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Numerical analysis of rapid drawdown: Applications in real cases

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Abstract

In this study, rapid drawdown scenarios were analyzed by means of numerical examples as well as modeling of real cases with in situ measurements. The aim of the study was to evaluate different approaches available for calculating pore water pressure distributions during and after a drawdown. To do that, a single slope subjected to a drawdown was first analyzed under different calculation alternatives, and numerical results were discussed. Simple methods, such as undrained analysis and pure flow analysis, implicitly assuming a rigid soil skeleton, lead to significant errors in pore water pressure distributions when compared with coupled flow-deformation analysis. A similar analysis was performed for the upstream slope of the Glen Shira Dam, Scotland, and numerical results were compared with field measurements during a controlled drawdown. Field records indicate that classical undrained calculations are conservative but unrealistic. Then, a recent case of a major landslide triggered by a rapid drawdown in a reservoir was interpreted. A key aspect of the case was the correct characterization of permeability of a representative soil profile. This was achieved by combining laboratory test results and a back analysis of pore water pressure time records during a period of reservoir water level fluctuations. The results highlight the difficulty of predicting whether the pore water pressure is overestimated or underestimated when using simplified approaches, and it is concluded that predicting the pore water pressure distribution in a slope after a rapid drawdown requires a coupled flow-deformation analysis in saturated and unsaturated porous media.

Keywords: Hydro-mechanical coupling; Coupled flow-deformation analysis; Numerical analysis; Drawdown; Landslide; Pore water pressure

1. Introduction

Drawdown may be a critical factor in the stability of slopes that are initially partially or totally submerged. The reduction of water level has two effects: reduction of the stabilizing external hydrostatic pressure due to the unloading effect of removing water, and modification of the internal pore water pressure. It is well known that if the drawdown velocity is too high, a delay is produced in the dissipation of pore water pressures inside the slope, and the remaining excess pore water pressures may induce a slope failure. The effects of water drawdown on the stability of slopes and dams have been reported from different perspectives based on laboratory tests (Yan et al., 2010; Wang et al., 2012), numerical analyses (Viratjandr and Michalowski, 2006), and limit analyses (Gao et al., 2014). Previous research includes evaluation of the effect of the hydraulic properties through solution of the uncoupled-flow problem (Song et al., 2015), investigation of the influence of drawdown on slope stability using a flow program for calculation of transient seepage and a coupled program for deformation and stability analysis (Berilgen, 2007), presentation of coupled flow-deformation analysis (Brinkgreve et al., 2015), and analysis of real cases (Zhang et al., 2010; Li et al., 2010). In addition, examples of drawdown-induced failures can be found in Sherard et al. (1963) and Lawrence Von Thun (1985).

The estimation of pore water pressure distributions due to a drawdown is therefore an important factor in analysis of the slope stability. Historically, two approaches to predicting the pore water pressure regime after a drawdown have been

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developed: undrained analysis and the flow method. The first has been applied to the case of relatively impervious soil slopes, in which pore water pressures do not dissipate during drawdown events. Therefore, only the effect of the change in the total stress against the slopes is incorporated in the calculation. Early descriptions of this approach were published by Skempton (1954) and Morgenstern (1963), and more recent descriptions have been published by Lane and Griffiths (2000) and Vandenberge (2014). The second approach involves the calculation of drawdown-induced pore water pressures by means of solving the flow problem caused by a change in hydraulic boundary conditions. This method implicitly assumes that the soil skeleton is rigid. Therefore, it does not consider any modification of the initial pore water pressure induced by the change in the total boundary stress. In addition, as long as no mechanical equations are solved in this approach, no effects of soil deformation during drainage are included. Methods developed to handle this problem include flow net analysis (Reinius, 1955; Cedergren, 1967); methods based on an ad hoc hypothesis (typically Dupuit-type assumptions) (Brahma and Harr, 1962; Stephenson, 1978); finite element analysis of flow in saturated soil, which requires calculation of the position of the free surface (Desai, 1977; Cividini and Gioda, 1984); and finite element analysis of saturated and unsaturated flow (Neumann, 1973; Pauls et al., 1999).

In practice, neither of these approaches can reliably approximate the situation in the field, because natural and compacted soils do not behave in a rigid or undrained manner. A coupled flow-deformation analysis should be used to obtain a drawdown-induced pore water pressure distribution. A general formulation has been applied in this analysis, including equilibrium equations and balance equations of fluid and gas, to solve the drawdown problem in a coupled way. However, when only the flow problem is solved, but the mechanical equations are not considered, we refer to this case as uncoupled analysis, in which soil is assumed to be rigid. The undrained case is solved by means of the fully coupled formulation without allowing water flow.

The drawdown in a single slope is discussed first in this paper, to highlight the convenience of using a coupled flow-deformation approach. Then, a controlled drawdown event carried out at the Glen Shira Dam, Scotland, is presented. This case allows the validation of the computational results through comparison with field measurements. Finally, the paper also describes an incipient landslide located in the left margin of the Canelles Reservoir. The landslide was triggered by a reservoir drawdown. A hydro-mechanical analysis of a representative cross-section consistent with the available data is presented.

All the analyses presented were conducted with the finite element program Code_Bright. A theoretical description of this code is given in Olivella et al. (1996). The code was developed based on the finite element method for analysis of thermo-hydro-mechanical problems in geological media. The code deals with the deformable porous media as a mixture of three phases (solid, liquid, and gas). Solid corresponds to minerals, and liquid and gas correspond to water and dry air filling the pores, respectively. The theoretical approach consists of a set of governing equations, including a momentum balance equation, a mass balance equation, and constitutive laws. The latter describe thermal and hydraulic convective and advective flows, density changes of the components due to changes in stress and temperature, capillarity pressure evolution, and the constitutive mechanical response of the porous media. Several constitutive models are currently implemented. In this study, two models were used to simulate the soil response. A linear elastic model that requires two parameters (Young's modulus and Poisson's ratio) was selected as a simple model to analyze the effect of the mechanical response on the pore water pressure evolution in slopes subjected to a drawdown. A more complex constitutive model was used when evaluating the effect of the elastoplastic behavior observed in soils. The Barcelona basic model (BBM) presented by Alonso et al. (1990) was selected as a proper constitutive model for simulating the soil response in saturation and unsaturation conditions. It is a critical state model defined in terms of the net stress (the total stress in excess of the air pressure) and suction (the difference between the pore water pressure and air pressure), which can simulate the dependence of the stiffness and strength on suction and collapse (the soil deformation at a constant stress due to the reduction in suction).

2. Drawdown-induced pore water pressure in simple slope

Fig. 1 shows the geometry of a single slope analyzed in this section. The slope, initially fully submerged, experiences a drawdown of the water level (50 m). The figure also indicates the positions of two singular points P_A and P_B, discussed below.

An elastic constitutive law was used to characterize the soil. Concerning the hydraulic description, the retention curve was defined by means of the Van Genuchten (1980) model. In the model, the parameters P_0 and Λ control the air entry value and the shape of the retention curve, respectively, and had assigned values of $P_0 = 0.30$ MPa and $\Lambda = 0.33$ in this study. The maximum and minimum degrees of saturation S_{rmax} and S_{rmin} were assumed to be $S_{rmax} = 1$ and $S_{rmin} = 0$, respectively. The relative permeability (k_{rel}) varied with the degree of saturation (S_r), following a cubic law ($k_{rel} = k_{sat}S_r^3$). A constant saturated permeability, k_{sat}, with the value of 10^{-10} m/s, was used in all the calculations. This is a low value, typical of an impervious material in engineering applications.

The pore water pressure in the initial state was considered to be hydrostatic, determined by the maximum water level at the top of the slope. The case of an instantaneous drawdown was

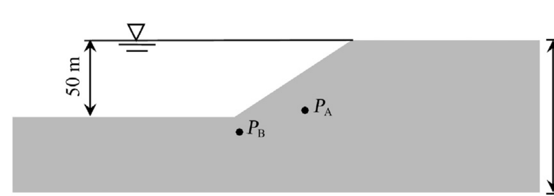

Fig. 1. Geometry of slope.