World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:10, No:10, 2016

Numerical Analysis of Rapid Drawdown in Dams Based on Brazilian Standards

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***Abstract*—**Rapid drawdown is one of the cases referred to ground stability study in dam projects. Due to the complexity generated by the combination of loads and the difficulty in determining the parameters, analyses of rapid drawdown are usually performed considering the immediate reduction of water level upstream. The proposal of a simulation, considering the gradual reduction in water level upstream, requires knowledge of parameters about consolidation and those related to unsaturated soil. In this context, the purpose of this study is to understand the methodology of collection and analysis of parameters to simulate a rapid drawdown in dams. Using a numerical tool, the study is complemented with a hypothetical case study that can assist the practical use of data compiled. The referenced dam presents homogeneous section composed of clay soil, a height of 70 meters, a width of 12 meters, and upstream slope with inclination 1V:3H.

***Keywords*—**Dam, GeoStudio, rapid drawdown, stability analysis.

I. Introduction

THE geotechnical engineering recognizes that risks are inherent in any activity that involves natural phenomena or materials. Based on this perspective, the engineer must seek a balance between the technical, economic, and security conditions. Regarding the dam projects, in order to achieve these goals, it is necessary to carry out geotechnical investigations before, during, and after the construction.

The construction safety of a dam must be treated in a compatible manner with consequences of a possible failure. In this way, knowing the risk is relevant for a suitable design.

Regarding the safety of dams, in Brazil, [1] provides that massive study must be conducted in four distinct phases: end of construction, rapid drawdown, stable percolation, and seismic. Based on this perspective, the study focuses on presenting solutions to the problem of rapid drawdown. In this way, GeoStudio 2007 software was used; specifically, the platforms SEEP/W for flow modeling and SLOPE/W for slope stability analysis. Similarly, this problem can be solved in the other software.

II. Rapid Drawdown

Rapid drawdown problem has two variables that should be thoroughly studied: flow and ground stability. The theoretical basis of this problem is explained in the following subsections.

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A. Flow Analysis

The simulation of the flow problem at rapid drawdown state involves two types of analyses, which are known as: percolation in continuous flow considering that flow conditions do not vary with time, and analysis in transient flow when there is a variation in flow conditions over time. In this stage of the paper, the flow theory applied in SEEP/W is reviewed.

Darcy's law explains the principle that governs how fluid moves in the subsurface. Equation (1) shows saturated one-dimensional flow in the direction y:

$$Vy = ky\frac{\partial h_w}{\partial y} \tag{1}$$

where v_y corresponds to the flow in y direction, ky designates the permeability coefficient, and ∂hw/∂y represents the hydraulic gradient.

The continuity equation states that the variation of volumetric water content, θ, at a time, t, is equal to the variation in flux densities v_x, v_y, and v_z, as shown in (2) [2].

$$\frac{\partial \theta}{\partial t} = -\nabla v \tag{2}$$

where θ is the volumetric water content and ∇v corresponds the divergent flow. In this context, (3) sets ∂θ term as:

$$\partial \theta = -\partial (\frac{V_w}{V_o}) \tag{3}$$

where V_w is the volume of water in the element and V_0 corresponds to the initial overall volume of the element.

Regarding the present study, flux is two-dimensional, thus (2) can be simplified to (4).

$$\frac{\partial \theta}{\partial t} = -(\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{y}) \tag{4}$$

Replacing Darcy's law (1) in (4), it is possible to obtain (5). This equation, introduced by Richards, consists of the law that rules the transient flow in anisotropic porous media.

$$\frac{\partial}{\partial x}(kx\frac{\partial h_x}{\partial x}) + \frac{\partial}{\partial x}(ky\frac{\partial h_y}{\partial x}) = \frac{\partial \theta}{\partial t} \tag{5}$$

Richards also examined the flow in unsaturated media (6), where the permeability is defined through θ.

$$\frac{\partial}{\partial x}(k_x(\theta)\frac{\partial h_x}{\partial x}) + \frac{\partial}{\partial x}(k_y(\theta)\frac{\partial h_y}{\partial x}) = \frac{\partial \theta}{\partial t} \tag{6}$$

It is important to clarify that in the areas where the soil is saturated, permeability is considered constant. It is also noteworthy that this research did not consider the anisotropy of the soil. Therefore, (6) can be simplified to (7).

$$\frac{\partial}{\partial x}(k(\theta)\frac{\partial h_x}{\partial x}) + \frac{\partial}{\partial x}(k(\theta)\frac{\partial h_y}{\partial x}) = \frac{\partial \theta}{\partial t} \tag{7}$$

In this study, the software used was SEEP/W 2007. SEEP/W uses finite element method for solving two-dimensional flow problems in saturated and unsaturated media, besides permanent or transient flow. The formulation above was obtained from the software tutorial [3].

SEEP/W also uses finite element method in numerical solution of Richards' equation; however, there are two adjustments that had to be made. It is necessary to add the term Q, which consists of the boundary condition imposed by the user, and the substitution of $\partial\theta$.

Regarding the substitution of $\partial\theta$, initially (8) is considered for a linear relationship on the period of volumetric water content variation with the matric suction variation.

$$\partial \theta = m_w \partial (u_a - u_w) \tag{8}$$

where u_w represents pore-water pressure, u_a is the pore-air pressure, m_w is the coefficient of the volumetric water content variation in relation to the matric suction variation (u_a - u_w).

The pore-air pressure is assumed to be constant and equal to zero; hence, pore pressure can be separated in elevation head and position in the y-axis, as in (9):

$$(u_a - u_w) = y_w (H - y) \tag{9}$$

where y_w represents the unit weight of water; H elevation head; and y designates the position on y-axis. In this context, SEEP/W solves the transient flow equation as shown in (10):

$$\frac{\partial}{\partial x}(k(\theta)\frac{\partial h_x}{\partial x} + \frac{\partial}{\partial x}(k(\theta)\frac{\partial h_y}{\partial x}) + Q = m_x \gamma_w \frac{\partial (H - y)}{\partial t} \tag{10}$$

For continuous flow, volumetric water content remains constant, and (7) is simplified to (11):

$$\frac{\partial}{\partial x}(k(\theta)\frac{\partial h_x}{\partial x} + \frac{\partial}{\partial x}(k(\theta)\frac{\partial h_y}{\partial x}) = 0 \tag{11}$$

In order to use SEEP/W, it is important to highlight that the input of parameters was carried out through two functions and a density parameter which are: curve of volumetric water content variation related to matric suction, curve of permeability variation related to matric suction, and parameter m_v.

Suction can be measured by two distinct levels. First, it is associated with the pore-pressure measurement related to the portion of matric suction. Secondly, it is related to the stress required to remove a soil water molecule in gaseous phase (osmotic suction). In this study, it was considered just the matric suction because it represents, approximately, the total suction.

The characteristic shape of the curve is related to several factors; e.g., the grain size and the mineralogical aspects of soil. The function of volumetric water content variation, presented in software, is related to volumetric water content which is obtained by the product of porosity and the degree of saturation.

SEEP/W has four available methods to develop a function of volumetric water content, which are: estimation according to grain size, based on a sample set of built-in functions in the software, and other two equations based on the known curve with adjustment parameters. The details of each method are displayed in the auxiliary document of GeoSlope [3].

Fig. 1 illustrates a typical characteristic curve of silty soil. It is possible to notice the hysteresis between the trajectories of wetting and drying.

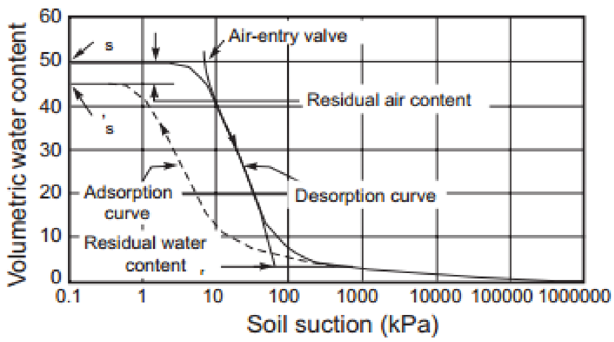

Fig. 1 Typical soil-water characteristic for silty soil (Fredlund and Xing, 1994 – in [13])

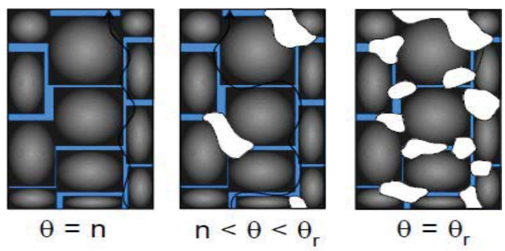

Fig. 2 Flow paths for saturated and unsaturated soils [3]

The water flow through soil, in saturated or non-saturated conditions, is related to the hydraulic conductivity function. Regarding the saturated soils, all pores are filled with water, and consequently, represent flow channels. In this study, related to the unsaturated soils, the voids filled with air increase the tortuosity of the flow (Fig. 2). Thus, it is possible to observe that non-saturation of the soil hinders water transport and reduces permeability. Therefore, it becomes clear that the flow is related to the amount of water present in the soil.

Regarding GeoStudio functions, prediction methods which can estimate the hydraulic conductivity function are used. In this context, it is necessary to provide the saturated permeability values (obtained in conventional tests - Subsection III. b) and the volumetric water content (product of porosity and the degree of saturation) [3]. It is also important to review the definition of m_v. This parameter is related to the volumetric compressibility coefficient obtained in oedometric test. This coefficient can be estimated from the relationship presented in (12):

$$m_v = \frac{1}{M} \tag{12}$$

where m_v represents the volumetric compressibility coefficient, and M corresponds to the modulus of elasticity in oedometric compression.

Modulus of elasticity in oedometric compression was defined in [4] as constrained modulus. This property is defined in (13).

$$M = \frac{E(1-\mu)}{(1+\mu)(1-2\mu)} \tag{13}$$

where E is the Young's modulus, and μ represents the Poisson's ratio.

According to the software tutorial [3], the accuracy of parameter m_v is relevant only in the case of significant increase or loss of water. Hence, rapid drawdown represents a scenario for which this parameter is relevant; thus, it will be discussed in this paper.

Parameter m_v is traditionally obtained by oedometric tests. Moreover, it can also be acquired from triaxial tests or using Marchetti Dilatometer test [5].

B. Slope Stability Analysis

Slope stability analysis is performed by [6] and is quoted in [1]. The method uses a calculation routine based on the limiting equilibrium.

Considering Mohr-Coulomb criterion of rupture, analysis requires two input parameters of resistance and another of unit weight. These parameters are known as: undrained cohesion, undrained friction angles (zero or close to zero) and saturated unit weight.

Resistance parameters are obtained from consolidated undrained triaxial test (Subsection III. c). On the other hand, the saturated unit weight is usually obtained from hydrostatic balance test [7].

III. Tests and Parameters

To use appropriate parameters during numerical modeling, it is necessary to use data obtained in some specific tests. Briefly, it is emphasized that the required tests are: unidimensional consolidation, permeability, triaxial compression/consolidated undrained (Subsection III.c), and the soil-characteristic curve. The importance of each test in the rapid drawdown process is described below.

A. Oedometric Test

Oedometric test, prescribed by [8], provides properties of material loaded in axial drained form. The parameter obtained in the test that will give a numerical correspondence to the modeling is the volumetric variation coefficient (m_v). This parameter is variable, but may be considered constant within a variation range. Equation (14) shows how to obtain the data:

$$m_v = \frac{a_v}{1-e_0} \tag{14}$$

where a_v is compressibility coefficient and e_0 represents initial void ratio.

The calculation of m_v is obtained from the compressibility coefficient (15) within a certain range of loading.

$$a_v = \frac{\Delta e}{\Delta \sigma'_v} \tag{15}$$

where Δe corresponds to the void ratio variation, and $\Delta\sigma'_v$ is the vertical stress variation.

Regarding (15), the vertical stress variation can be defined as the difference between soil's weight before and after rapid drawdown. On the other hand, the vertical stress is defined in (16):

$$\sigma'_v = \gamma \cdot h \tag{16}$$

where γ represents unit weight of soil, and h is depth based on crest elevation.

B. Permeability

Ground permeability is a parameter with notorious variance, mainly on compacted soils. Therefore, to approximate the real conditions from the modelled ones is still a great challenge. Nevertheless, it is extremely important to know the order of magnitude of the permeability coefficient. For this, tests must be conducted as prescribed by [9] or [10]. Furthermore, it is also possible to obtain the permeability coefficient from field tests.

C. Consolidated Undrained (CU) Triaxial Compression Test

Consolidated undrained triaxial compression test determines the resistance characteristics of soil, simulating field conditions where soil was completely consolidated, and then submitted to shearing efforts without water outlet. This condition is extremely important for the rapid drawdown study because it represents the reality of low permeability materials (clayey soils) submitted to this process. Therefore, well representing the real conditions, it is possible to obtain the following parameters: cohesion, friction angle (≈zero), and Young's modulus. The standard that regulates this test is in [11].

D. Characteristic Curve

Characteristic curve is important to simulate the ground behaviour subjected to the rapid drawdown. This property allows to consider the influence of unsaturated soils and uses the following parameters: hydraulic conductivity, shear resistance, and volumetric variation. To determine the properties of the curve, standard test method for measurement of soil potential (suction) using filter paper should be employed [12].

IV. Using the Software

The case study will be performed with a symbolic dam. The geometry is shown in Fig. 3 as a uniform section, vertical, and horizontal filter and shell inclination of 1V: 3H. To simplify, the dam starts at zero elevation; thus, the crest elevation of 70 m corresponds to the value of its total height. However, the objective of this study is to provide parameters for the rapid drawdown, so the parameters for filter and foundation were considered irrelevant.

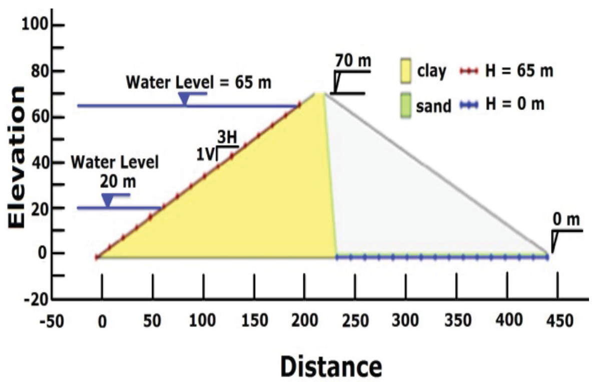

Fig. 3 Dam's geometry

A. Flow Analysis

For the analyses in SEEP/W, mesh size was defined by finite elements with sides of approximately 1 meter. Fig. 3 displays the boundary conditions set by the reservoir elevation head in the upstream shell (in red) and the neutral charge in the filter (in blue).

Flow analyses, presented in Figs. 4 and 5, were performed with two distinct situations of dam operation. First, a normal operation with initial conditions for steady flow was considered. Second, it was taken into account the rapid drawdown, and consequently, the transient flow.

Shell material is the same for both analyses and it is defined as "Saturated/Unsaturated" model. Regarding the hydraulic parameters, it should be inserted by using functions of volumetric water content variation and permeability variation.

For the presented study, the function of volumetric water content was determined as "Data Point Function". This function is estimated based on a "Sample Function" which is, in this case, a silty clay soil. Posteriorly, it is required to insert the initial condition of water volume in "Saturated WC" which was set as 0.33.

Volumetric water content function can be adjusted with definition of maximum and minimum suction and the number of increments. Other possible adjustments can be made with the option "Curve Fit" or with the direct editing of the points. In a real case, using data obtained from tests, the characteristic curve can be inserted point by point.

In this paper, other values were maintained as the software standard configuration. Parameter m_v is the most relevant one for a drawdown study, since it's a simulation practically all saturated with high volume water outlet. In this study, m_v was estimated from (13), considering Young's modulus as $2x10^{-4}$ kPa and Poisson's ratio as 0.3. Consequently, the order of magnitude of mv parameter was $6x10^{-5}$ kPa^{-1}.

Permeability function is also a "Data Point Function", estimated using Van Genuchten method from moisture function. The saturated permeability parameter was set as $1x10^{-7}$ m/s and 1% of residual water. For this proposed case, other values were maintained as software standard configuration.

In seepage analysis using permanent flow, upstream elevation head is considered constant and was set as 5 meters below the crest (elevation of 65 meters).

The permanent flow analysis results are presented in Fig. 4 with isolines of pore pressure in kPa.

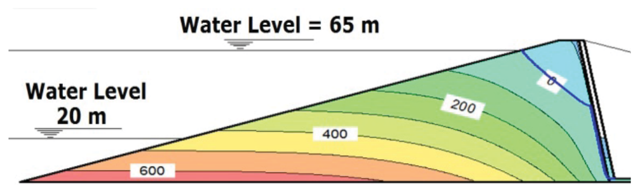

Fig. 4 Permanent flow

The input data for boundary conditions, called Head (H), has in "Constant" option the value of 65 meters for "Action", applied on the upstream shell, and the magnitude of 0 m applied to the filter.

Seepage analysis of rapid drawdown is time dependent, therefore flow is transient. In this case, it is necessary to set the analysis time which is 3,000,000 seconds or 34,7 days.

The downstream boundary condition is maintained as the previous analysis. On the other hand, on the upstream, reservoir water level is lowered linearly from elevation 65 m to 20 m in 34,7 days.

The result of rapid drawdown analysis in transient flow is presented in Fig. 5 using pore pressure isolines in kPa. It is noted that there was a reduction in pore pressure, relieved from the upstream slope.

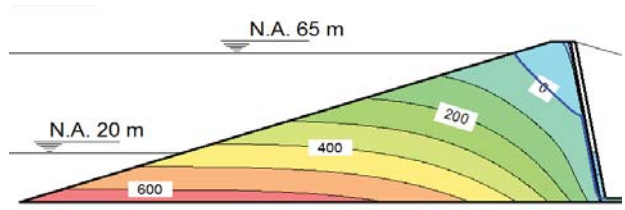

Fig. 5 Transient flow

Using SEEP/W, analysis configuration is performed by option "KeyIn Analyses", "Transient" type, and using "Time" with the duration of 3,000,000 seconds. Permanent flow analysis should be selected in "Parent" option, with "Initial PWP" as "Parent Analysis". The upstream boundary condition is maintained as Head (H), but defined by "Spline Data Point Function", where in 1 second head elevation is 65 meters and in 300.000.000 seconds is 20 m.

B. Stability Analysis

Using SLOPE/W, boundary conditions were defined in "Grid and Radius" option by determining a 15x15 grid of rupture circles centers and 15 radiuses along the embankment. Moreover, pore pressure initial condition was imported from SEEP/W.

Shell's material parameters for analysis in SLOPE/W are presented in Table I.

TABLE I
PARAMETERS USED IN SLOPE/W

Cohesion	80	kPa
Fiction Angle	10	°
Unit Weight of Soil	18	kN/m³

The result of slope stability analysis is shown in Fig. 6. The isolines were defined with a 0.1 increment. In this case, the minimum safety factor suggested by [1] is achieved (SF = 1.1).

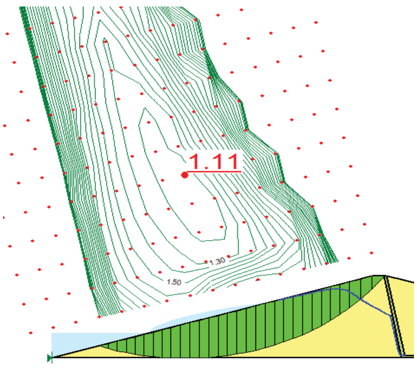

Fig. 6 Safety factor for rapid drawndown condition

The configuration analysis on the software is performed in "KeyIn Analyses", "Morgenstern-Price" type. Transient flow analysis should be selected in "Parent" option, with "Initial PWP" as "Parent Analysis". In "Slip Surface" tab, the movement direction is from right to left using "Grid and Radius" option.

V. CONCLUSION

A realistic and appropriate simulation of a rapid drawdown depends not only on correct use of the software, but also it mainly depends on the correct use of parameters. Thereby, this paper contributes explaining the proper way to obtain and use the data. It is noteworthy that the analyzed dam conceives an illustratively configuration, using parameters in a simple and representative way. Although is not the focus of this research, it is worth emphasizing that instrumentation program is essential in order to do retro analyses and to maintain safe dam operation.

ACKNOWLEDGMENT

The authors would like to thank FAP-DF for the financial support, provided as grants to present the paper at the conference.

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