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Optimization of drawdown procedures of partially submerged slopes

Optimisation de les procédures de vidange des pentes summergés

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ABSTRACT
The paper investigates the stability of earth dams or reservoirs under drawdown conditions taking into account suction effects, usually neglected in routine analyses. An unsaturated soil profile above the water table is assumed and soil suction values are estimated by an appropriate soil-water characteristic curve. Starting from full and partial submergence levels, stability analyses are performed both for rapid and slow drawdown conditions, by varying non-dimensional suction parameters. Results and practical implications in drawdown procedures are discussed, demonstrating that the negative pore-water pressures can significantly accelerate a safe drawdown process.

RÉSUMÉ
Cet article analyse la stabilité des barrages de terre ou des réservoirs en condition de vidange en considérant les effets de la succion, que normalement on néglige. Sous l'hypothèse de degré de saturation variable avec la profondeur, les valeurs de la succion du sol sont estimées à travers une courbe caractéristique sol-eau. En partant par un niveau de submersion total ou partiel, les analyses de stabilité sont obtenues en conditions de rapide et lent vidange, en variant les paramètres non dimensionnels de succion. Les résultats démontrent que la succion peut accélérer remarquablement les procès de vidange.

1 INTRODUCTION

In the geotechnical practice stability analyses are usually performed by two-dimensional limit equilibrium methods or finite element method neglecting the soil suction and its effects on shear strength. This approach is always conservative but in some cases it can be unrealistic; moreover, in back analysis exclusion of suction effects can result in an over-estimate of the back-calculated saturated shear strengths.

In past years the role of suction in slope stability has long been recognized and a theoretical framework has been established to predict volume change, shear strength and permeability for unsaturated soil (Bishop, 1959; Fredlund and Morgestern, 1977; Alonso et al., 1990; Wheeler and Sivakumar, 1995; Bolzon et al., 1996; Vanapalli et al., 1996; Chiu and Shackelford, 1998; and many others). The theory for incorporating negative pore-water pressures into a slope stability analysis was derived, explained and illustrated by Fredlund and Rahardjo (1993).

The aim of this paper is to evaluate the effect of soil suction in stability of partially submerged slopes in drawdown conditions.

2 STABILITY ANALYSIS UNDER DRAWDOWN CONDITIONS

The stability of slopes under drawdown conditions are usually analysed considering two limiting conditions, namely slow and rapid drawdown (Lane and Griffiths, 2000). In the slow drawdown situation the water level within the slope is assumed to equalise the reservoir level at any time. In case of rapid drawdown, which represents the most critical condition, it is assumed that, in a fine-grained soil, the pore-water pressures within the embankment continue to reflect the original water level (Morgestern, 1963).

Desai (1977) studied an intermediate case assuming a linear drawdown over time and calculating the position of the phreatic surface by a seepage analysis using the finite element method. However the factors of safety calculated by the limit equilibrium method are found to be only slightly higher (2-8%) than those from sudden drawdown analysis.

Recently Lane and Griffiths (2000) analysed the stability under drawdown conditions by the finite element method giving operational charts to control drawdown rates in order to maintain an appropriate factor of safety.

Referring to the simple slope shown in Figure 1, the drawdown procedure proposed by Lane and Griffiths (2000) is based on the stability analysis performed for three different conditions: (i) slow drawdown, (ii) rapid drawdown from the initial level (L_i) to a generic intermediate level, (iii) full rapid drawdown from an intermediate level (Figure 2). The intersections between the horizontal line representing the acceptable safety factor and the curves (ii) and (iii) individuate two drawdown levels L_1 and L_2, respectively. These levels define a safe drawdown procedure consisting in four phases (see Figure 2): rapid drawdown from L_i to L_1 (A→B); equalisation of pore-water pressure (B→C); slow drawdown from L_1 to L_2 (C→D) and finally full rapid drawdown from L_2. The duration of both equalisation and slow drawdown phases is inversely proportional to soil permeability.

It is rare in practice for earth dams or embankments to be fully submerged and it is reasonable to suppose that in working conditions a zone above the water table remains unsaturated. In the following sections the procedure proposed by Lane and Griffiths (2000) is replicated taking into account the suction effects. Practical implications are discussed by varying suction parameters of a simple slope.

3 SOIL MODEL

Figure 1 shows the geometry of the simple homogeneous slope with a height H and an inclination β to the horizontal. It is supposed that a firm layer exists at the base of the slope. The soil is characterised by the saturated unit weight γ_{sat}, dry unit weight

γ_d, effective cohesion c' and effective angle of shearing resistance ϕ'. The water table is assumed to be horizontal at a depth L_i below the crest; for the rapid drawdown analyses the external water level is considered to be suddenly lowered to a depth L_f below the crest. Seepage effects are neglected.

Above the phreatic surface, a saturated zone is assumed (capillary fringe, Fig. 1); the height of this zone, h_{sat}, is numerically related to the air-entry value (Bouwer, 1978):

$$h_{sat} = \psi_b / \gamma_w \quad (1)$$

where ψ_b is the air-entry value or bubbling pressure and γ_w is the unit weight of water.

The air-entry value (and hence the capillary rise) was found to depend on several factors including soil type, plasticity, void ratio and dry density (Khalili & Khabbaz, 2001).

In the capillary fringe water is supposed to be in hydrostatic conditions at the negative pressure u_w (with reference to the atmospheric pressure); u_w is calculated on the basis of the height above the water table, h_w:

$$-u_w = \gamma_w \cdot h_w \quad (2)$$

Above the capillary fringe a profile of the degree of saturation S_R has to be necessarily introduced; in this study S_R is assumed to decrease upward with the following power law:

$$S_R = S_{R0} + (1 - S_{R0})(1 - x^m) \quad (3)$$

where x is the vertical distance of the point from the top of the capillary fringe normalised respect to the height of the unsaturated soil, h_{uns} (see Fig.1); S_{R0} is the degree of saturation at the top of the slope; m is a coefficient that describes the trend of S_R with depth; a value of $m=2$ is assumed in the present analyses.

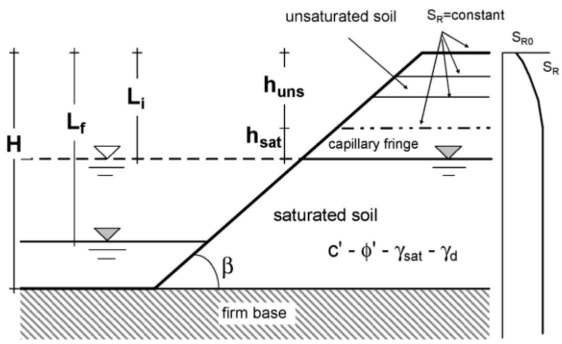

Figure 1. Geometry of the slope

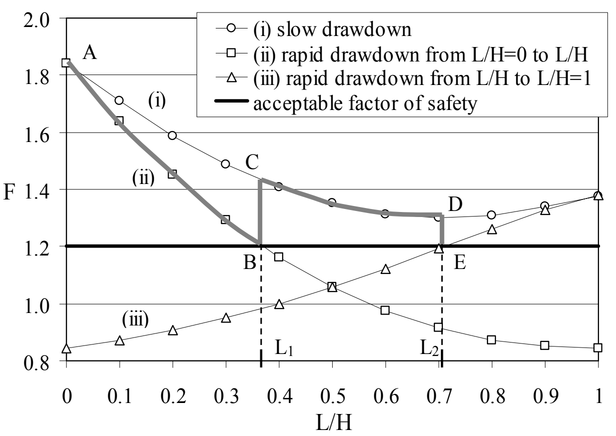

Figure 2. Stability analyses and drawdown phases for the slope of Fig.1 neglecting soil suction; $\cot\beta = 2$; $\phi' = 20°$; $c'/\gamma H = 0.05$.

The shear strength of soil above the water table is calculated according to the approach of Khalili and Khabbaz (1998) based on the effective stress approach (Bishop, 1959):

$$\tau = c' + [(\sigma - u_a) + \chi(u_a - u_w)]\tan\phi' \quad (4)$$

where: c' is the effective cohesion of saturated soil; ϕ' is the effective angle of shearing resistance of saturated soil; σ is the total normal stress; u_a is the pore-air pressure, u_w is the pore-water pressure, χ is a numerical coefficient equal to 1 in the capillary fringe, whereas in the unsaturated zone the following correlation is considered:

$$\chi = [\psi_b / (u_a - u_w)]^{0.55} \quad (5)$$

An alternative approach available in the literature is proposed by Fredlund et al. (1978), who formulated a shear strength equation using two stress parameters, i.e. the net normal stress (σ-u_a) and the matric suction (u_a-u_w):

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \quad (6)$$

where ϕ^b defines the rate of change in strength for a change in matric suction. By comparison of (4) and (6), the two approaches can be considered equivalent, provided that:

$$\tan\phi^b = \chi \tan\phi' \quad (7)$$

Considering that for a suction range of 0-500 kPa the saturated friction angle ϕ' can be assumed constant (e.g. Vanapalli et al., 1996), (4) and (6) show that as the suction increases, the χ coefficient and therefore ϕ^b decreases, according to observed experimental behaviour (e.g. Gan et al., 1988; Mahalinga-Iyer and Williams, 1995; Nishimura and Fredlund, 2001).

The soil suction can be calculated by the soil-water characteristic curve on the basis of the amount of water in the soil, expressed by the volumetric water content, the gravimetric water content or the degree of saturation. Different equations have been proposed to represent sorption or desorption curves (e.g. Gardner, 1958; Brooks & Corey, 1964; Campbell, 1974; van Genuchten, 1980; Clapp and Hornberger, 1978; McKee and Bumb, 1987; Kosugi, 1994; Fredlund and Xing, 1994). For the purpose of this study the Brooks & Corey (BC) function (Brooks and Corey, 1964) appears to be appropriate:

$$(u_a - u_w) = \psi_b \left(\frac{1 - S_{RES}}{S_R - S_{RES}} \right)^{1/\lambda} \quad (8)$$

where: S_R is the degree of saturation; S_{RES} is the residual degree of saturation; λ is the pore-size distribution index. The parameters of the BC function may be determined by either graphical or automatic numerical procedures (e.g. Russo, 1988). Statistical analyses of the BC parameters across USDA soil textures classes are given by Mc Cuen et al. (1981) and Sillers and Fredlund (2001). Combining (5) and (8), the effective stress parameter χ can be written as:

$$\chi = \left(\frac{S_R - S_{RES}}{1 - S_{RES}} \right)^{0.55/\lambda} \quad (9)$$

Vanapalli et al. (1996) proposed a similar expression assuming implicitly $\lambda = 0.55$. Consequently, the contribution of soil suction to shear strength can be expressed as:

$$\chi(u_a - u_w) = \psi_b \left(\frac{1 - S_{RES}}{S_R - S_{RES}} \right)^{0.45/\lambda} \quad (10)$$

4 RESULTS AND ANALYSIS

Stability analyses were performed by the Bishop's simplified method (Bishop, 1955). The search for the critical failure surface was performed with an automatic search routine implemented in the computer code AUTOJB (Bellezza, 2000), assuming a saturated and a dry unit weight of the soil equal to $2\gamma_w$ and $0.8\gamma_w$, respectively (i.e. porosity n = 0.4 and specific gravity G_s = 2.67). The weight of a slice in the unsaturated zone was calculated by an average degree of saturation obtained by integrating (3). Note that in previous studies dealing with slopes subjected to drawdown conditions (Desai, 1977; Griffiths and Lane, 1999; Lane and Griffiths, 2000) a constant total unit weight is assigned to the entire slope, both above and below the water level.

In this paper the effects of suction parameters are investigated for a 2:1 slope with $\phi' = 20°$ and $c'/\gamma H = 0.05$. Suction effects are considered by the degree of saturation at the crest of the slope, S_{R0} (Fig. 1) and by the parameters of the BC function: the normalised air-entry value ($\psi_b/\gamma H$), the pore-size distribution index (λ) and the residual degree of saturation (S_{RES}). The base values of S_{R0}, $\psi_b/\gamma H$, λ and S_{RES} are assumed equal to 0.5, 0.03, 0.33 and 0.1, respectively. The base value of λ represents an average over all texture classes of the U.S. Dep. of Agriculture texture triangle (Mc Cuen et al., 1981).

The same stability analyses of Figure 2 are repeated in Figure 3 taking into account the suction effects. Suction effects are found to slightly modify the position of the critical slip surfaces that pass through the crest of the slope and partially in the unsaturated zone.

For an acceptable safety factor of 1.2 the first drawdown level L_1 remains constant (about 0.38) because the slope is entirely submerged, whereas the second drawdown level L_2 decreases from 0.70 to 0.64 (Figures 2 and 3). In order to quantity the suction effects in drawdown analyses two non-dimensional parameters can be defined:

$$\Delta_R = \frac{L_{1s}}{L_1} - 1 \quad (11a) \qquad \Delta_S = 1 - \frac{L_{2s} - L_{1s}}{L_2 - L_1} \quad (11b)$$

where L_{1s} and L_{2s} are the drawdown levels considering the suction effects. Δ_R (≤ 1) describes the increase of the drawdown level during the first rapid drawdown, whereas Δ_S (≤ 1) represents the shortening of the slow drawdown phase. Values of $\Delta_R = 0$ and $\Delta_S = 0$ imply no suction effect. $\Delta_R = 1$ means that it is possible to empty completely the reservoir starting from the initial level; $\Delta_S = 1$ means that, for the given acceptable safety factor, $L_{1s} \geq L_{2s}$ and therefore the slow drawdown phase is not necessary.

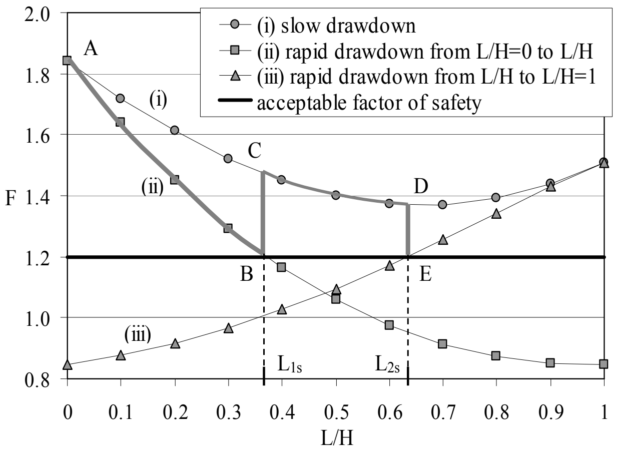

Figure 3. Stability analyses and drawdown phases for the slope in Fig.1. $cot\beta$=2; ϕ'=20°; $c'/\gamma H$=0.05; $\psi_b/\gamma H$=0.03; S_{RES}=0.1; λ=0.33.

The Δ_R and Δ_S values are plotted in Figure 4 as a function of the degree of saturation at the crest of the slope (S_{R0}) for three different values of the initial water level, representing usual working conditions. The Δ_R values are close to zero because the initial drawdown levels are close or coincident to the crest and consequently the suction acts only in a small zone. An appreciable effect on Δ_R (=5%) is found for the lower S_{R0} (=15%) and for the greater initial submergence level (= 0.2). On the contrary, the Δ_S values are always significant ($\geq$ 20%) and increase as S_{R0} decreases and the initial submergence level increases, up to values of 40-70% depending on the initial level. The practical implication is a considerable shortening of the time required for the slow drawdown phase.

Figure 5 plots the values of Δ_R and Δ_S by varying the pore-size distribution index of the BC function for three values of the initial water level. Δ_S is found to decrease as λ decreases, but its variation is significant only for λ less than 0.3. For initial submergence level equal to 0.2, Δ_S varies from 30 to 76%.

Figure 6 shows the influence of the normalised air-entry value on the coefficients Δ_R and Δ_S for three different initial water levels. All the Δ_S curves have a similar trend with a maximum value of Δ_S at a $\psi_b/\gamma H$ equal to 0.2. The maximum values of Δ_S are found to be 0.49, 0.56 and 0.71 for $(L/H)_I$ = 0, 0.1 and 0.2, respectively.

The observed maximum value of Δ_S is mainly due to the soil shear strength above the water table. As the air-entry value increases, an increased zone in the failure mass passes from an unsaturated state to the capillary fringe (see (1)). In the first part of the curves, the factor of safety F (and then L_{2s} and Δ_S) rises because in (10) the contribution of an increased ψ_b prevails on the increase in S_R. Moreover, the suction rates in the capillary fringe are greater than those calculated by (10). At higher air-entry values, the factor of safety slightly falls because the increased weight of the soil in the upper zone of the failure mass starts to have a destabilizing influence on slope stability.

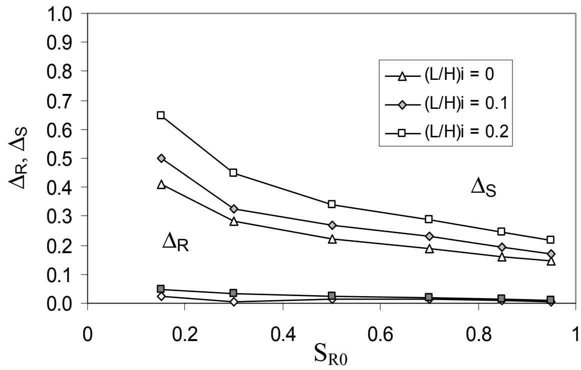

Figure 4. Influence of S_{R0} on Δ_R and Δ_S values. $cot\beta$=2; ϕ'=20°; $c'/\gamma H$=0.05; λ = 0.33; $\psi_b/\gamma H$=0.03; S_{RES}=0.1.

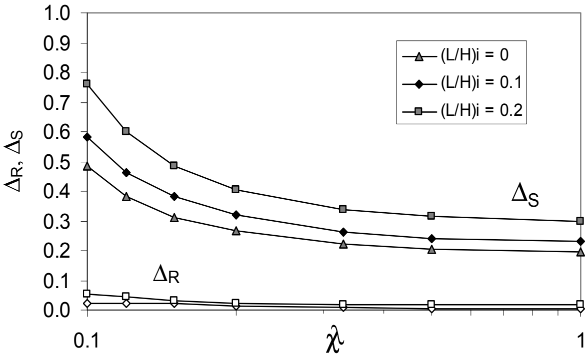

Figure 5. Influence of the coefficient λ of the BC function on Δ_R and Δ_S values. $cot\beta$=2; ϕ'=20°; $c'/\gamma H$=0.05; $\psi_b/\gamma H$=0.03; S_{RES}=0.1; S_{R0}=0.5.

Finally it should be noted that, for a given initial water level $(L/H)_i$, a threshold value of the normalised air-entry exists beyond which the coefficient Δ_S is independent of $\psi_b/\gamma H$ because the slope is entirely saturated and the negative pore-water pressure is everywhere calculated by (2).

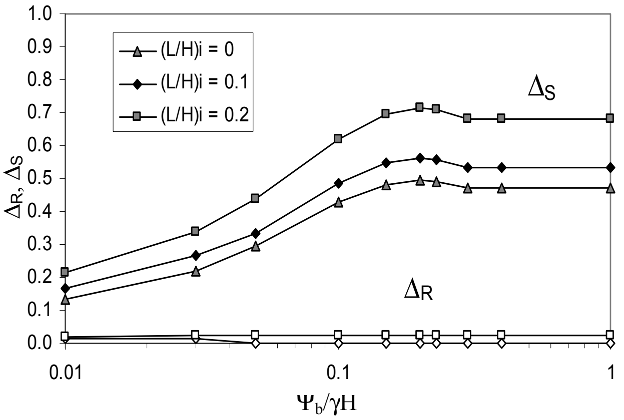

Figure 6. Influence of the normalised air-entry value of the BC function on Δ_R and Δ_S. $cot\beta=2$; $\phi'=20°$; $c'/\gamma H=0.05$; $S_{RES}=0.1$; $\lambda=0.33$; $S_{R0}=0.5$.

5 CONCLUSIONS

Drawdown procedures of a partially submerged slope have been compared considering and neglecting negative pore-water pressures in the soil, for an assigned factor of safety. For a c'-ϕ' soil and a 2:1 slope, stability analyses have been carried out by varying dimensionless suction parameters for three different values of the initial water level, representing usual working conditions of earth dams or reservoirs.

The results refer to a homogeneous slope with a simplified distribution of degree of saturation. For practical applications stability analyses should be based on in situ measurements of soil suction rather than on degree of saturation profiles and soil water characteristic curves. However, the results shown in this study highlight the role of soil suction on stability of slopes in drawdown conditions. In particular, the suction in the zone above the water table was found to give a negligible increase in the first rapid drawdown level, but a significant reduction (up to 70%) in the time of the slow drawdown phase.

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