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Full Length Article

Evaluation of behaviors of earth and rockfill dams during construction and initial impounding using instrumentation data and numerical modeling

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ABSTRACT

In this study, the behavior of Gavoshan dam was evaluated during construction and the first impounding. A two-dimensional (2D) numerical analysis was conducted based on a finite difference method on the largest cross-section of the dam using the results of instrument measurements and back analysis. These evaluations will be completed in the case that back analysis is carried out in order to control the degree of the accuracy and the level of confidence of the measured behavior since each of the measurements could be controlled by comparing it to the result obtained from the numerical model. Following that, by comparing the results of the numerical analysis with the measured values, it is indicated that there is a proper consistency between these two values. Moreover, it was observed that the dam performance was suitable regarding the induced pore water pressure, the pore water pressure ratio r_u, settlement, induced stresses, arching degree, and hydraulic fracturing probability during the construction and initial impounding periods. The results demonstrated that the maximum settlement of the core was 238 cm at the end of construction. In the following 6 years after construction (initial impounding and exploitation period), the accumulative settlement of the dam was 270 cm. It is clear that 88% of the total settlement of the dam took place during dam construction. The reason is that the clay core was smashed in the wet side, i.e. the optimum moisture content. Whereas the average curving ratio was 0.64 during dam construction; at the end of the initial impounding, the maximum amount of curving ratio in the upstream was 0.81, and the minimum (critical) amount in the downstream was 0.52. It was also concluded that this dam is safe in comparison with the behaviors of other similar dams in the world.

1. Introduction

Engineering and economical investigations in dam construction projects throughout the world indicate that, in many cases, rockfill dams with impervious clay cores are the best selection for the final design (Rezaei and Salehi, 2011). This approach makes the investigation of different issues affecting the stability of rockfill dams worthwhile. In the field of earth and rockfill dams, monitoring of typical physico-mechanical behaviors is a fundamental issue. Measurements of displacements, total stresses, pore water pressures, and arching ratio can be used to carry out a number of tasks (ICOLD, 1982), such as characterizing the dam's overall behavior (Pagano et al., 1998), checking the behavior of specific zones, obtaining information about the in situ mechanical properties of embankment soils (Marsal and Resendiz, 1975), and finally, supporting the difficult task of evaluating dam safety and efficiency (Gould and Lacy, 1993).

Duncan (1996) and Kovacevic et al. (1994) are the main contributors to the state of the art in finite element analyses of embankment deformation behaviors, mainly for zoned earth and rockfill dams. They discussed the analysis methods and their limitations, available constitutive models of stress–strain relationship, and areas of uncertainty. As Duncan (1996) pointed out, most analyses from the literature are of Class C1 according to Lambe (1973), which may account for the generally good agreement between predicted and observed deformation behaviors.

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An important component of embankment dam modeling is the consideration of collapse settlement of susceptible rockfills and earthfills on wetting. The collapse settlement most affects the initial impounding for the upstream dam abutment, but the collapse settlement has also been observed in the downstream dam abutment following wetting due to rainfall, leakage or tail-water impoundment. Incorporating collapse settlement into constitutive models adds further complexity and greater uncertainty in the estimation of material parameters in laboratory and field conditions due to the dependency of collapse settlement on compacted water content, compacted density, applied stress and material properties. Justo (1991) and Naylor (1997) proposed methods for incorporation of collapse settlement of rockfill into constitutive models. Naylor (1991) performed the finite element analysis for Beliche dam, a central core earth and rockfill dam, by considering the collapse settlement of the upstream rockfill in the modeling.

The effect of pore water pressure dissipation in earthfill during construction was also considered by a number of authors including Eisenstein and Law (1977) and Cavounidis and Hoeg (1977), amongst others. For these cases, the incremental embankment construction was modeled as a two-stage process, the first stage modeling the new layer construction using undrained properties for the core and the second stage modeling pore water pressure dissipation. In most cases, pore water pressure development in the core is ignored. For wet placed earthfill, where high pore water pressures are developed during construction, the core is often modeled using undrained strength and compressibility parameters, and the permeability is assumed as sufficiently low such that pore water pressures will not dissipate during the period of construction.

Zhou et al. (2011) assessed the settlement behavior of Shuibuya dam during construction, initial impounding, and two years after operation. They carried out two-dimensional (2D) numerical analyses using finite element method (FEM), and compared the results with the data measured by the instruments in terms of settlements. In addition, back analysis was performed by utilizing hybrid generic algorithms (HGAs). The results represented this technique as a successful one for controlling the dam deformation. Furthermore, the results demonstrated that the settlement increased apparently after the initial impounding, but the rate of settlement decreased and tended to stabilize over time.

Mahin Roosta and Alizadeh (2012) assessed the nonlinear behavior of rockfill material using numerical analyses and laboratory tests. To estimate the collapse settlement phenomena in the rockfill dam during inundation, strain-hardening and strain-softening models in the fast Lagrangian analysis of continua (FLAC) software (Itasca, 2002) were modified based on the data obtained from laboratory tests. The results helped dam engineers to better predict the nonlinear behavior and collapse settlements in the upstream shell. In addition, the effect of impounding process on the overall stability of a high dam was considered by Luo et al. (2015). The dam behavior predicted using the three-dimensional (3D) numerical modeling is in good agreement with field measurement in terms of stress and strain distribution characteristics in the dam and foundation, especially when the feedback parameters were adopted for numerical analysis.

As can be seen, previous researches did not consider all parameters in rockfill dams such as settlement, pore water pressure, vertical stress, and arching ratio during the periods of construction and initial impounding in a comprehensive study. This paper presents the evaluation of these parameters in an earth and rockfill dam in stages of dam construction and operation using instrumentation data and numerical modeling. It first introduces the Gavoshan rockfill dam, then reviews the results of settlement, pore water pressure, vertical stress, and arching ratio during construction and the first impounding. Finally, these results are compared with the monitored ones.

2. Main feature of Gavoshan dam

Gavoshan dam is 123 m high, the length of the crest is 650 m and the volume of the container is approximately 550×10^6 m^3 (Mahab Ghodss Engineering Consulting Co., 2009). The dam is a rockfill dam with a clay core and is located in Kurdistan Province, Iran. The purpose of building the Gavoshan dam was to harness Gaveh Rood River and to supply water to irrigate approximately 31,000 ha of downstream lands and also to provide 63×10^6 m^3 of drinking water and 11 MW of electrical energy to Kermanshah Town. To make clear the dam's behavior, accurate instruments were installed in five sections, including piezometers, measurement cells for total soil mass pressure, settlement meters and inclinometers, as shown in Fig. 1. Taking into account the foundation type, the height of the earthfill and the depth of the valley, the profile located at 0 + 365 km was considered as the most critical cross-section of the Gavoshan dam regarding the accumulation of pore water pressure, the maximum settlement and tolerance, as presented in Fig. 2. In rockfill dams, the most critical section regarding stability is always the highest section assuming that other conditions are similar in all points. Also most of the stresses, displacements and pore water pressures usually take place in this section. Since there are a number of sections in Gavoshan dam where instruments are set up, it is impossible to analyze all these sections within the limited duration of the present research, only the stress–strain behavior on critical sections is analyzed. Clearly, if the behavior of the dam in critical sections is understood accurately, this behavior could be generalized to all sections of the dam.

The construction of Gavoshan rockfill dam started in October 2000 (Fig. 3). Till 19 June 2004, 115 m of the dam was constructed and the initial impounding had begun. Four months after the initial impounding, on 22 October 2004, the construction was completed. Considering raining seasons in Kurdistan area and also the fact that the central core of the dam body could not be constructed in all seasons, only the 6 months between May and October in each year are suitable for earthfilling with clay materials. Also, considering the high volume of shell materials in the upstream and downstream central cores and the fact that it is impossible to simultaneously execute the construction of the central core and the shell, a part of the upstream and downstream shell is not constructed at the same time with the core, and in the seasons in which the earthfilling of central core is stopped, the construction of the remaining shell is executed.

3. Material properties and numerical modeling

Gavoshan dam was modeled using FLAC software, based on the finite difference method. Mohr-Coulomb elastoplastic model was used for the earthfill, filters and core. As the well-known failure model in soil mechanics, the model states that failure occurs when the shear stress τ and the effective normal stress σ' acting on any element in the material satisfy the following linear equation:

$$|\tau| = c + \sigma' \tan\phi \tag{1}$$

where c and ϕ are the cohesion and the internal friction angle, respectively. In terms of the principal effective stresses, the Coulomb's yield criterion can be expressed by the following equations:

$$\left.\begin{array}{l} f_{13} = (\sigma'_1 - \sigma'_3)/2 - (\sigma'_1 + \sigma'_3)\sin\phi/2 - c\cos\phi = 0 \\ f_{12} = (\sigma'_1 - \sigma'_2)/2 - (\sigma'_1 + \sigma'_2)\sin\phi/2 - c\cos\phi = 0 \\ \sigma'_1 \ge \sigma'_2 = \sigma'_3 \quad \text{(triaxial compression)} \end{array}\right\} \tag{2}$$