Effect of Horizontal Drains on Upstream Slope Stability During Rapid Drawdown Condition

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Abstract— The rapid drawdown case is one of the most severe loading conditions that an earthen slope can experience and it is quite common in embankment dams. Rapid drawdown can cause a temporary increase in pore water pressure. The increased seepage forces may lead to slope instability, causing the collapse of structure. This paper discusses the effect of horizontal drains on upstream slope of earthfill dams during rapid drawdown using finite elements and limit equilibrium methods. Changing of pore water pressure, outpouring seepage flow and factor of safety are inspected.

Keywords— earthfill dams, rapid drawdown, drain, stability, finite element method.

I. INTRODUCTION

Embankments may become saturated by seepage flow during a long term high reservoir stage. If subsequently the reservoir pool is drawn down faster than the pore water can escape, excess pore water pressures and reduced stability will result. This is called drawdown which is quite common in upstream slopes of embankment dams [3].

The stability of slopes under drawdown conditions are usually analyzed considering two limiting conditions, namely slow and rapid drawdown. In the slow drawdown situation the water level within the slope is assumed to equalize the reservoir level at any time. In case of rapid drawdown, which represents the most critical condition, it is assumed that the pore water pressure within the embankment continues to reflect the original water level. The lag of the phreatic line depends on factors such as: permeability of soils, drawdown rate, drawdown ratio and slope gradient [1].

When the countervailing upstream water pressure has disappeared, it causes a danger to the upstream slope. Soils inside the dam body remain saturated and seepage commences from it towards the upstream slope. Seepage and hydrodynamic pressures create downward forces acting on the upstream slope. Those are adverse to the stability and create a critical condition to the upstream slope. While the development of deep seated failure surfaces is possible, the effect on earthen side slopes is most commonly seen in the form of relatively shallow slope failures, which if left unattended lead to the gradual deterioration of the whole dam [10].

One of the most effective methods of dissipation of excess pore pressure and improvement of stability is use of upstream drains. These upstream drains are capable of draining the upstream slope and making the equipotential lines tend to become horizontal. They have a very significant effect on the stability of the upstream slope during rapid drawdown [8].

II. Theory of water flow in saturated and unsaturated soils

Seepage flows in saturated and unsaturated soils are governed by Darcy's law. One of the major differences between water flows in saturated soils and flows in unsaturated soils is that the coefficient of permeability is not a constant but a function of the degree of saturation or soil suction in an unsaturated soil. The governing equation for water flow through soil can be obtained by introducing Darcy's law into the mass continuity equation. The deformation of the soil skeleton is usually ignored for convenience. Taking the total hydraulic head h as the unknown and when the directions of the coordinate axes are the same as the directions of anisotropy of hydraulic conductivity, the general two-dimensional governing differential equation for water flow through soil is as follows:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) = \gamma_w \frac{\partial \theta_w}{\partial \psi} \frac{\partial h}{\partial t}$$

where, kx and ky are the coefficients of permeability in the x-direction and y-direction, respectively; γw is the unit weight of water; θw is the volumetric water content; ψ is the soil suction; and t is time. According to the equation, a soil-water characteristic curve, which is a relationship between the volumetric water content and the soil suction, as well as a permeability function, must be known for transient seepage analyses [10].

II. Description of problem

In order to investigate the effect of drains on upstream slope stability during rapid drawdown condition, a zoned dam is used as the experimental model for this study.

As shown in figure two the model is a zoned dam with a height of 23 m above the ground level, a crest of 8 m and a length of 146 m. Both upstream and downstream slopes have the inclination of 3H: 1V, which is so common in earthfill dams. The foundation is considered to be rigid. The maximum ware table is at 20 m above the ground level. that the permeability of drain material assumed to be much more than the permeability of membrane material.

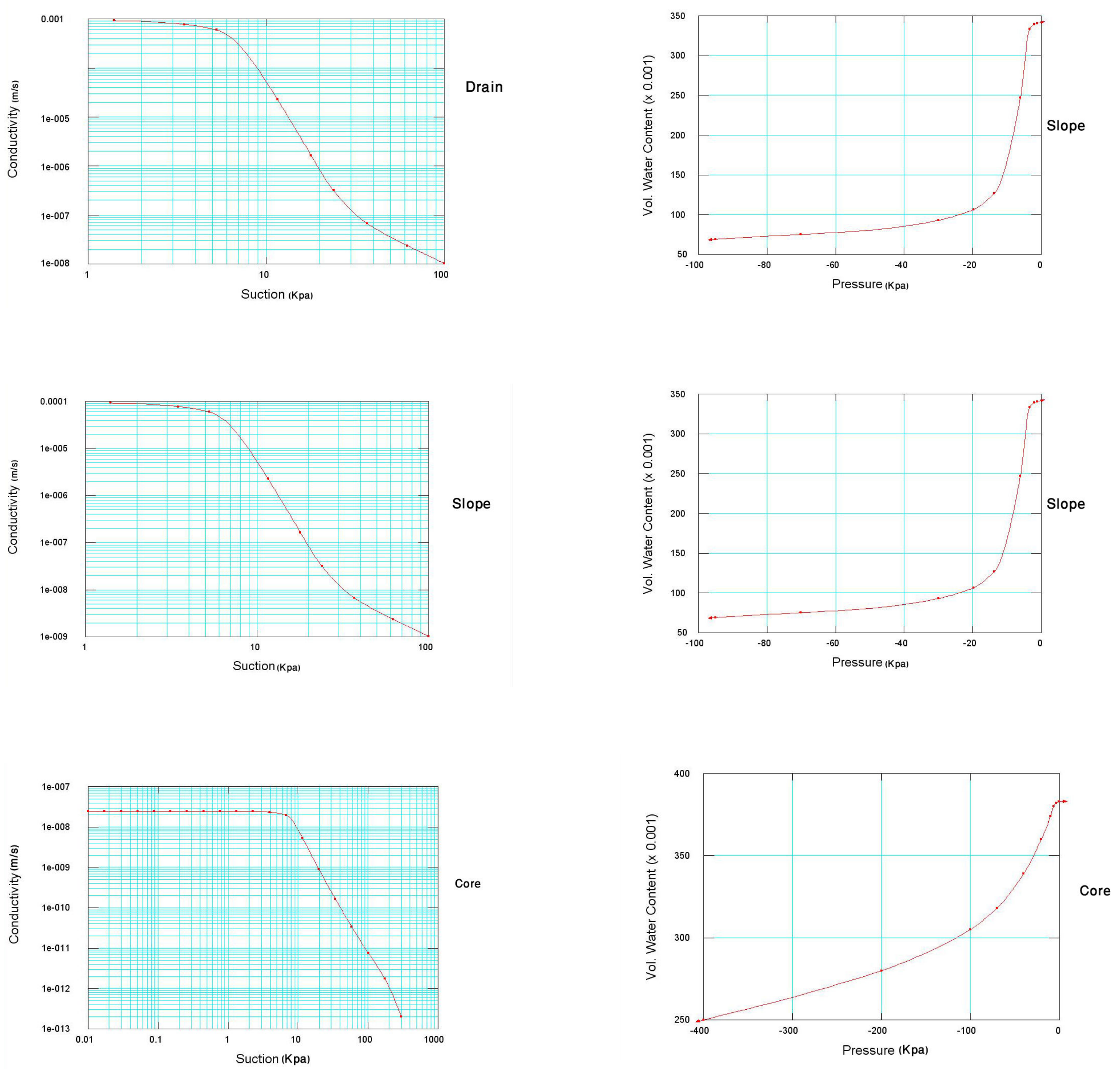

Fig. 1 Soil- water characteristic curve and permeability function of soils

The dam configuration and the horizontal drainage location are shown in figure 3. Four scenarios are analyzed base on different drainage configurations. The first scenario involved the dam configuration without drainage. In the second one the dam has one horizontal drain, And the next two scenarios involved the upstream slope has two and three horizontal drains. It should be mentioned that the drains length are considered to be half of horizontal length between slope surface and the core.

All the material parameters used in rapid drawdown analysis are shown in table 1. Except permeability, the other material properties are considered to be isotropic. It should be noted.

III. Method of analysis

As previously said, our purpose is investigation of effect of horizontal drains on upstream slope stability during rapid drawdown condition. In order to reach this goal the analyses are done in three stages.

First it is assumed that the water table is at the maximum level and then steady seepage analyses are established for all different drainage scenarios. From these analyses pore water pressure can be obtained in any region of dam. These pore water pressures will be used as initial conditions in rapid drawdown analyses. It should be mentioned that, the seepage analysis software SEEP/W (Geostudio 2004) is utilized to obtain pore water pressure distributions and phreatic line. This software is based on finite element method.

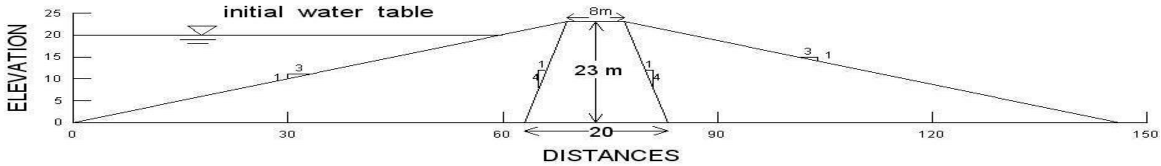

Fig. 2 Cross section of experimental model

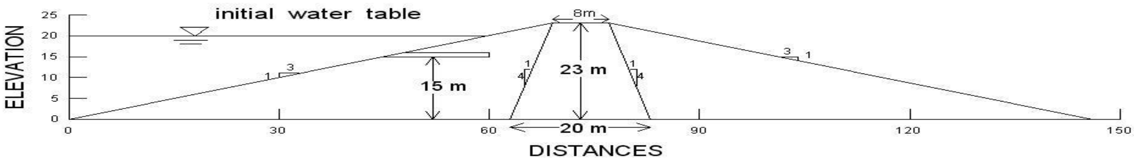

Fig. 3.a. Dam with one horizontal drains in upstream slope

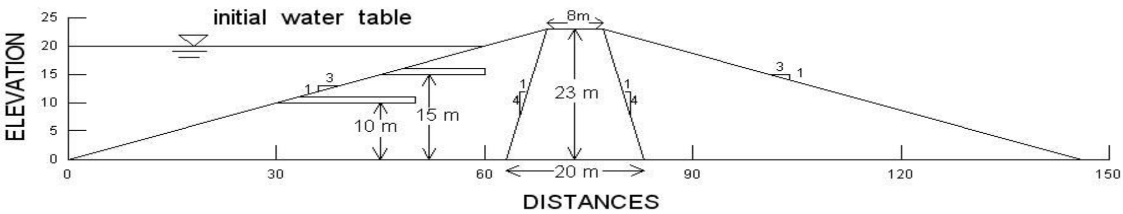

Fig. 3.b. Dam with two horizontal drains in upstream slope

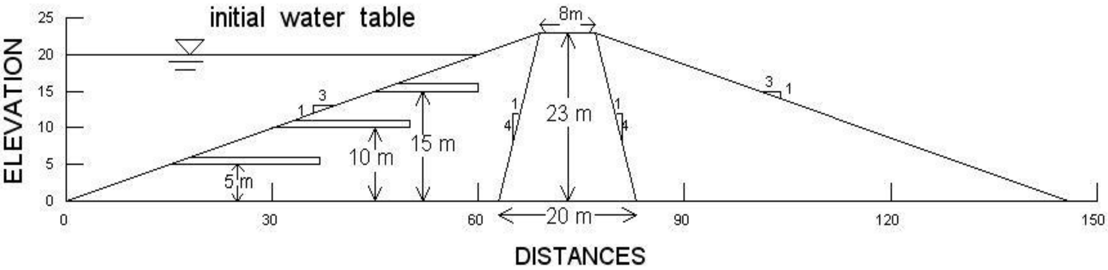

Fig. 3.c. Dam with three horizontal drains in upstream slope
Fig. 3 Different configuration of drains in upstream slope

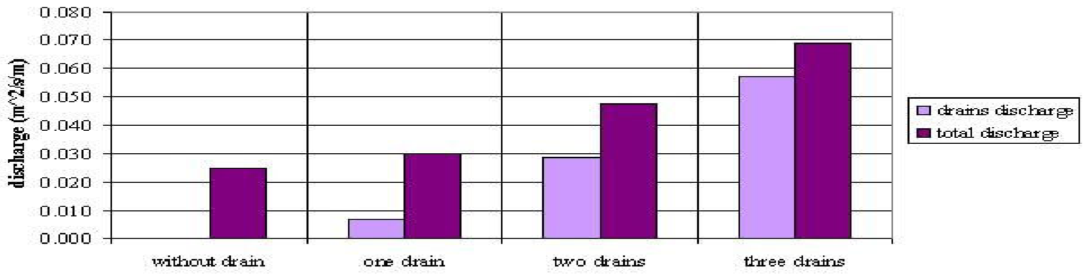

Fig. 4.a. drawdown ratio 0.25

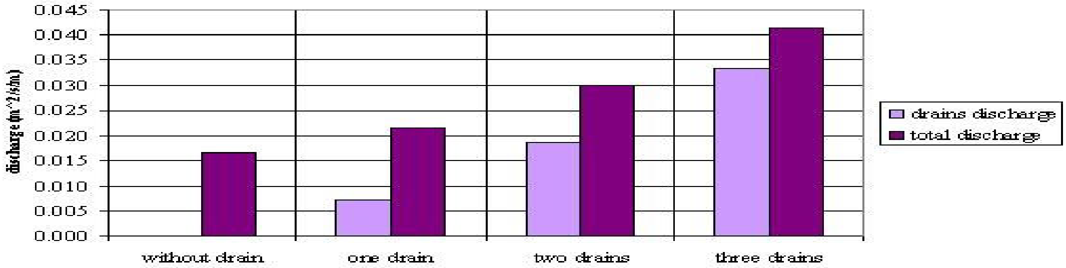

Fig. 4.b. drawdown ratio 0.50

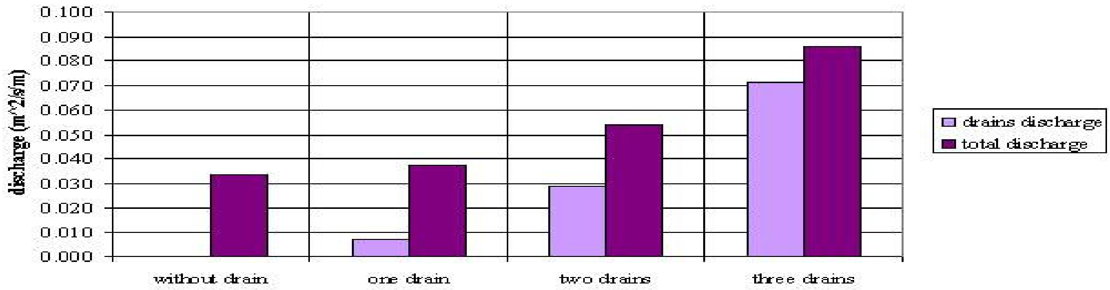

Fig. 4.c. drawdown ratio 0.75

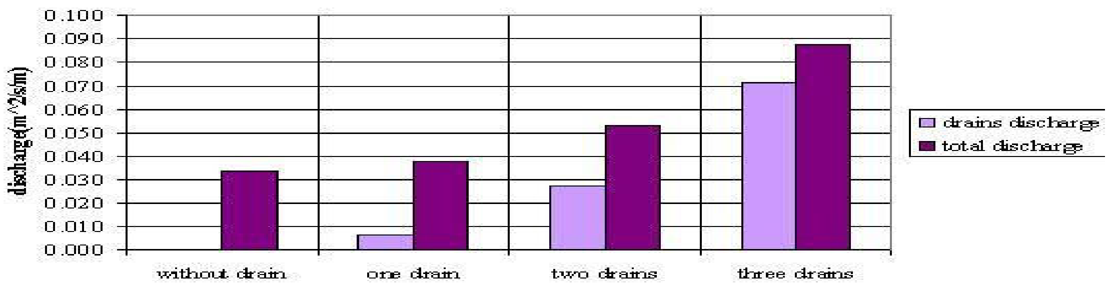

Fig. 4.d. drawdown ratio 1.00

Fig. 4 Seepage flow for different drawdown ratio

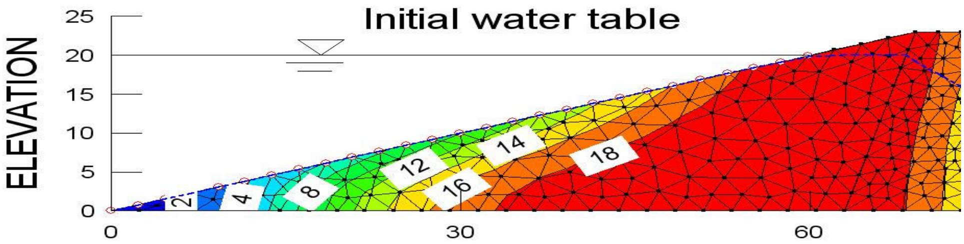

Fig. 5.a. Equipotential lines in case of no drain

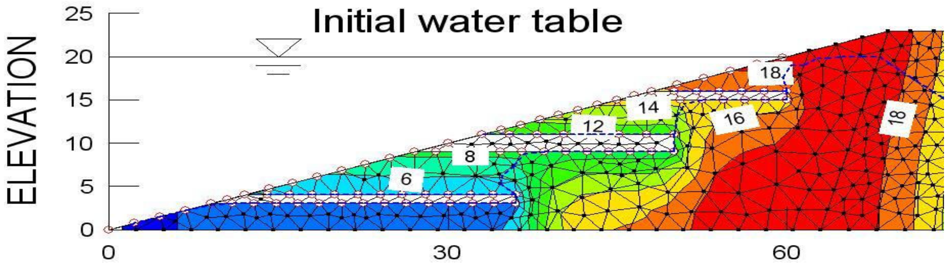

Fig. 5.b. Equipotential lines in case of three horizontal drains

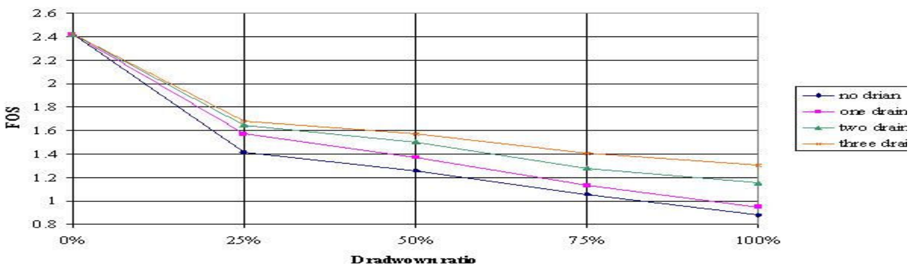

Fig. 6 Factor of safety for different for different drawdown ratio

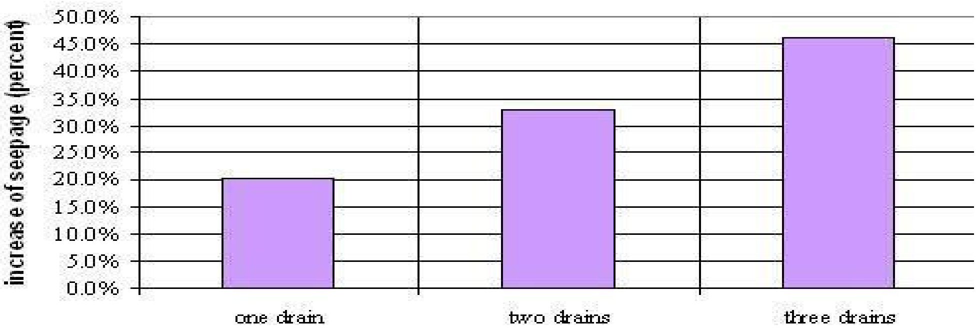

Fig. 6 The increase of seepage during long term condition

Table 1 Soil properties used in rapid drawdown analyses

	Φ(degree)	**C**(kPa)	**γ** (kN/m^3)	K_x/K_y	Failure criterion
Slope	32	10	21	5	Mohr coulomb
Darin	32	10	21	5	Mohr coulomb
Core	25	25	20	5	Mohr coulomb

In the second stage, the rapid drawdown is simulated by means of hydraulic functions. The water level in reservoir is supposed to lower quickly into four steps. The maximum water level lowered equally in 5 m for each step. The rate of drawdown is 1 m/day. The drawdown ratio 0.25, 0.50, 0.75 and 1 are modeled in this research. It should be noted that, due to water fluctuation in front of slope, the boundary condition for the slope below water level is not a constant total head boundary condition. So the total head is defined as a function of time and the function is applied to slope boundary below water level during rapid drawdown.
At the final stage, the software SLOPE/W (Geostudio 2004) that uses limit equilibrium method for slope stability analysis is utilized to assess the effect of drains on improvement of upstream slope stability during rapid drawdown. The Spencer analysis method is selected. The shear strength of soil is described by mohr coulomb failure criterion. The pore water pressures used in slope stability analyses are imported from rapid drawdown seepage analyses.

V. Results of analyses

A. Outpouring seepage flow during rapid drawdown

Due to existence of horizontal drains in upstream slope the seepage flow increases. In other words the outflow in case of presence of drains is much more than the case where there is no drain in upstream slope. As shown in figure 4 if there is only one drain in upstream slope, the increase in outpouring flow is up to 29%. In case of presence of two and three horizontal drains, the increase of seepage flow is up to 81% and 160%, respectively. It is so clear that the drains play an important role in expelling the outflow.
The upstream horizontal drains are capable of draining the upstream slope and making the equipotential lines tend to become horizontal. This effect is shown in figure 5.

B. Factor of safety

The results of stability analyses of upstream slope during rapid drawdown condition, are plotted in figure 6 for different drawdown ratio. It can be seen that for drawdown ratio 0.25 and 0.50 the factor of safety are more than the minimum allowable factor of safety (1.20) and there is no need to exist any drain in upstream slope. In order to reach the minimum allowable factor of safety, at least two horizontal drains should exist for drawdown ratio 0.75. At last for drawdown ratio 1, presence of three horizontal drains is necessary.
The interesting results shown in figure 6 indicate that the factor of safety decreases dramatically from the beginning of drawdown until the water table reaches 1/3 of initial water table. The value of safety factor, when water table reaches 1/3 initial water table, can be considered nearly minimum. In other words, the differences of safety factor are not so great for drawdown ratio 0.75 and 1.0. The explanation of this fact is that, in the initial stages of drawdown, the increased weight of the slope has a proportionally greater destabilizing effect than the increased frictional strength. At the lower levels of drawdown, the increased frictional strength starts to have a greater influence than the increased weight.
The existence of drains has great influence on factor of safety of upstream slope during drawdown condition. The increase of factor of safety is up to 12% if there is only one drain in upstream slope. In case of presence of two and three horizontal drains, the increase of safety factor of safety is up to 31% and 48%, respectively.

C. Increase of seepage during long term condition

The preparation of horizontal drains in upstream slope can cause increase of seepage during long term condition. This is the most undesirable effect of horizontal drains in upstream slope of which should be taken into consideration in design of earth dams. This matter is revealed in figure 7.

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