Safety of a protection levee under rapid drawdown conditions. Coupled analysis of transient seepage and stability

La sécurité d'une digue de protection en conditions de vidange rapide. Analyse couplée des écoulements transitoires et de la stabilité

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ABSTRACT: The rapid drawdown condition arises when submerged slopes of protection levees experience a rapid decrease of the external water level. In this paper the safety of a protection levee under rapid drawdown conditions is studied by numerically modeling this phenomenon as a coupled problem of transient seepage-deformation in a saturated/unsaturated medium. Analyses are performed based on finite element method by using the PLAXFLOW program for transient seepage analysis and the PLAXIS program for deformation, consolidation and stability analyses. The details of the proposed methodology are presented in this work. Also, recommendations for definition of material type (drained or undrained), type of soil constitutive model (Hardening Soil and Mohr Coulomb), boundary conditions and mesh generation of finite elements are provided. In the main part of the paper, the effects of multiple parameters such as position of phreatic surface, water drawdown ratio, drawdown rate and hydraulic conductivity are evaluated by a 2D model of stress-strain. Special emphasis is given to the study of the safety factor variation as a function of time obtained when assessing the stability of these earth structures. Finally, concluding comments about the results are exposed.

RÉSUMÉ: La condition de vidange rapide survient lorsque les pentes de digues de protection submergées expérimentent une réduction rapide du niveau d'eau externe. Dans cet article, la sécurité d'une digue de protection dans des conditions de vidange rapide est étudiée par modélisation numérique de ce phénomène comme un problème couplé de flux transitoire -déformation dans un milieu saturé / non saturé. Les analyses sont effectuées sur la base de la méthode des éléments finis en utilisant le programme PLAXFLOW pour l'analyse d'infiltration transitoire et le programme PLAXIS pour les analyses de déformation, de consolidation et de stabilité. Les détails de la méthodologie proposée sont présentés dans cet écrit. Également, des recommandations pour la définition du type de matériau (drainé ou non drainé), type de modèle constitutive de sol (Hardening Soil et Mohr Coulomb), conditions aux limites et de génération de maillage d'éléments finis sont fournis. Dans la partie principale de l'article, les effets de plusieurs paramètres tels que l'emplacement de la surface phréatique, le taux de vidange rapide, le rapport de vidange et la conductivité hydraulique sont évalués par un modèle 2D de contrainte-déformation. Une attention particulière est accordée à l'étude de la variation en fonction du temps des facteurs de sécurité obtenus lors de l'évaluation de la stabilité de ces structures en terre. Enfin, les observations finales sur les résultats sont données.

KEYWORDS: Protection levee, rapid drawdown, coupled analysis, transient seepage, slope stability, 2D model of stress-strain.

1 THE RAPID DRAWDOWN CONDITION

1.1 *The water drawdown phenomenon*

The water drawdown phenomenon can be divided in three modes (Fig. 1): a) *fully slow drawdown*, b) *fully rapid drawdown*, c) *general (transient) drawdown* (Duncan *et al.* 1990, Griffiths and Lane 1999, Lane and Griffiths 2000, Berilgen 2007, Huang and Jia 2009, Nian *et al.* 2011).

In the *fully slow drawdown* condition (Fig. 1a), the soil is assumed to be drained; in every moment of the drawdown the water level inside the levee (water table) equals the water level on the outside (the reservoir level), generating a steady-state flow condition, therefore the pore water pressure within the levee is hydrostatic condition. In the *fully rapid drawdown* mode (Fig. 1c), the soil is considered to be undrained, the water table is conserved at the initial level of the reservoir for every moment of the drawdown, so the pore water pressure inside the levee is the hydrostatic pressure. In both extreme cases, the water surface is assumed to be horizontal, except on the face of the slope for fully rapid drawdown mode, as shown in Figure 1c. For the *general (transient) drawdown* mode (Fig. 1b), a curvilinear water surface is generated within the soil structure whose position depends on the drawdown rate and the material properties (such as hydraulic conductivity, porosity, etc.), consequently the remaining pore water pressure within the levee is transient type (it varies as a function of time but also with the soil's ability to retain water).

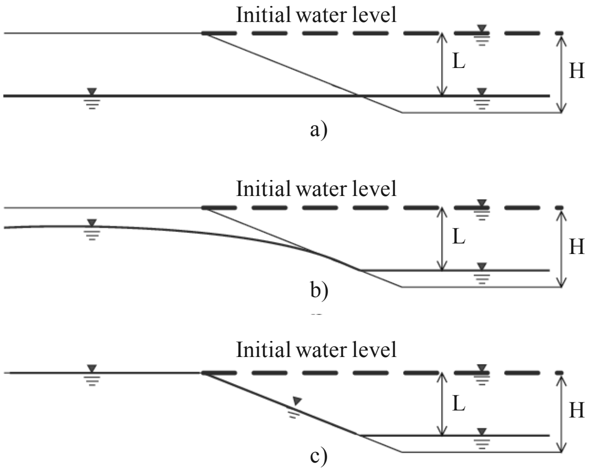

Figure 1. Water drawdown modes: a) Fully slow drawdown, b) Transient drawdown y, c) Fully rapid drawdown (Berilgen 2007).

1.2 *Classical methods for analyzing rapid drawdown*

Drawdown condition has been analyzed from different approaches depending on the progress in the field of classical soil mechanics. The analysis methods can be classified into two groups (Alonso and Pinyol 2008): a) water flow methods appropriated for and relatively permeable materials, b) undrained analysis methods applicable to low permeability materials.

The methods included in the first group solve the water flow problem within an earth slope subjected to changes of hydraulic boundary conditions as a function of time. According to these methods it is implicitly accepted that the solid skeleton of the materials involved in the drawdown phenomenon is rigid and no changes occur in the total stresses. Usually, recommendations for the study of relatively permeable materials are based on numerical, analytical or graphical groundwater flow techniques. However, these types of water flow methods do not consider the soil deformability which in the case of soft materials plays an important role in the velocity of dissipation of the pore water pressure.

The second approach considers only the pore water pressure change due to discharge of stresses associated to decrease of water level during the water drawdown phenomenon (mechanical problem). That is, the analysis is undrained type, in which water flow is negligible because of the significant drawdown rate compared with the permeability of material.

2 PROPOSED METHODOLOGY FOR ANALYSES

The stability analysis of a protection levee under rapid drawdown conditions requires the consideration of two effects: i) changes in total stresses due to external loads, such as hydrostatic pressure or overloading (e. g. bank protections sandbags, over-elevation on a levee height, etc.), and ii) seepage forces due to transient groundwater flow. According to the Terzaghi's principle (1943), the increase in total stresses in a saturated soil is equal to the sum of the effective stress plus the pore water pressure:

$$\Delta\sigma = \Delta\sigma' + \Delta p = \Delta\sigma' + (\Delta p_{seepage} + \Delta p_{excess}) \qquad (1)$$

Where $\Delta\sigma$ is the change in total stresses, $\Delta\sigma'$ is the change in effective stresses and Δp is the change in active pore water pressure, which is constituted by pore water pressure increases due to seepage ($\Delta p_{seepage}$) and pore water pressure increases due to changes in total stresses.

The pore water pressure due to seepage is computed by a water flow analysis. If the flow domain contains a water table that changes as a function of time, the problem becomes one of transient flow type. The excess pore water pressure due to changes in the total stresses is calculated by a stress-strain analysis. This pressure is not steady-state and changes with time (it increases or dissipates); therefore it also is a problem that requires be evaluated versus time. Additionally, during drawdown the dissipation of remaining pore water pressure (consolidation) may occur depending on material properties, drawdown rate and drawdown ratio. Consequently, to evaluate the stability of an earth structure subjected to rapid drawdown condition, it is required the coupling of the following analyses:

i) Transient-state seepage analysis.
ii) Deformation analysis.
iii) Consolidation analysis.
iv) Stability analysis.

Currently, numerical techniques are the most common solution, specially the finite element method. The preceding methodology is applied in the analyses performed herein, with a 2D plane-strain model using finite element programs: PLAXFLOW for the transient seepage analyses and PLAXIS for the deformation, consolidation and stability analyses (Delft University of Technology 2008), as shown below.

3 PARAMETRIC ANALYSES

3.1 *Problem statement*

In order to investigate the influence of rapid drawdown on stability of protection levees, analyses assuming the three different drawdown modes illustrated in Figure 1 were performed. For the *fully slow drawdown* mode, soil was assumed to be drained and only water flow analyses were carried out (uncoupled). For the *fully rapid drawdown* mode, soil was considered undrained and only undrained analyses were performed (uncoupled). For *transient drawdown* (Fig. 1b), a coupled analysis was performed and soil was assumed to be undrained.

3.2 *Geometric, hydraulic and mechanical properties, and initial and boundary conditions*

A homogeneous and isotropic levee (H = 6 m height and 2:1 slope) was considered in analyses, as illustrated in Figure 2.

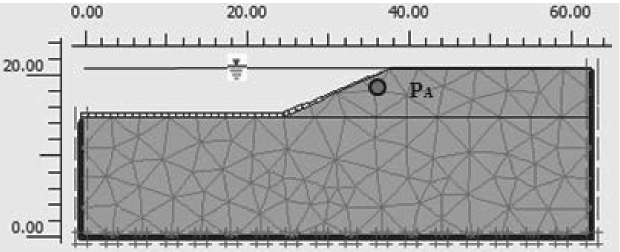

Figure 2. Simplified geometry of the analyzed levee.

The mechanical, hydraulic and rigidity properties of both the levee and the foundation soil were assumed in calculations as provided in Table 1. Similarly, in the analyses two different hydraulic conductivities (k=1×10^{-4} and 1×10^{-6} cm/s) and two drawdown rates (R=0.1 m/d and 1.0 m/d) were studied. The capacity of soil to retain water was defined by the *approximate Van Genuchten model* (1980).

For modeling the domain a fairly refined mesh was generated by using 15 nodes triangular finite elements, because they provide more accurate results in more complex problems, such as bearing capacity and stability analyses (Nagtegaal *et al.* 1974, Sloan 1981, Sloan and Randolph 1982). Standard boundary conditions were assumed (fixed bottom). The initial stress state was generated by using the K0 procedure. All model boundaries were considered to be impervious, except the surface of foundation soil, the slope and crown of the levee (see Fig. 2). It was also assumed that the reservoir level is initially located at the maximum elevation (21 m, corresponding to L=0).

3.3 *Numerical modeling*

For the numerical modeling of the problem, it was initially assumed that flow conditions within the embankment correspond to a steady-state (Δt = 0; L/H = 0), thus a steady-state flow analysis was firstly performed, which was followed by deformation and consolidation analyses. In this last analysis, a minimum pore water pressure was assumed within the levee (p_{excess} = 0.1 kPa), because the study is performed supposing that elapsed time is long enough to allow that the excess pore water pressure caused by the filling of the reservoir is dissipated. The relation L/H is called *drawdown ratio*, where L represents the position of the water level in the reservoir with respect to the crown of the levee at the end of each stage of the drawdown, and H is the height of the levee.

Subsequently, the drawdown phenomenon was simulated considering 5 stages (L/H = 0.2, 0.4, 0.6, 0.8 and 1), starting from level L = 1.2 m up to level L = 6 m (the total drawdown in this study). Each stage represents a time of the drawdown (Δt =

1.2, 2.4, 3.6, 4.8 and 6 days for drawdown rate R = 1.0 m/d and Δt = 12, 24, 36, 48 and 60 days for drawdown rate R = 0.1 m/d). Assuming these data, an iterative analysis was performed modeling in the following way:

i) *Transient-state seepage analysis*.- The variation of water level was evaluated by a transient-state flow analysis and the pore pressures induced by seepage ($p_{seepage}$) were calculated by using the PLAXFLOW program. In this analysis a linear variation of hydraulic head versus time was specified as a boundary condition.

ii) *Deformation analysis*.- The results obtained in the seepage analysis were used by PLAXIS and a deformation analysis in order to evaluate the excess pore water pressure induced by changes in total stresses was then performed.

iii) *Consolidation analysis*.- Finally, the dissipation of excess pore water pressure occurred during the drawdown condition was computed.

iv) *Stability analysis*.- After completing the drawdown stages, stability analyses were carried out for each stage (including the initial steady-state condition) using the results obtained in all previous analyses.

Table 1. Mechanical, hydraulic and rigidity properties of both the levee and the foundation soil.

Property	Unity	Value
γ (soil unit weight)	kN/m^3	20
k (hydraulic conductivity)	cm/s	1×10^{-4} and 1×10^{-6}
c' (effective cohesion)	kN/m^2	10
□′ (effective friction angle)	°	20
ψ (dilatancy angle)	°	0
E_{50}^{ref} (secant stiffness for CD triaxial)	kN/m^2	1000
E_{oed}^{ref} (tangent oedometer stiffness)	kN/m^2	1000
E_{ur}^{ref} (unloading/reloading stiffness)	kN/m^2	3000
ν (Poisson's ratio)	---	0.2
P^{ref} (reference stress)	kN/m^2	100
m (power for stress dependent on stiffness)	---	0.7

3.4 *Results of analyses*

With the aim of better understand the drawdown phenomenon, a material having a hydraulic conductivity of $k = 1\times10^{-6}$ cm/s and drawdown rate of R = 1.0 m/d was considered to initially study the influence of drawdown ratio on remaining pore water pressure within the levee. Figure 3 shows the progress of the pore water pressure computed at point P_A (which is illustrated in Figure 2), assuming the three drawdown modes mentioned before (Fig. 1). In this figure it can be observed that in the *fully slow drawdown* mode the pore water pressure significantly decreases as a function of the drawdown ratio L/H, whereas in the *fully rapid drawdown* the pore pressure remains constant and is equals to the initial pore pressure (steady-state), because in this case it is assumed that water surface is preserved at the initial level during each time of the drawdown. In the *transient drawdown*, the pore water pressure does not decrease at the same drawdown ratio as in the *fully slow drawdown*, but it is not conserved as high as in the *fully rapid drawdown* case. In this situation, the resulting pore water pressures are not in equilibrium with the new boundary conditions, so a transient flow regime is developed. This is due to the remaining water seepage within the body of the levee momentarily prevents the dissipation of pore pressures generated during the drawdown. In the same Figure 3 it can also be concluded that if an analysis taking into account the distribution of remaining pore water pressures and assuming *fully slow* or *fully rapid drawdown* modes is performed, the safety factors of the slope when external water level changes are underestimated or overestimated, respectively. Therefore, to analyze the stability of protection levees under drawdown conditions is recommended that a transient flow analysis type is applied.

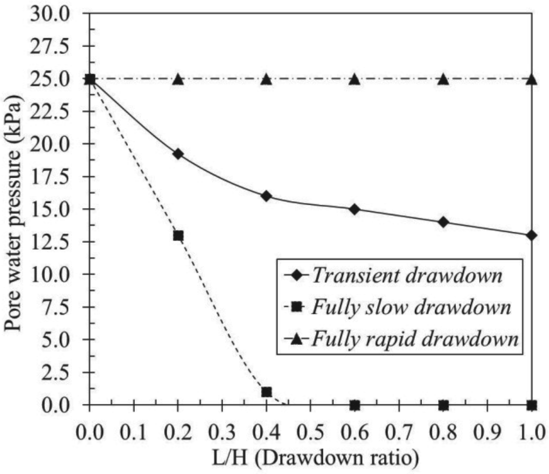

Figure 3. Pore water pressure versus drawdown ratio (L/H) considering different drawdown modes for H=6 m height, $k=1\times10^{-6}$ cm/s permeability and R=1.0 m/d drawdown rate.

Subsequently, the effects of hydraulic conductivity k and drawdown rate R on slope stability were analyzed. Figure 4 illustrates the variation of safety factor (FoS) as a function of the drawdown ratio (L/H) for different combinations of k and R assumed in analyses. From the above figure it can be seen that the behavior of low permeability soils ($k = 1\times10^{-6}$ cm/s) subjected to a relatively rapid drawdown rate (R = 1.0 m/d) is very similar to that showed in Figure 1c (the phreatic surface practically remains near the crown of the slope), consequently in this situation it can be supposed a *fully rapid drawdown* condition and an undrained method can be applied for calculations, that is, groundwater seepage analyses can be omitted. For more permeable soils ($k = 1\times10^{-4}$ cm/s) and a relatively slow drawdown rate (R = 0.1 m/d), the soil behavior is similar to Figure 1a (the water table practically descends at the same time than the reservoir water level), as a result, in this case a *fully slow drawdown* condition can be assumed and a water flow analysis (uncoupled) can only be utilized for calculations, this is because the excess pore water pressure generated by changes in the total stresses dissipates at the same velocity than the water level in the reservoir decreases. For intermediate conditions concerning to permeability and drawdown rate, calculations cannot be approximated to these two extreme cases, due to the computed safety factors differ from reality. For such cases, it is necessary to apply coupled transient flow-deformation analysis. From Figure 4 it can also be concluded that the dissipation velocity of pore water pressure mainly depends on the permeability of material and the drawdown rate.

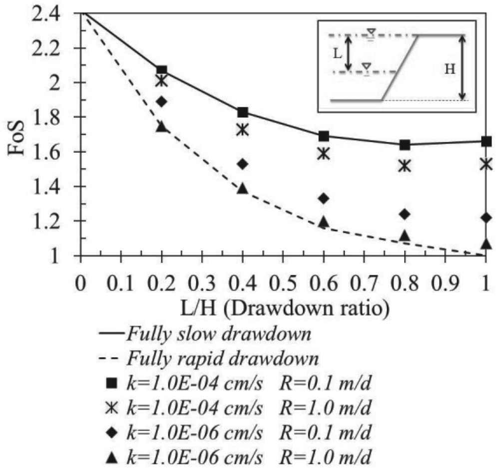

Figure 4. Variation of F○S with drawdown ratio (L/H) for H=6 m height and 2:1 slope.

Finally, the influence of varying the constitutive model and its parameters for predicting horizontal displacements was studied (Fig. 5). The safety factors in the analysis of the analyzed levee were also computed (Fig. 6). For these purposes, two constitutive models were assumed in analyses: Mohr Coulomb (MC) and Hardening Soil Model (HSM).

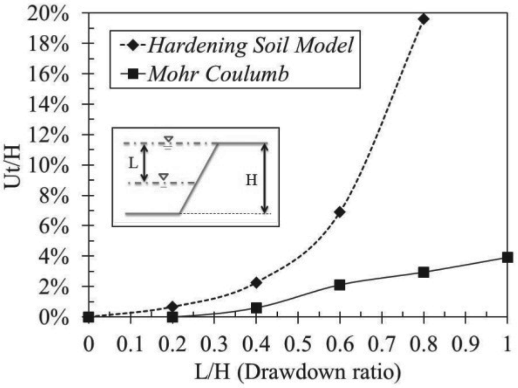

Figure 5. Horizontal displacements at the toe of the slope obtained by MC and HS constitutive models ($k=1\times10^{-6}$ cm/s and R=1.0 m/d).

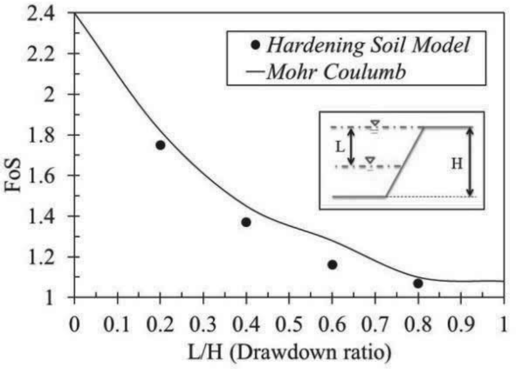

Figure 6. F○S as a function of drawdown ratio (L/H) computed by MC and HS models ($k=1\times10^{-6}$ cm/s and R=1.0 m/d).

From results presented in Figures 5 and 6 it can be drawn the following concluding comments:

- During the consolidation phase the MC model exhibits unrealistic horizontal deformations and lower than those obtained by the HSM model, due to: a) the HSM shows a plastic behavior at stress levels lower than the MC (Gens, 2012), b) in the loading and unloading process horizontal stresses in the HSM are larger than in the MC model, and c) the HSM has major peaks values of excess pore water pressure generated during loading or unloading process (Berilgen, 2007).

- When using the phi-c reduction method in combination with advanced constitutive models, these models behave such as the Mohr-Coulomb model, since stresses dependent on rigidity and the behavior obtained due to hardening effects are excluded from the analysis. In this case, the stiffness is calculated at the beginning of the calculation stage and remains constant until the calculation phase is completed.

4 GENERAL CONCLUSIONS

As demonstrated in this paper, the stability of a submerged slope under drawdown conditions (partial or total) is mainly affected by the properties of the material constituting the levee and the drawdown rate and drawdown ratio.

From results of parametric analyses it was observed that the *fully rapid drawdown* condition occurs when the water level of the reservoir descends more quickly than the remaining pore water pressures ($\Delta p_{seepage}$ and Δp_{excess}) are dissipated within the levee precisely caused by the drawdown, and no necessarily due to a total decrease of the water surface in a given period of time (minutes, hours or days). Finally, from slope stability analyses the safety factor was observed to decrease when the drawdown ratio (L/H) increases.

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