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ABSTRACT

The aim of this paper is to study the transient flow caused by rapid filling and drawdown in levees constructed in order to protect urban areas exposed to flooding. In particular, the behavior of typical protection levees constructed in Villahermosa City in Tabasco Mexico affected by intense rainfalls at the end of 2007 is assessed. The analyses are performed by numerical modeling based on finite element method. The emphasis is on the study of time variation of flow velocities and hydraulic gradients in several points of interest within these structures. Results of parametric analyses varying magnitude and velocities of filling or drawdown are also given. Besides, the changing configuration of *saturation* and *desaturation lines* at different times of the transient flow is illustrated. Finally, general conclusions concerning these types of analyses are provided.

INTRODUCTION

The levees built near rivers, lakes and channel slopes are frequently subjected to sudden changes of water level (increments or decrements), which modify flow conditions inside the soil mass. Flow velocities, hydraulic gradients and seepage forces are developed that, in extreme conditions, can cause the total failure of the structure. These phenomena, known as *rapid filling* and *rapid drawdown*, are complex problems in which magnitude and velocity of filling or drawdown, hydraulic conductivity and porosity of materials constituting the levee, and also geometry of slope and initial boundary conditions of flow are involved. Damages and landslides observed in the *Grijalva* River margins in Villahermosa (Tabasco, Mexico) during floods of 2007 are largely attributed to these phenomena. This paper focuses on studying the transient flow, particularly the variation with time of flow velocities and hydraulic gradients which are generated within the levees protecting Villahermosa City against flooding as water levels increase and decrease because of the rain cycles and dams discharge in the region.

TRANSIENT FLOW ANALYSIS

Approach and basic equation

The transient flow in an isotropic and homogeneous soil domain is governed by the following partial differential equation:

$$div\left[kgrad\left(h\right)\right]+c\frac{\partial h}{\partial t}=Q \tag{1}$$

Where k is hydraulic conductivity of soil, h is hydraulic potential (also named hydraulic head), c is specific capacity of soil, t is elapsed time and Q is a discharge quantity corresponding to a possible source within the medium.

Equation (1) combines Darcy's law and continuity of flow. It can easily be generalized to the case of heterogeneous and anisotropic soils. In the case of partially saturated soils, specific capacity depends on porosity and degree of saturation. Deformability of soil skeleton is commonly ignored. At the same time, degree of saturation and permeability depend on local pressure (Van Genuchten 1980).

In the analyses performed in this study it is accepted that initially the water surface in contact with slope is at a certain elevation (lower or higher level) and that because of any natural or artificial cause, it rapidly ascends or descends to a higher or lower level. These oscillations in water level generate a transient flow by rapid filling and drawdown within the levee as illustrated in Figures 1a and b, respectively.

In what follows, it will also be accepted that a steady-state condition initially exists within the levee.
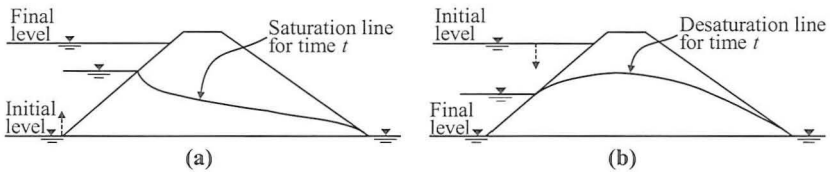

Figure 1. Schematic representation of (a) rapid filling and, (b) rapid drawdown phenomena.

General methods of solution

The methods that can be used for evaluating transient flow conditions due to rapid filling or drawdown phenomenon include:
- Analytical solution of partial differential equations (Alberro 2006).
- Approximate graphical method named *transient flow nets* (Cedergren 1989).
- Numerical techniques such as *finite element method* (e.g. *Plaxflow*, Delft University of Technology 2007), or *finite differences* (e.g. *Flac3D*, ITASCA Consulting Group Inc. 2009).

Numerical methods are the most common. They have been applied by different authors (Freeze 1971; Lam and Fredlund 1984; Lam et al. 1987; Ng and Shi 1998; Auvinet and López-Acosta 2001; Huang and Jia 2009; Auvinet and López-Acosta 2010; among others). The present study focuses on the finite element technique, which is discussed briefly below.

Finite element method (FEM)

Finite element method is a numerical technique which provides approximate solutions of partial differential equations for certain problems. Numerical techniques are preferred with increasing frequency due to their capability for solving complex

problems in which equation (1) can be generalized to non homogeneous and/or anisotropic materials (Lam et al. 1987; Auvinet and López-Acosta 2010). In this study the FEM, using the *Plaxflow* algorithm (Delft University of Technology, 2007), is applied to solve transient flow problems by means of the approximate solution of equation (1). This algorithm utilizes the previously mentioned Van Genuchten model to represent flow in unsaturated soils and allows carrying out transient flow analyses in two different ways: (a) *Step-wise conditions* and, (b) *Time-dependent conditions*. This last situation is assumed in this paper. It explicitly considers the continuous time variation of water surface level, which is represented by particular data of water level introduced by tables. The *Plaxflow* algorithm provides hydraulic potential field, flow velocity field, pore pressure, degree of saturation field, among others, as exposed below.

APPLICATION TO A PROTECTION LEVEE

Problems of levees in Villahermosa Tabasco, Mexico

The *Grijalva* basin in Tabasco State Mexico is constituted by a complex system of rivers, which converge mostly in two rivers crossing Villahermosa City: *Carrizal* and *Grijalva* (Auvinet et al. 2008). In order to protect this city and other towns of the state from floods, two types of levees or dikes have been constructed: (a) Protection levees built on the margins of the rivers, and (b) Protection levees built around exposed urban areas (Fig. 2). Flooding in the *Grijalva* watershed occurring in 2007, exhibited the vulnerability of these structures. In many instances, the problems were classified as geotechnical, and they were related to rapid filling and drawdown conditions due to the oscillations of river water levels and to the seepage forces generated by rain infiltration at the crown of the levees. It has been observed (Auvinet et al. 2008) that problems in banks of rivers commonly begin with erosion, which in some parts (depending on the type of soil) is originated by *piping* and can result in landslides (Fig. 3). These eroded sections are generally protected with levees of clay material. Elements more resistant to erosive attack of water of river such as rockfill, *bolsacreto* or *colchacreto* system (concrete bags), breakwaters, sheet pile walls, etc. are also used. The banks of the river or the levees fail when the weight of these structures exceeds the bearing capacity of soil (Fig. 3). Generally, failure occurs in low shear strength strata, such as very compressible clays and peats which are erratically found in the banks of Villahermosa Rivers. It has been also detected that factors such as scour of the river bed, over-elevation of levees or overloading caused by weight of additional protection such as bags of sand, cause instability of levees. In addition, as said above, intense rainfalls in the region originate large and quick variations of the water surface of rivers and lagoons of the area.
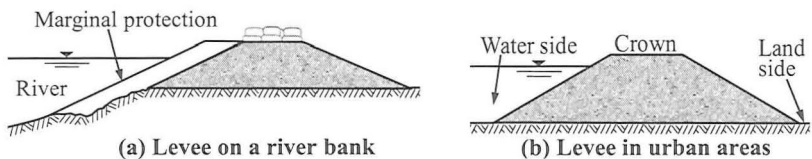

(a) Levee on a river bank   (b) Levee in urban areas
Figure 2. Types of protection levees constructed in Villahermosa, Mexico.
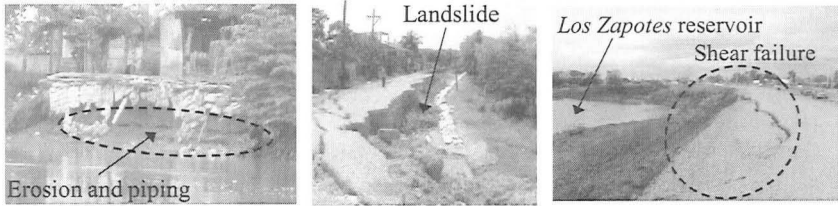
Figure 3. Evidences of instability in river banks and protection levees induced by rapid filling and drawdown.

Modeling of transient flow caused by rapid filling and drawdown

The transient flow caused by rapid filling and drawdown phenomena in a typical protection levee in Villahermosa City is assessed. Analyses are performed by means of the finite element method, using the *Plaxflow* algorithm (Delft University of Technology 2007). Simplified geometry of studied domain including soil foundation of levee is illustrated in Figure 4. The numbers of material layers are shown in the same figure. Properties of these materials are given in Table 1 (Auvinet et al. 2008).
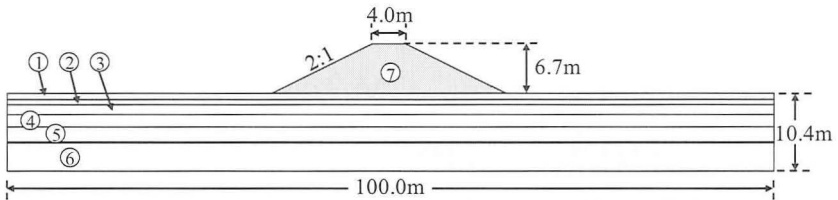

Figure 4. Simplified geometry and material number of the studied domain.

Table 1. Properties of material layers.

N°	Material	Hydraulic conductivity, k	Void ratio, e
1	Clay sand (SC)	0.0864 m/d (1×10^{-6} m/s)	0.43
2	Sandy clay of low plasticity (CL)	0.0864 m/d (1×10^{-6} m/s)	0.50
3	Organic sandy-clay silt of high plasticity (OH)	0.00864 m/d (1×10^{-7} m/s)	0.90
4	Clay sand (SC)	0.0864 m/d (1×10^{-6} m/s)	0.43
5	Silty sand (SM)	0.0864 m/d (1×10^{-6} m/s)	0.43
6	Organic clay of high plasticity (OH)	0.00864 m/d (1×10^{-7} m/s)	0.90
7	Clay levee	0.00864 m/d (1×10^{-7} m/s)	0.70

Data from the *Gaviotas* pluviometric station were taken into account for analyses of transient flow corresponding to a period of intense rainfalls from October

16 to November 29, 2007 (National Water Commission CONAGUA 2009). Based on these data, boundary conditions assumed for analyses are as follows:

– *For filling*: water surface ascends from initial level of 13.7m up to maximum level of 16.4m, in a period of 17 days (variation is illustrated in Figure 5a).

– *For drawdown*: water surface descends from maximum level of 16.4m up to final level of 11.3m, in a period of 27 days (variation is shown in Figure 5b).
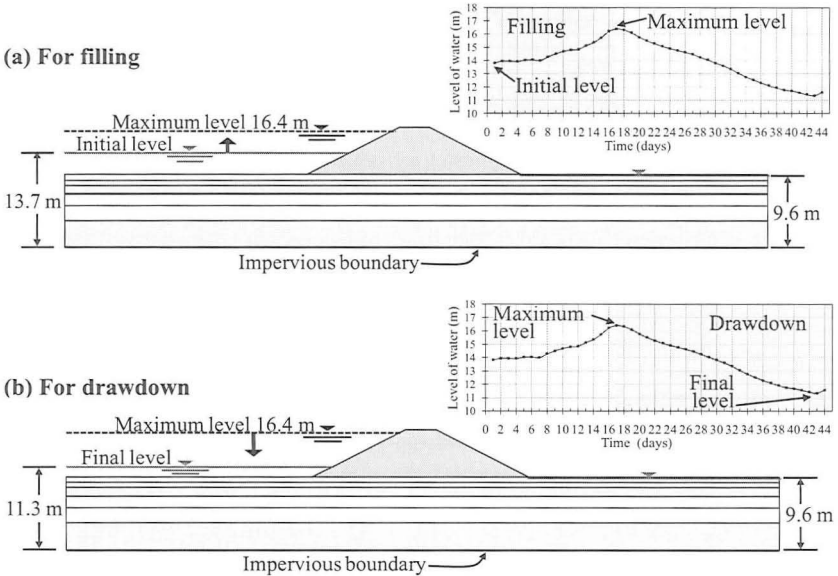

(a) For filling

(b) For drawdown

Figure 5. Boundary conditions assumed for analyses.

Results of analyses

Initial steady-state condition

An initial steady-state flow condition with the water level as indicated in Figure 5a is assumed. Results obtained in this case are shown in Figures 6a-d, concerning to pore pressure, hydraulic potential, hydraulic gradient and flow velocities, respectively. The two last figures reveal that highest values of gradient ($i_{max}\approx1$) and velocity ($V_{max}=1.2\times10^{-2}$ m/d) occur at the toe of downstream slope of levee. This hydraulic gradient is practically equal to the so-called *critical hydraulic gradient*, i_{cr}, which refers to effective stresses being zero (no contact stress between soil particles), causing in the soil the phenomenon known as *piping*. The critical hydraulic gradient varies between 0.9 and 1.1, with an average close to 1 for most sandy soils (Braja 2004). The prior result shows that the levees built without internal drainage (e.g. lack of a toe drainage blanket) can be affected by erosion due to *piping* in their normal operating conditions.
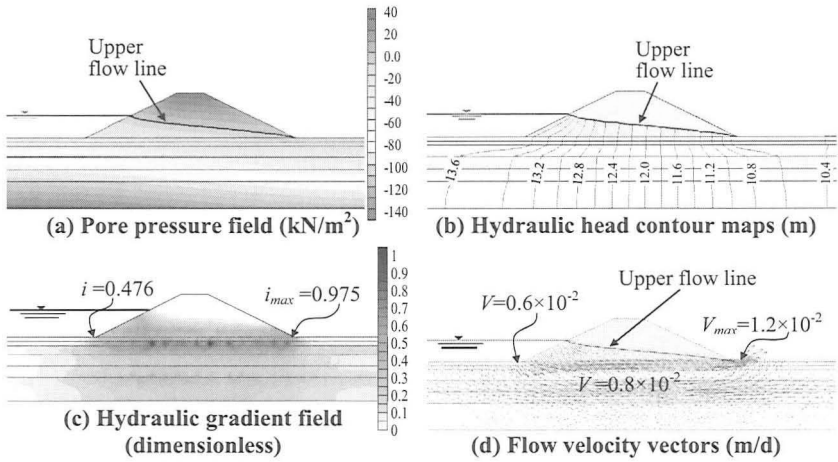
(a) Pore pressure field (kN/m²)

(b) Hydraulic head contour maps (m)

(c) Hydraulic gradient field
(dimensionless)

(d) Flow velocity vectors (m/d)

Figure 6. Results for initial steady-state flow condition.

Transient conditions

Figures 7a y b represent degree of saturation in the studied domain for two typical times during rapid filling and drawdown (17 and 44 days, respectively). In these figures can also be observed how the position of the water surface changes within the levee during rapid filling and drawdown. These free surface lines which separate unsaturated material (upper part) from saturated material are named *saturation lines* (for filling) and *desaturation lines* (for drawdown). Other authors prefer to call them *phreatic lines* (Lam and Fredlund 1984; Lam et al. 1987; Huang and Jia 2009). Some of these lines obtained at several times during both rapid filling and drawdown phenomena are illustrated in Figures 8 and 9, respectively. These lines exhibit the following characteristics:

– They are at atmospheric pressure.
– They are neither flow lines nor equipotential lines.
– At those points where they are intersected by equipotential lines, they satisfy the property: $h=z$ (hydraulic head=position).

(a) Day 17 of filling
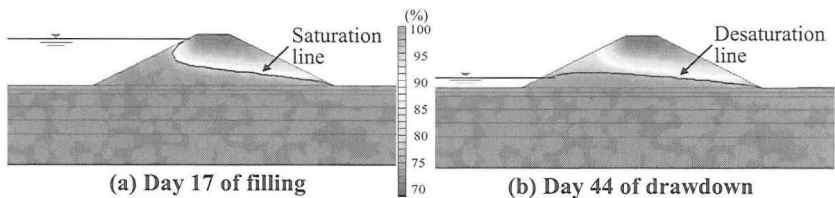
(b) Day 44 of drawdown

Figure 7. Degree of saturation (%) at different times during the transient flow.
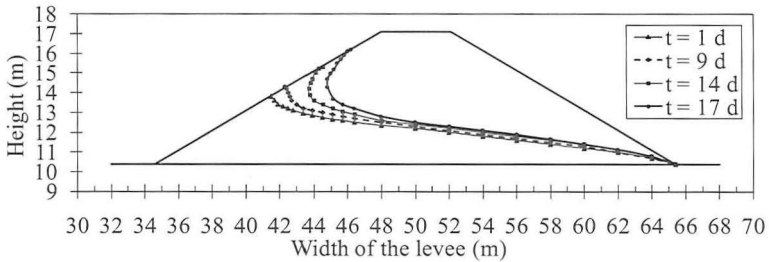
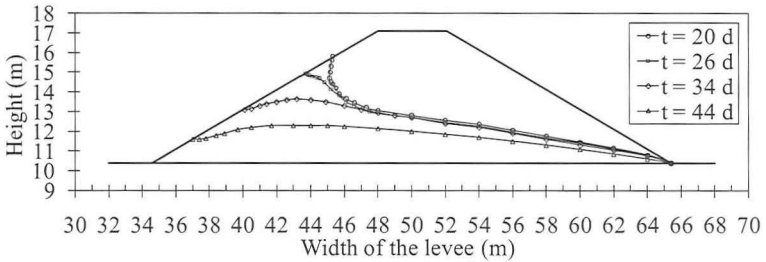Figure 8. Saturation lines during filling (day 1 to 17, see Fig. 5a).

Figure 9. Desaturation lines during drawdown (day 20 to 44, see Fig. 5b).

In the same way, it is interesting to note that during transient flow certain regions of higher hydraulic gradients and flow velocities are generated, as appreciated in Figures 10 and 11, respectively. Predominantly the highest values of hydraulic gradients and velocities take place at the toe of downstream slope of levee. Specifically, the gradient values of those areas greater than the so-called critical gradient (>1) could facilitate *global piping* through the body of levee or through the foundation soil (Figure 10). These above mentioned highest values occur when maximum level of water surface is achieved. Additionally, Figure 11a shows that during rapid filling velocity vectors are directed towards downstream and during rapid drawdown the direction of some of these vectors changes towards upstream (Figure 11b). Particularly, during rapid drawdown it can be observed that velocities and gradients generated near the upstream slope as water level descends are not negligible; in extreme conditions they could facilitate *local erosion* of material in those zones. It should be again pointed out that the *desaturation line* is not rigorously a *flow line* since velocity vectors cross it (Figure 11b). Finally, from Figures 10 and 11, it can also be observed that in general the highest values of flow velocity occur in the more pervious materials of the studied domain. In contrast, the highest values of hydraulic gradient arise in the less pervious materials of this domain. This is a suggestion that instability problems of levees could not be solved by constructing them with more impervious material, but rather building them with more pervious material or even placing drains in strategic areas of the body of levees. Some authors have indeed concluded that soils with a low permeability such as clayey and silty soils are more prone to slope failure than granular materials (Pradel and Raad 1993).
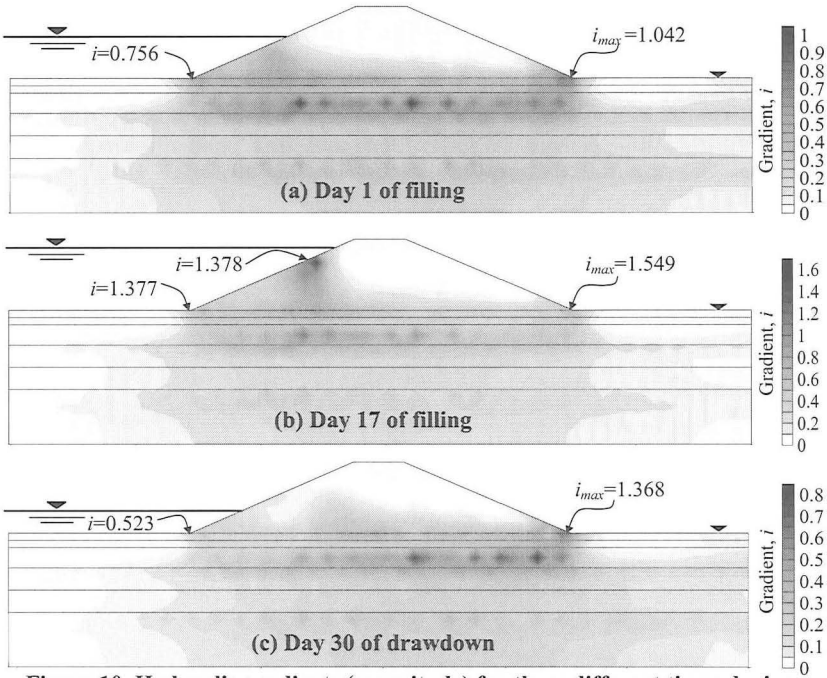
Figure 10. Hydraulic gradients (magnitude) for three different times during rapid filling and drawdown.
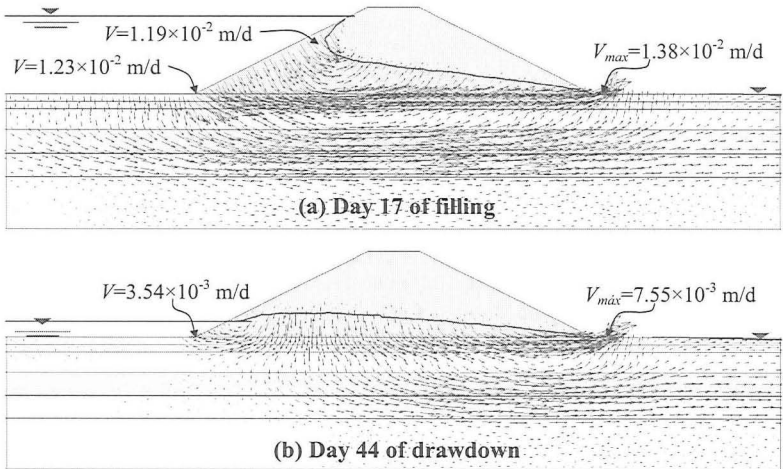

Figure 11. Velocity vectors (magnitude) for two different time intervals during rapid filling and drawdown (exaggerated scale).

In addition, parametric calculations were carried out varying filling and drawdown rate of original data from the *Gaviotas* pluviometric station (National Water Commission CONAGUA 2009). The summary of these results is provided in Figures 12 and 13. These figures lead to the following comments: (a) for higher filling rate, the maximum values of flow velocities occur at the toe of upstream slope of levee (Fig. 12); (b) in contrast, for lower filling rate, the maximum values of flow velocities occur at the toe of downstream slope of levee (Fig. 13).
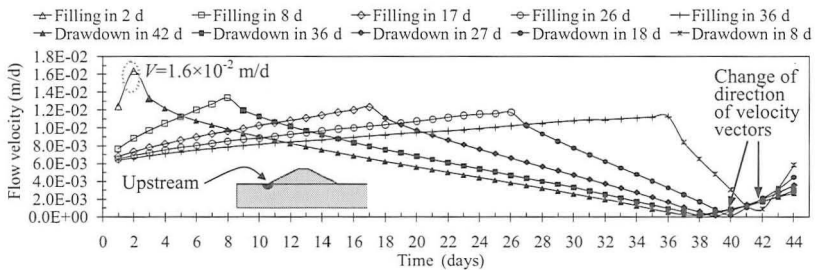

Figure 12. Flow velocity as a function of time for different filling and drawdown rates (at the toe of upstream slope of levee).
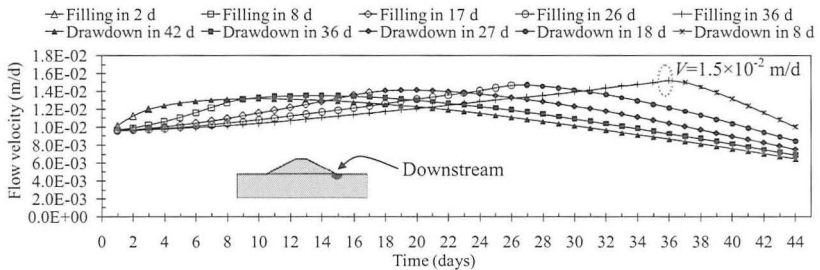

Figure 13. Flow velocity as a function of time for different filling and drawdown rates (at the toe of downstream slope of levee).

CONCLUSIONS

The transient flow caused by rapid filling and drawdown in typical levees of Villahermosa City in Tabasco Mexico, constructed to protect the population against flooding, was studied. Analyses were performed by numerical modeling using finite element method. Data from intense rainfalls occurred at the end of 2007 were considered in calculations. From results of analyses, some general conclusions can be drawn: (a) in both rapid filling and drawdown conditions, the highest values of flow velocities and hydraulic gradients occur at the toe of downstream slope of levee. The hydraulic gradient values of those areas greater than the so-called *critical gradient* could facilitate *global piping* through the body of levee or through the foundation soil; (b) during drawdown the flow velocities and hydraulic gradients generated near the upstream slope as water level descends are not negligible; in extreme conditions (e.g. steady intense rain for some time), they could facilitate *local erosion* of material

in those areas and jeopardize slope stability. Currently, stability of slopes in this type of levees subjected to unsaturated transient flow considering the suggestions of recent researches (Griffiths 1994; Huang and Jia 2009) is also being assessed.

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