ARTICLE IN PRESS

ENGEO-04416; No of Pages 11

Engineering Geology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Combined effect of hysteresis and heterogeneity on the stability of an embankment under transient seepage

K. Liu, P.J. Vardon *, M.A. Hicks, P. Arnold

Geo-Engineering Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands

ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form 14 October 2016
Accepted 16 November 2016
Available online xxxx

Keywords:
Embankment
Hysteresis
Reliability
Slope stability
Spatial variability
Transient seepage

ABSTRACT

The stability of most earth embankments is strongly influenced by the water content of the soil. The water content directly influences the suction or pore pressure in the soil, as well as the mass of material, thereby affecting the stress state and strength, and leading to changes in the stability. These aspects are coupled by the so-called soil water retention behaviour, which is observed to be a hysteretic phenomenon. Moreover, soils are known to be spatially variable or heterogeneous in nature, which can lead to preferential flow paths and stronger or weaker zones. In this paper the behaviour of a heterogeneous earth embankment subjected to cyclic water level fluctuation, including the impact of hysteresis, is investigated. The soil property values governing the unsaturated hydraulic response of the embankment are considered as spatially random variables, with the mechanical property values considered deterministic in order to isolate the impact of the hydraulic behaviour. The Monte Carlo Method (MCM) is used to conduct probabilistic analyses and an assessment of the relative influence of material properties illustrates that the saturated hydraulic conductivity, k_{sat}, plays a dominant role in the slope stability. Moreover, in the initially drying condition, the average factor of safety (FOS) and the 95th percentile FOS of the slope considering hysteresis are smaller than those without considering hysteresis, at all times, while the variability of the FOS considering hysteresis is larger than that when not considering hysteresis. In practice, this means that slopes under seepage conditions, which are assessed to have a low FOS, should be assessed including the hysteretic behaviour to ensure stability.

1. Introduction

Slopes under seepage conditions, with both saturated and unsaturated zones, are common and of great concern in geotechnical engineering (Chen and Zhang, 2006; Rahardjo et al., 2010). The saturated–unsaturated seepage in the slope has a significant impact on the slope stability, via changes in shear strength and volumetric weights, and is strongly related to the water retention behaviour of the unsaturated soil (Gui et al., 2000; Le et al., 2012; Zhu et al., 2013; Zhang et al., 2015; Zhang et al., 2016).

The soil water retention curve (SWRC) describes the relationship between the suction head, h_s, and a measure of the water content, in this paper the volumetric water content (VWC), θ, and in addition impacts the hydraulic conductivity, k, which further affects the distribution of pore water pressure (PWP) in the soil (Lam et al., 1987; Yang et al., 2012). Hysteresis in the water retention behaviour of unsaturated soils describes a non-unique relationship between h_s and θ, and thus also between h_s and k (Jaynes, 1984; Pham et al., 2005; Wu et al., 2012). Moreover, due to the existence of hysteresis, the VWC in the soil under cyclic drying and wetting processes may exhibit a significantly different response as compared to the non-hysteretic case (Ma et al., 2011). Indeed, the differences in the PWP and VWC induced by the hysteresis in the SWRC contribute to a hysteretic shear strength response which affects the stability and reliability of the slope (Bishop, 1959).

However, to simplify seepage analyses the effect of hysteresis is commonly ignored (e.g. Tsaparas et al., 2002; Le et al., 2012), even though it may generate inaccurate predictions of the distributions of PWP and VWC. Tami et al. (2004) investigated the variation in the suction profile in a soil column with a hysteretic SWRC. It was found that, due to the hysteresis, the suction at the newly reached steady state after a certain period of infiltration was significantly affected by the initial water content prior to the infiltration process. Yang et al. (2012) studied the variation of matric suction and VWC in a soil column under cyclic precipitation and evaporation. It was found that the computed results were closer to the experimental results when considering hysteresis.

Recently, several researchers have investigated the effect of hysteresis on the stability of soil slopes. Ebel et al. (2010) pointed out that simulations ignoring hysteresis could underestimate the potential for landslides. Ma et al. (2011) conducted an experimental and numerical study of a soil slope to assess the effect of hysteresis, both on the hydraulic response and the slope stability. It was found that the distribution of

* Corresponding author.
E-mail address: p.j.vardon@tudelft.nl (P.J. Vardon).

http://dx.doi.org/10.1016/j.enggeo.2016.11.011

Please cite this article as: Liu, K., et al., Combined effect of hysteresis and heterogeneity on the stability of an embankment under transient seepage, Eng. Geol. (2016), http://dx.doi.org/10.1016/j.enggeo.2016.11.011

Notation

c'	effective cohesion
$c_f{}'$	factored effective cohesion at slope failure
COV	coefficient of variation
E	Stiffness (Young's modulus)
FOS	factor of safety
g	gravitational acceleration
G_s	specific gravity of the soil particles
h	pore water pressure head
h_s	suction head
$h_{s,ae}$	air-entry suction head
$h_{s,ae,d}$	air-entry suction head for the main drying curve
$h_{s,ae,w}$	air-entry suction head for the main wetting curve
k	hydraulic conductivity
k_{sat}	saturated hydraulic conductivity
k_x	hydraulic conductivity in the x direction
k_z	hydraulic conductivity in the z direction
l	scale of fluctuation
l_h	scale of fluctuation in the horizontal direction
l_v	scale of fluctuation in the vertical direction
m	fitting parameter for the soil water retention curve
MCM	Monte Carlo method
n	fitting parameter for the soil water retention curve
PWP	pore water pressure
s	matric suction
S	effective degree of saturation
SWRC	soil water retention curve
t	time
T_1	period of the first sinusoid
T_2	period of the second sinusoid
u_a	pore air pressure
u_w	pore water pressure
ν	Poisson's ratio
VGM	van Genuchten–Mualem model
VWC	volumetric water content
WL	water level
x	coordinate in the horizontal direction relative to upstream toe of embankment
$\boldsymbol{X}$	vector of parameters
z	coordinate in the vertical direction relative to upstream toe of embankment
α_d	approximately the inverse of the air-entry suction head for main drying curve
α_w	approximately the inverse of the air-entry suction head for main wetting curve
γ	unit weight of soil
γ_w	unit weight of water
θ	volumetric water content
θ_s	saturated volumetric water content
θ_r	residual volumetric water content
κ	slope of the scanning curve
μ	mean
ξ	degree of anisotropy of the heterogeneity
ρ	correlation coefficient between two points
ρ_w	density of water
σ	standard deviation
σ_t	total stress normal to the sliding plane
τ	shear stress
φ'	effective friction angle
φ_f	factored effective friction angle at slope failure
χ	scalar defining the suction-induced effective stress

water content was influenced by hysteresis and that the calculated FOS of the slope considering hysteresis recovered quickly after rainfall and was larger than that without considering hysteresis for any given time.

Most research that includes the effect of hysteresis focuses on homogeneous soils. Conversely, if the heterogeneity of soil property values is taken into account, the impact of hysteresis is typically not accounted for (Arnold and Hicks, 2010, 2011; Zhu et al., 2013). However, Nakagawa et al. (2012) highlighted the importance of considering both hysteresis and heterogeneity in the simulation of unsaturated flow by comparing numerical results with experimental data. Very few studies have incorporated hysteresis and heterogeneity in the assessment of slope stability. Yang et al. (2013) accounted for the effect of hysteresis and spatial variability of soil property values, i.e. of the saturated hydraulic conductivity and some SWRC fitting parameters, in a one-dimensional infiltration problem. It was shown that the combined effect of hysteresis and heterogeneity of soil property values increased the uncertainty in the estimation of the ability to prevent penetration in soil covers, compared to the non-hysteretic but heterogeneous case. Zhang (2007) incorporated both hysteresis and heterogeneity into the stability analysis of a 2D slope under cyclic precipitation and evaporation, with the analysis starting on the wetting SWRC. The results suggested that simulations without considering the effect of hysteresis may underestimate the slope reliability.

This paper investigates the slope stability of an embankment under transient seepage, i.e. due to a cyclic external water level. The effects of both hysteresis and heterogeneity of the soil property values on the seepage response are considered. First, the mechanical and stochastic model framework for slope stability under saturated–unsaturated seepage is briefly introduced. Next, the numerical implementation of the framework is explained, and a specific example then utilised to investigate the impact of considering hysteresis for a homogeneous embankment. Finally, the effect of spatial variability of the soil property values is considered, by conducting a probabilistic analysis of the slope stability and comparing the results of the hysteretic and non-hysteretic cases.

2. Formulation

2.1. Governing flow equation

The governing equation of 2D transient unsaturated–saturated flow is based on mass conservation. In the flow analysis, the soil skeleton is considered to be rigid, which means that any volume change during the seepage process is not accounted for. Therefore, the governing flow equation, in incremental form, is (e.g. Celia et al., 1990)

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial h}{\partial z}+k_z\right)=C(h)\frac{\partial h}{\partial t} \quad (1)$$

where k_x and k_z are the hydraulic conductivities in the x and z directions, respectively, h is the PWP head, t is time and $C(h)=\partial\theta/\partial h$ is the specific moisture capacity function with θ being the VWC. The same description of mass conservation can be used for heterogeneous porous media (e.g. Gui et al., 2000) with an appropriate selection of hydraulic conductivities at each location.

2.2. Water retention behaviour

The SWRC is a function relating the suction head, h_s, with θ. The suction head is defined as the negative component of h and is represented by

$$h_s=-h=s/\gamma_w=(u_a-u_w)/\gamma_w \quad (2)$$

where s is the matric suction, u_a is the pore air pressure, which is assumed to be atmospheric in this paper, u_w is the PWP and γ_w is the unit weight of water.