A comparison between monitoring and analysis of Taleghan rockfill dam during construction

Comparaison des donnés de surveillance au cours de la construction et les résultats de l'analyse du barrage en enrochement de Taléghan

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ABSTRACT

The construction of 103 m high Taleghan rockfill dam in Iran has recently been completed and reservoir impounding has also recently been started. The behavior of different sections of the dam have been monitored during construction using various devices such as settlement gauges, earth pressure cells and pore pressure piezometers. A comprehensive finite element study has been implemented in this regard as well to study the behavior of Taleghan rockfill dam during construction with consideration of unsaturated behavior of the materials of the dam. A 2D coupled analysis was performed using ABAQUS software. The behavior of the materials of the core and rockfill were assumed to follow Modified Drucker-Prager/Cap and Modified Drucker-Prager respectively. Shear and volumetric plastic strains and stresses, displacements and pore pressure in different parts of the dam obtained from the analysis are compared with the stresses, displacements and pore pressures measured by monitoring devices. Two important aspects of the geomechanical behavior of the dam during construction namely arching effect and pore pressure ratio (r_u) both theoretically using FE analysis and experimentally using measured values are addressed in this paper as well.

The results of the comparison show that a good agreement between analyses and observational data is present using unsaturated and double surface plasticity soil model. However, the outcome of the comparison shows that elastic and single surface elasto-plastic models are not able to well predict the behavior of the core of earth and rockfill dams during construction. The "arching effect" is also observed in clay core of the dam based on both numerical analysis and the measurements of earth pressure cells installed and monitored in the core of the dam.

RÉSUMÉ

La construction du barrage en enrochement de Talégan en Iran, haute de 103m, a été achevée récemment et sa mise en eau vient d'être commencée. Le comportement de différentes parties du barrage, pendant sa construction, a été surveillé au moyen des appareils de mesurés telles que les gages de tassement, les cellules de pression totale et les piézomètres. Il a été étudié également avec la méthode des éléments finis basé sur le comportement non-saturé du sol de noyau du barrage. Un modèle couplé, à deux dimensions, a été utilisé avec le programme ABAQUS. Le comportement des matériaux du noyau en argile et du remblais en roche ont été supposés d'obéir respectivement aux critères de Drucker-Prager/Cap et Drucker-Prager Modifié .Les contraintes et déformations plastiques de cisaillement et volumiques obtenues par l'analyses numériques sont comparées aux résultats des mesures .Le présent article se concentre sur deux spécificités géo-mécaniques ,à savoir l'effet de vouté et le rapport de la pression intersticielle, (ru).

Cette étude démontre une concordance satisfaisante entre les résultats de mesures et ceux des analyses. Elle montre aussi que contrairement au model de plasticité à double surfaces, les modèles élasto-plastiques à surface unique ne sont pas capables de prévoir correctement la réponse du noyau des barrages en terre et en enrochement au cours de leur construction. L'affect de voute se manifeste aussi bien dans l'étude expérimentale que dans les analyses numériques.

Keywords : Rockfill dam, construction, modeling, monitoring, analysis

1 INTRODUCTION

There are a number of points that should be looked at during the construction period of earth and rockfill dams. One is the "arching" effect in the core of these dams. Arching across the core of zoned embankments has important implications on the deformational behavior of the core during construction as well as on the potential for hydraulic fracturing during impounding of the reservoir. Arching in zoned embankments with narrow cores may develop due not only to the compressibility of the core with respect to the supporting shoulders, but also to the lateral stress transfer from the core to the abutments. Bishop (1952), for undrained conditions in peddled core dams, and Nonveiller and Anagnosti (1961), for fully drained conditions in zoned embankments, have developed some methods for assessment of arching in embankments with narrow cores. The progress in finite element analysis and improvements in constitutive models for more accurate modeling of the stress-strain behavior of the materials of earth and rockfill dams allow for more realistic assessment of arching in zoned embankments, as shown by Dounias et al. (1996), Naylor et al. (1997) and Haeri and Faghihi (2008).

In addition to "Arching", the amount of pore pressure build up in the clay core of earth and rockfill dams due to the construction process can be critical in terms of embankment stability. Generally, dissipation of this pore pressure in the core takes a long period of time due to the low permeability of the core and the time needed for consolidation of the material. At the time of placement, earthfill materials are partially saturated. However due to the weight of the overburden pressure, the air in the pores is solved in the water and pore water pressure builds

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up. The developed pore water pressure in the core of earth and rockfill dams during construction is dependent on a number of factors including the initial degree of saturation, compressibility and permeability of the material, time of construction, the method and degree of compaction of the earthfill, and applied stress levels.

Ng and Small (1999) for investigating the hydraulic fracturing in Hyttejuvet dam used Saturation-Pore pressure curve to account for the unsaturated behavior of the material of the dam. Gens et al. (1997) by consideration of air pressure and a state surface for the shell studied the pore pressure build up in the core of the El Limonero dam during construction and first impounding processes.

Consideration of the proper modeling of the material with regards to unsaturated behavior can lead to a more precise prediction of generation and dissipation of pore water pressure in the core of earth and rockfill dams. In addition, the type of constitutive models implemented for the material of the core has significant effect on the precise prediction of pore water pressure generation.

2 TALEGHAN DAM (IRAN)

Taleghan dam is a clay core rockfill dam with a maximum height of 103 m and a crest length of 1000 m. Typical cross section and different materials of each zone are shown in Figure1.

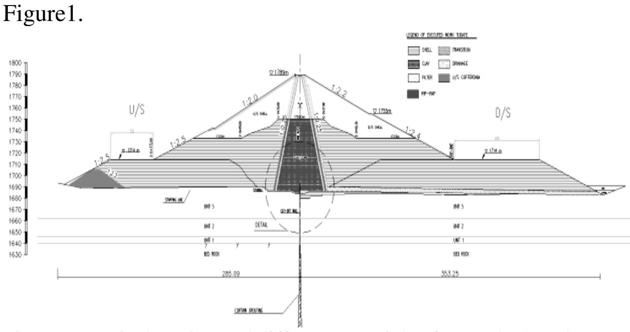


Figure 1. Typical section and different materials of the Taleghan dam.

3 FINITE ELEMENT ANALYSIS OF TALEGHAN DAM IN CONSTRUCTION STAGE:

2D coupled finite element analyses considering unsaturated behavior of the material are performed using ABAQUS software.

The software considers the unsaturated behavior of the dam using “Sorption” curve. This curve represents the absorption and exorption of the water to or from the soil which is the same as soil-water characteristic curve (SWCC) in saturation-suction space. Bilinear displacement and pore pressure element namely CPE4P is used for this analysis. The model consists of 2248 four-nodded isoperimetric continuum elements and each node has four degrees of freedom for displacements and pore pressure.

Construction is modeled in 10 layers with 10 m height (last layer 13 m). The time of construction in the analysis for each step is considered the same as the real time spent for construction based on the measured values from elevation 1690, the foundation level at maximum cross section of the dam. Figure 2 shows the construction sequences of the dam with time.

It can be inferred from this figure that after the height of the dam is reached to 60 m the construction is halted for 6 months during construction. Also, the first impounding of the dam started 2 months after the completion of the dam construction as shown in Figure 2.

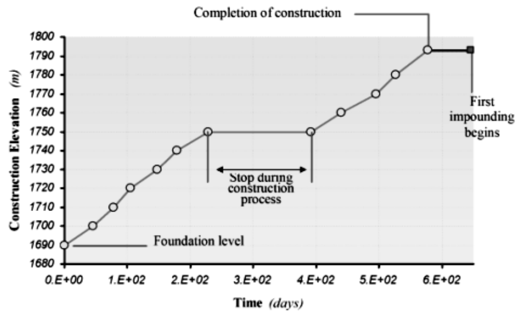


Figure 2. Variation of the height of Taleghan Dam with time during construction (beginning of the construction: 2004/4/14)

3.1 *Material properties*

In modeling of the Taleghan dam, a double surface elasto-plastic model (Modified Drucker-Prager/Cap) is used for the core and Unit 2 of the foundation, and single surface elasto-plastic model (Modified Drucker-Prager) is used for coarse grain materials. The parameters of each model derived based on the tests on the material of different parts of the dam.

4 RESULTS OF THE ANALYSIS AND COMPARISON WITH INSTRUMENTS

4.1 *Analysis results using elasto-plastic model*

Figure 3 represents the contours of vertical deformation in the dam. The significant deformation of the core and Unit 2 can be seen in this figure due to compression plastic strain on the cap surface. The maximum settlement of 1.6 m takes place at the midheight of the core.

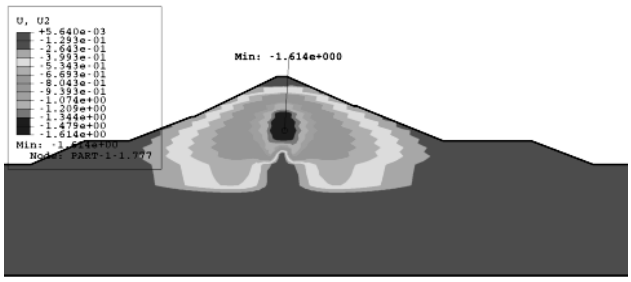


Figure 3. Settlement contours at the end of construction

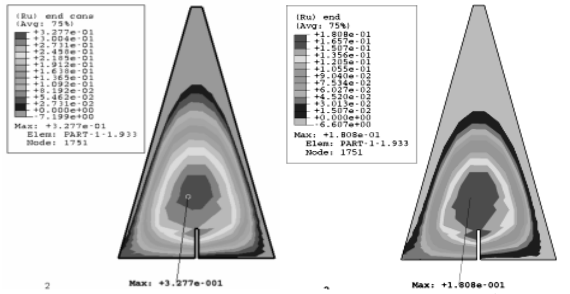
It is convenient to consider the pore water pressures in terms of r_u , the pore water pressure ratio, as defined in Equation (1)

$$r_u = \frac{u}{\sigma_{22}} \quad (1)$$

where r_u = pore water pressure coefficient, u= pore water pressure, σ_{22} =total vertical stress. Contours of (r_u) in the core of Taleghan Dam is shown in Figure 4.

The maximum amount of r_u takes place in the middle of the core and it is 0.3 at the end of construction.

Contours of vertical effective stress in the core at the end of construction are represented in Figure5. Also, the direction of principal stresses at mid height of the dam is shown in this figure. The load transfer and arching effect can be inferred from both pictures.



(a) (b)

Figure 4. Contours of r_u in the core (a) at the end of the construction $(t \approx 577\ day)$; (b) at the beginning of the impounding $(t \approx 647\ day)$ ..

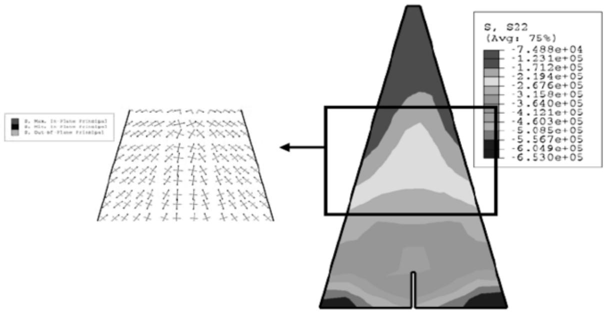


Figure 5. Contours of vertical effective stress in the core and direction of the principal stresses at the end of construction $(t \approx 577\ day)$.

Figure 6 shows the comparison between (γh) and the amount of vertical stress in different elevations of the dam. The arching effect in reducing the vertical stress in the core can be seen in these pictures. Comparing the vertical stresses in the core shows that the maximum load transfer occurs at the mid height of the core (elevation 1750) which is shown in Figure 7.

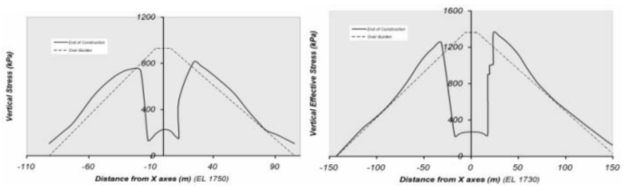


Figure 6. Comparison between the amount of γh and vertical effective stress at the end of construction in different elevations.

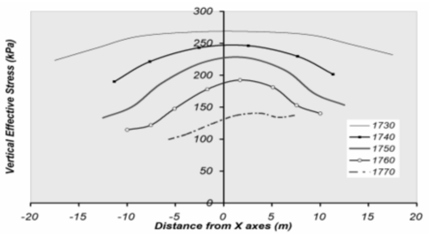


Figure 7. Comparison between the amounts of vertical effective stress in the core at the end of construction in different elevations.

4.2 *Comparison between results of the analyses and the monitoring*

In this section the results of the 2D analysis of Taleghan dam are compared with the outcomes of the instruments installed in the maximum cross section of the dam. The computed pore water pressure in the core, settlement in the shell and core, and the stress in the core are compared with the measured data. The results of the analyses are compared with the measured values from the nearest instrument. Figure 8 shows the configuration of earth pressure cells, piezometers, and deformation monitoring gauges in the dam which are considered for comparison.

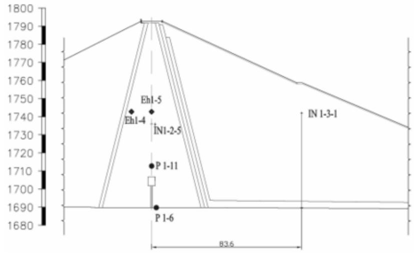
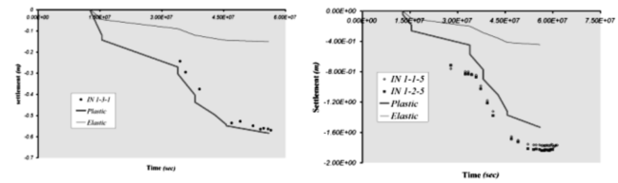


Figure 8. Instrument locations selected for comparison with the analysis.

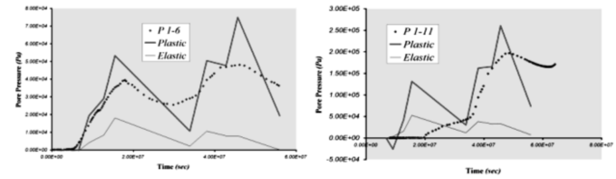
Figure 9(a) represents the measured data at *IN1-1-5* in the core and at elevation 1736 on the axis of the dam and at *IN1-2-5* in the core, 2 m away from the axis of the dam at the same elevation. It can be seen in this figure that the calculated settlement with Cap model compares well with the measured values, however, the elastic (and single surface elaso-plastic) models can not accurately predict the amount of settlement. Time history of settlement at *IN1-3-1* in the shell for elevation 1742, 83.6 m away from the axis of the dam is shown in Figure 9(b). It can be seen from this figure that the result of the analysis using plastic model is in very good agreement with the measured values, however the elastic model gives the results far from the reality.



(a) (b)

Figure 9. Computed and measured settlement (a) in the shell (b) in the core.

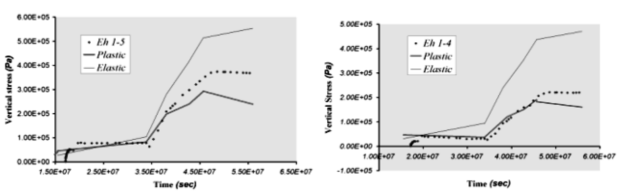
Figure 10 shows the comparison between the pore pressures resulted from the analyses with those measured by piezometer *P1-6* located at elevation 1690, 2.6 m far from the dam axis and piezometer *P1-11* at elevation 1713 on the dam axis. The analysis predicts a very high pore pressure generation before the time lag during the construction process, however, this is not recorded by piezometer *P1-11.* Also a significant pore pressure generation begins after the height of the dam exceeds 60 m during construction period. Apart from these two points, in general, the results of the analysis using Modified Drucker-Prager/Cap compares well with the measured data.



(a) (b)

Figure 10. Computed and measured settlement in the core at piezometers (a) P1-6 (b) P1-11.

The amount of vertical total stress at elevation 1743 in two earth pressure cells located at dam axis (*Eh 1-5*) and 11.25 m far from the dam axis (*Eh 1-4*) are shown in Figure 11.



(a) (b)

Figure 11. Computed and measured total vertical stress in the core at (a) Eh1-5 (b) Eh1-4.

As indicated in these figures the predicted stresses using elastic model results in much higher values when they are compared with those measured by instruments. However, the results of the analysis using double surface elasto-plastic model are in good agreement with the measured data. Figure 12 shows the total stress in the section of the core at the height of 55 m from the foundation level (elevation 1745) resulted from the elastic and elasto-plastic analysis. Also the measured data in the core at maximum cross section and elevation 1743 is represented in this figure. It can be seen that the total earth pressures resulted from the analyses and instruments are much less than the amount of γh at the same height. This fact illustrates how the load transfers from the core to the shell.

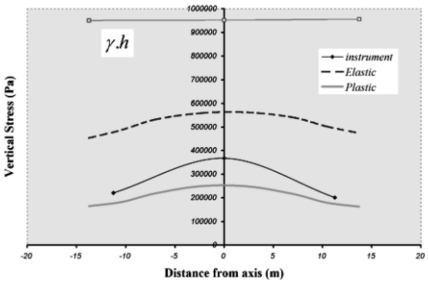


Figure 12. Computed and measured total vertical stress and the amount of γh in the core at El. 1743 and El. 1745.

5 CONCLUSIONS

In this study, the behavior of Taleghan rockfill dam is investigated using finite element method. Coupled unsaturated material model considering double surfaces plasticity is implemented for the analyses of the stage construction of the dam. Results of the analyses indicate that the "Arching effect" occurs in the core as a result of the differential vertical deformation between the core and the shells of the dam . The comparison shows that the maximum load transfer takes place at the mid-height of the core. Also the pore water pressure generation and dissipation in the core, foundation and filters are modeled during construction accounting for the pore pressure dissipation by time.

Comparison of the results of instruments and the analyses indicate that the elastic as well as single surface elasto-plastic models failed to predict the behavior of the core of the rockfill dam during construction. However, the results of analysis using double surface elasto-plastic analysis, in terms of stress, deformation and pore water pressure, compare well with the measured values from monitoring instruments. The comparison also, indicates that the Modified Drucker-Prager/Cap model for the core and the Unit 2 of the foundation that is fine grained, and Modified Drucker-Prager model for coarse grain materials of the dam and foundation can well predict the behavior of the rockfill dam during construction if the material parameters are well defined.

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