surface. As these are largely implemented into the engineering practice, they have been subject of evolution in the last years as introduction of unsaturated parameters or laws, application of modern optimization techniques based on genetic management of computations, multiple wedge analysis etc. (Tran and Srokosz, 2012);
- numerical methods using displacement-based finite element method (FEM), using various constitutive models, enabling to calculate the progressive failure and safety using "phi-c reduction" or "shear stress reduction" techniques;
- limit analysis approaches based on lower and upper bound theorems of classical plasticity (Tran and Srokosz, 2012);
- variation methods;
- probabilistic methods; etc.

In the following parts of the paper we will address only LEM.

For taking into account the soil shear strength modification due to suction evolution, several methods are available and implemented in commercial software. We will refer to and later apply some of the methods included in SVSlope software, which are estimating in different manners the shear strength depending on unsaturated soil conditions. These are: Unsaturated Phi-b, Unsaturated Fredlund, Unsaturated Vanapalli, Unsaturated Khalili and Unsaturated Vilar model. (SVOffice 2009)

The Unsaturated phi-b method defines the parameter ϕ^b as the angle defining the increase in shear strength for an increase in matric suction $(u_a - u_w)$. The unsaturated shear strength angle varies between 0^o and ϕ'. Fredlund and al. (1978) proposed the following equation (1), as the failure criterion for an unsaturated soil, expressed in terms of two stress state variables, the net normal stress $(\sigma - u_a)$ and the matric suction $(u_a - u_w)$ (Fredlund, 2005).

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \tag{1}$$

where: - shear strength; c' - effective cohesion; σ_n - total normal stress; u_a - pore air pressure; u_w - pore water pressure; ϕ^b - unsaturated shear strength angle, generally taken equal to half of the effective friction angle value, in absence of other tests (Krahn, 2007).

The Unsaturated Fredlund method requires the entry of the soil-water characteristic curve (SWCC), depending on the volume of water present in the soil at a particular suction level. (Fredlund and Xing, 1994). This method makes use of Fredlund and Xing (1991) equation (2):