NUMERICAL MODELING OF EARTHEN DAM: VALIDATION WITH FIELD DATA  
(ICID2018_C_012)

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ABSTRACT

Proper design, construction, and monitoring of actual behaviour of earthen dams during their construction and operation depends on its stability and the factor of safety under several possible destabilizing conditions. Monitoring the generation of pore water pressure in earthen dams during different operations (end of construction, reservoir filling, steady state condition and reservoir drawdown) gives information on the behaviour of the structure and its interaction with the foundation. Field or laboratory prototype monitoring results can be used in validating the finite element models developed to perform the numerical analysis. The accuracy of the finite element models which are used to simulate the real field scenarios becomes acceptable when the data obtained from these models agrees reasonably well with the monitored data. The main objective of the paper is to validate a numerical model of earthen dam, developed in GeoStudio, and to explore the accuracy of numerically simulated water pressure magnitudes by comparing the same with the monitored data. To meet this objective, a finite element analysis of the Glen Shira Dam, Scotland was performed considering a drawdown condition, and the results from the numerical results were compared with the field measurements. The monitored data and the data obtained from the model agrees reasonably well, thus indicating further usage of the model to simulate other destabilizing scenarios.

Keywords: Earthen dams, Drawdown, Finite Element Analysis, Monitored Data

1 INTRODUCTION

The evolution of Finite Element Method (FEM) from a research tool into a daily engineering tool has resulted in its immense application for the analysis of geotechnical engineering problems. Its ability to tackle complex real field situations has placed it next to conventional design methods. However, with many advantages provided by the usage of FEM, like every other method, it also suffers from some limitations. These limitations can lead to unrealistic results and many a times these limitations go unrecognized by the users. Insipite of the development of easy-to-use finite element programs, creating a good model that can capture all the uncertainties and complexities associated with the real field problem is not an easy task. Predicting accurate and realistic design quantities (i.e. pore pressures, structural forces, bearing capacity, safety factor, displacements, stresses, drainage capacity, pumping capacity, etc.) is difficult. These limitations are more likely to get pronounced in geotechnical applications as the highly non-linear and heterogeneous behaviour of the soil material makes it difficult for the numerical models to capture its character accurately.

The choice of the constitutive model (stress-strain relationship) plays a vital role as these constitutive models which are developed in a continuum, are used to model soil behavior in finite element method (FEM). On the other hand, the corresponding set of model parameters used in modeling should also be considered carefully when creating a finite element model for a geotechnical project. The model, no matter how complex, will always be a simplified representation of the actual soil behaviour that forms one of the main limitations in the numerical modeling process. Hence, some or the other features of soil behaviour will not be captured by the model. Therefore, validation of the numerical models with the actual field scenario becomes essential.

Validation confirms the accuracy with which the model captures the reality. The correctness and acceptability of the numerical model, once established with proper validation, makes it more reliable to be used in different design process. In this paper, a numerical model simulating the drawdown condition in the reservoir of an earthen dam was validated with real field condition.

Drawdown becomes a critical factor to assess the stability of slopes that are initially submerged, either partially or wholly. During drawdown, there is removal of reservoir water that results in an unloading effect, leading to the reduction of the stabilizing external hydrostatic pressure, which leads to the modification of the internal pore water pressure as well. The dissipation of pore water pressure is very much dependent on the rate of drawdown. If the drawdown rate is high (rapid drawdown), a noticeable delay occurs in the dissipation of pore water pressures within the slope, and the remaining excess pore water pressures may induce a slope failure on the side of the reservoir. There are studies which have reported the effects of water drawdown on the
slope stability and dams 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). Solution of the uncoupled-flow problem to evaluate the effect of hydraulic properties have been studied in previous researches (Song et al., 2015). There are investigations which are carried out to calculate transient seepage induced by the influence of drawdown on slope stability using a flow program, whereas, a coupled program has been used for deformation and stability analysis (Berilgen, 2007). Coupled flow-deformation analysis examples (Brinkgreve et al., 2015), and examples of real field case studies are available in literature (Zhang et al., 2010; Li et al., 2010). Sherard et al. (1963) and Lawrence von Thun (1985) have studied different drawdown induced failure cases which indicates the importance of water pressure measurements during the drawdown condition. Therefore, in slope stability analysis the estimation of pore water pressure induced due to drawdown becomes very important.

Thus, the main objective of the paper is to validate a numerical model which is used to simulate reservoir drawdown condition in an earthen dam, developed in GeoStudio, and to ascertain the accuracy of numerically simulated water pressure magnitudes by comparing it with the field monitored data. To meet this objective, a finite element analysis of a drawdown condition of the Glen Shira Dam, Scotland was performed, and the results from the numerical analyses were compared with the field measurements. This validation helps in determining the correctness of the numerical models developed in GeoStudio which can further be used to predict different entities.

2 MODE FOR THE STUDY

The model used in the present study is the Glen Shira Dam which has an embankment height of 16 m and has a thin reinforced concrete wall at the center. Compacted well-graded non-plastic moraines mainly forms the embankment. The compacted moraines on the upstream slope is covered by a rockfill shell to increase the stability of the upstream shoulder.

Figure 1. Model for the present study

Paton and Semple (1961) gives a detailed description of the dam and its materials. The cross-section of the Glen Shira Dam is shown in Figure 1. The embankment has a crest width of 3 m and it has a free board of 1 m. The foundation height and width are chosen to be 10 m and 108 m, respectively. The upstream and downstream slope inclinations have been shown in Figure 1.

2.1 Material properties

In numerical modeling, the correct assignment of the material models with proper input parameters plays an important role. In this validation study, Seep/w and Sigma/w modules of Geostudio have been used. In Seep/w analysis, the embankment has been modeled using ‘saturated/ unsaturated’ material model, while the foundation has been modeled using ‘saturated only’ material model. In Sigma/w, the ‘elastic-plastic material’ model has been used to perform the analysis. The embankment materials having modeled using ‘saturated/ unsaturated’ material model requires the assignment of the hydraulic conductivity function and the volumetric water content function for the analysis. These functions for the different embankment materials have been shown in Figure 2(a) and Figure 2(b).

Figure 2(a). Hydraulic conductivity function

Figure 2(b). Volumetric water content function
The various soil properties used in the modeling have been obtained from literature (Alonso and Pinyol 2016; Paton and Semple 1981; USBR 2014; Seep/w 2012; Sigma/w 2012), coupled with proper engineering judgment. The different material properties: cohesion (c), angle of internal friction (ϕ), unit weight of the materials (γ), modulus of elasticity (E_{modulus}) and permeability (k) used in the analysis have been listed in Table 1.

Table 1: Material properties used in simulation

<table>
<thead>
<tr>
<th></th>
<th>c (kPa)</th>
<th>ϕ (°)</th>
<th>γ (kN/m^3)</th>
<th>E_{modulus} (kPa)</th>
<th>k (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morainic fill</td>
<td>15</td>
<td>25</td>
<td>18</td>
<td>5000</td>
<td>8.64 x 10^{-5}</td>
</tr>
<tr>
<td>Graded filter</td>
<td>0</td>
<td>25</td>
<td>16</td>
<td>10000</td>
<td>8640</td>
</tr>
<tr>
<td>Concrete core wall</td>
<td>12</td>
<td>20</td>
<td>18</td>
<td>25000</td>
<td>8.64 x 10^{-3}</td>
</tr>
<tr>
<td>Rockfill</td>
<td>0</td>
<td>30</td>
<td>16</td>
<td>15000</td>
<td>86.4</td>
</tr>
<tr>
<td>Foundation</td>
<td>12</td>
<td>18</td>
<td>20</td>
<td>30</td>
<td>8.64 x 10^{-11}</td>
</tr>
</tbody>
</table>

2.2 Analyses methodology

The main objective of this work was to ascertain the accuracy of the numerically simulated water pressures generated during a reservoir drawdown condition in the Glen Shira dam. The results obtained from Geostudio were validated with field-monitored data, as well as compared to the results obtained with the aid of another finite element program termed Code_Bright. The data used for comparison were obtained from Alonso and Pinyol, 2016. The field data was monitored at five different points as shown in Figure 1 with the help of the piezometers (Alonso and Pinyol, 2016). Barcelona basic model (BBM) was adopted as a suitable constitutive model in Code_Bright finite element program, which can simulate the effect of the elasto-plastic behavior of soils during saturated and unsaturated conditions (Alonso and Pinyol 2016).

The present numerical study has been conducted with the aid of Seep/w and Sigma/w modules of Geostudio. The modeling of the Glen Shira dam construction was conducted in simple steps. In Geostudio, at first, the dam model was simulated for initial ‘steady state seepage analysis’, in Seep/w, to establish the existing pore water pressures and total head conditions. The initial stress conditions were generated using the ‘in-situ analysis’ of Sigma/w. The drawdown of the reservoir has been simulated using the ‘Coupled Stress/PWP analysis’ in Sigma/w, in which the pore water pressure generated in the steady state analysis and stresses generated in the in-situ analysis were used to define the initial conditions for the transient state. The rate of reservoir drawdown is a function of total head with time, as shown in Figure 3, and the same has been assigned as a boundary condition along the upstream side of the dam. Results obtained from the analyses have been compared with the existing field and numerical data to check if the numerical model developed in Geostudio is accurate or not. A detailed analysis of the results obtained from the simulations along with the discussions is provided in the subsequent section.

3 RESULTS AND DISCUSSIONS

The variation of total head with time that has been obtained from the numerical simulations performed in Geostudio have been compared with the measured values obtained from the five different piezometer readings as shown from Figure 4 to Figure 8. The results from the finite element program, Code_Bright, has also been plotted in the figures to get a better understanding of the nature of the variation of total head with respect to time during reservoir drawdown condition. The drawdown history of the reservoir level has also been indicated in the figures.

Figure 3. Reservoir drawdown condition

Figure 4. Measured and calculated water pressures in Piezometer 1
The figures give a detailed comparison between the simulated values of water pressures along with the corresponding measured values of the water pressures from the five piezometers. It has been observed that water pressures values obtained from the numerical model simulated using coupled flow/deformation analysis in Geostudio agrees reasonably well with the measured values from the field as well as with the calculated values obtained from Code_Bright (simulated using a coupled flow-elastic deformation analysis for saturated/unsaturated conditions). The pattern of recorded water pressures is well captured by the numerical model. Consideration of certain field heterogeneity in permeability and/or soil stiffness is probably required for a better agreement between the measurements and calculations.

An attempt has been made to plot the total head contours obtained from Geostudio and to compare the same with the computed results from Code_Bright (Alonso and Pinyol, 2016) and with the interpolated values putted by Paton and Semple (1961). The distribution of total head contours inside the shell for a drawdown from 14 m to 5.2 m have been shown from Figure 9 (a) to Figure 9 (c).
plotted by Paton and Semple, 1961 (c) computed results from Geostudio.

The total head contour values and distribution obtained from Geostudio gives very similar nature when compared with the computed and interpolated values.

4 CONCLUSIONS

A well-documented case history (Shira Dam) was analyzed using Geostudio to provide insight into the accuracy of the numerical model in simulating drawdown problem. Soil (a compacted moraine) with intermediate permeability between impervious clays and free draining granular materials has been used as the dam material for this study. It should be added that materials with this intermediate permeability are very common in dam engineering. The fully coupled flow/deformation analysis has been used to simulate this problem. The results from the analysis have been compared with the calculated values obtained from Code.Brightand with the measured values from the field. The comparison shows a reasonably good agreement of the water pressure values obtained from Geostudio along with the field-measured values and calculated values from the finite element program. Thus, it indicated that the numerical model simulated in Geostudio is capable of capturing the drawdown scenario accurately to a significant extent and it can further be used to simulate other destabilizing scenarios.

5 REFERENCES


