3D numerical analyses of behavior of a high rockfill dam with clay core in narrow canyon

Abbas Soroush[1], M. Pourakbar[1], and A. Nabizadeh[2]

[1] Department of Civil Engineering and Environmental Engineering, Amirkabir University of Technology, 424 Hafez Ave, 159163-4311, Iran.
[2] School of Civil Engineering, Iran University of Science and Technology, Narmak, 1684613114, Iran.

ABSTRACT

The behavior of earth dams in narrow valleys, especially in the vicinity of abutments, has been always a matter of concern. Since these dams are high, the consequences of their potential failure are disastrous; therefore, they acquire a great importance. The hydro-mechanical behavior of an earth dam constructed in a narrow canyon is highly affected by three-dimensional geometric effects. Thus, 3D analyses would be necessary for studying the behavior of large earth dams in narrow canyons. This paper presents the results 3D numerical analyses carried out on the Masjed-e-Soleyman rockfill dam. The Hardening Soil Failure Criterion was employed for the materials of the dam body and, effective stress parameters have been used for the soils strength to enable computing pore water pressures in the dam. Then, the results were compared with the corresponding measured values recorded from the dam body. Finally, results for the 2D analyses were employed to show the importance of considering 3D effects.

Keywords: Rockfill dam; 3D analyses; Numerical analyses; Narrow valley

1 INTRODUCTION

Over the past decades, embankment dams have shown to be one of the most common types of the dams that have been constructed and manipulated. The advent of new technologies has enabled to increase the height of these dams from 100 to more than 300 meters. Generally, stresses and deformations are the most significant factors for the safety of a high embankment dam.

An accurate prediction of the behavior of a high rockfill dam during construction and impounding acquires a very high attention, especially when the dam is constructed in narrow valleys. The valley shape is a major factor in this behavior, especially narrow valleys, due to the significant effects of cross-valley arching or reduced vertical stresses. Thus, the valley shape influences all aspects of a dam behavior, including feasibility studies, detailed design, and construction phase (Bui et al, 2002; Chen et al, 2014).

The initiative researches of Nonveiller et al. (1961) showed that arching phenomena (load transferring) not only occurs between the core and shell but also can occur between the dam and abutments in narrow valleys. In another study, Yu et al. (2005) carried out series of parametric studies to investigate three-dimensional effects of the valley on the stability of an earth/rockfill dam by considering some factors, such as geometrical characteristics of the dam and topography of the canyon. They concluded that the length/height ratio of the dam noticeably influences the 3D safety factor.

The main objective of this study is to study thoroughly the behavior of the Masjed-E-Soleyman (MES) rockfill dam during its construction phase. The Hardening Soil Failure Criterion was employed for the numerical analyses, and effective stress parameters have been utilized for the soil's strength to enable computing pore water pressures in the dam. Then, the 3D analyses have been performed to consider the impacts of some factors such as canyon shape, gradient of dam slope and height of the dam, and a comparison between the results of 3D and 2D analyses for MES dam have been presented.

2 MASJED-E-SOLEYMAN DAM

2.1 General Features

The 187 m high MES clay core rockfill dam was constructed between 1996 and 2001, and its impounding commenced in late 2000. The dam, located on the Karun River in Khuzestan province, produces 1500 MW of hydroelectric energy annually. The crest length is 480 m and the reservoir volume is about (228×108). The longitudinal and highest cross section of the dam are shown in Figures 1 and 2, respectively (Pourakbar et al, 2017).

2.2 Dam Body Materials

Core materials (CL+GC) with about 80% fines and 20 % sand-gravel having optimum moisture content of 13.8 % were placed wet of optimum (wopt +2%) and highly compacted (98% relative compaction) in layers of 20 cm final thickness. Quality control tests showed after compaction degree of saturation of the core was in average about 95%. Filters with 5 m width were placed over 50 cm thick layers. Quality control tests reported the relative density of 80% and 94% for filters materials in zones 2A and 2B, respectively (see in Figure 2). The rockfill shell materials are conglomerates extracted from quarries, and sand-stone/clay-stone spoils from foundation and diversion tunnels excavation compacted dry in layers of about 70-100 cm final thickness. The dam foundation materials are considerably stronger and stiffer than embankment materials.

2.3 Instrumentation Results

Four sections of the dam, including Ch160, CH260, CH360 and CH435 as shown in Fig. 1, were instrumented with pressure cells, piezometers, surface settlement marks, settlement gauges and inclinometers. A considerable number of instruments, especially in the upstream slope, were subjected to damage, and therefore, malfunctioned during the impounding. A typical instrumented cross-section for CH260 is presented in Fig. 2.

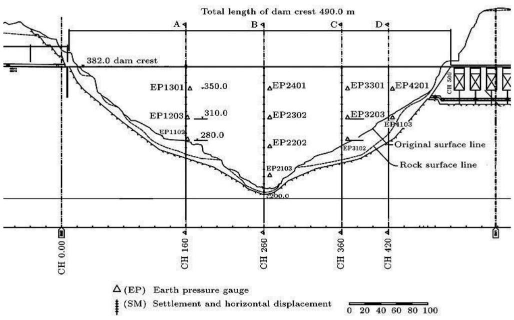


Fig. 1. Central valley cross section of MES rockll dam.

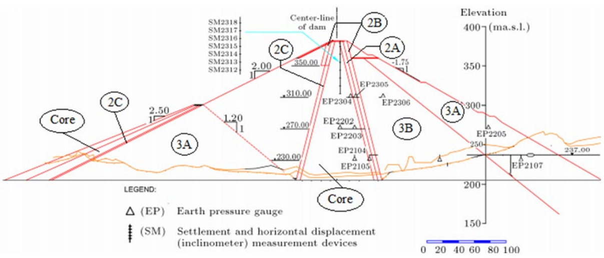


Fig. 2. Highest cross-section of MES dam (CH. 260).

3 THREE DIMENSIONAL ANALYSES

3.1 Modeling

The 3D FEM analysis for MES dam was carried out by PlAXIS 3D, and the general characteristics of this model have been presented in Fig. 3. The basic soil elements of the 3D finite element mesh are the 10-node tetrahedral elements. The model included construction phase, which was simulated in construction and filling of 35 layers of material by consolidated materials for each layer (i.e. consolidation process was included in the analyses for all layers).

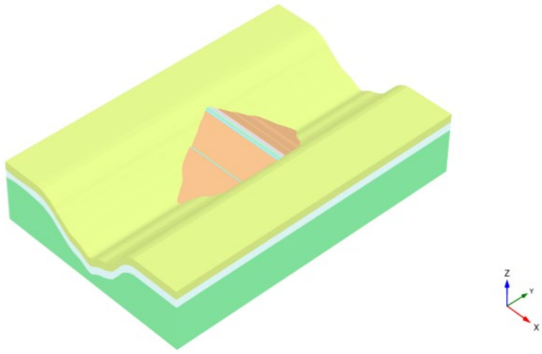


Fig. 3. Overall 3D view of model

Tables 1 and 2, present a summary of the material properties of different zones within the dam body and foundation materials, respectively. The analyses were carried out using effective stress mechanical parameters.

3.2 Analyses results

The results of the three dimensional analyses in terms of displacements, vertical stresses and pore water pressures within the dam are shown in Figures 4 to 7. Fig. 4 (a) illustrates contours of vertical displacements after construction for the cross-section CH260. As expected, a maximum settlement of about 3.9 m was occurred in about mid-height of the dam in core centerline.

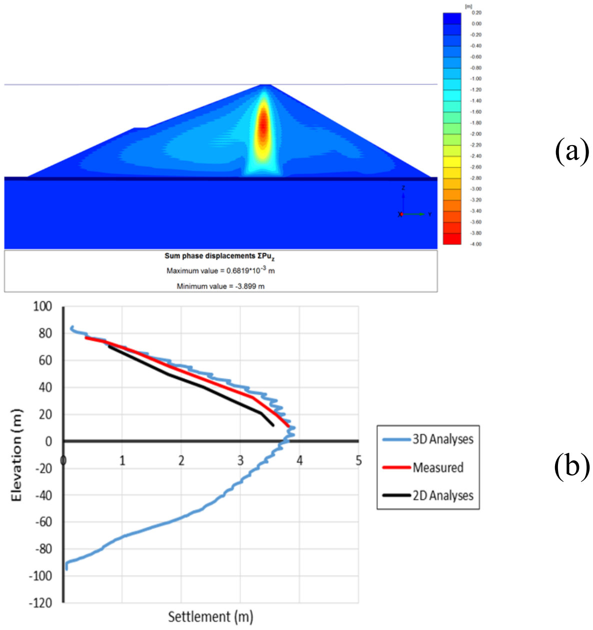


Fig. 4. (a) Contours of vertical displacements for section CH. 260 after construction phase (b) comparison of computed 2D and 3D settlements results with the measured values.

Table 1. Dam body material properties

Material	γ_{dry} (kN/m^3)	γ_{sat} (kN/m^3)	K_x (cm/S)	K_y (cm/S)	E_{50}^{ref} (kPa)	E_{oed}^{ref} (kPa)	E_u^{rref} (kPa)	c' (kPa)	φ' (º)	Ψ (º)	P_{ref} (KPa)	m	R_f

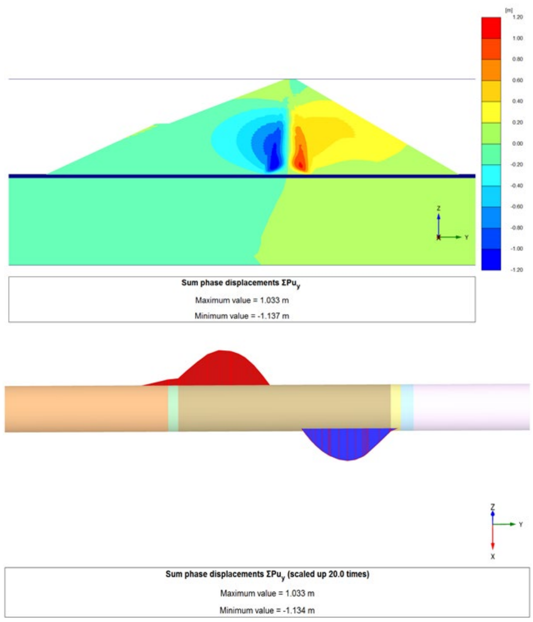
2A	20.5	23.2	2×10^{-2}	2×10^{-2}	72000	94780	216000	0	45	5	1200	0.5	0.8
2B	18.3	19.7	2×10^{-2}	2×10^{-2}	72000	94780	216000	0	41	11	1200	0.5	0.8
2C	22.9	23.2	2×10^{-2}	2×10^{-2}	126000	167000	378000	0	41	11	1200	0.5	0.7
Core	21.5	22.5	2×10^{-8}	1×10^{-8}	26000	21000	78000	25	31	0	600	0.7	0.7
Shell (3A)	22.6	23.5	1×10^{-2}	1×10^{-2}	117000	116771	351000	0	45	15	1200	0.35	0.8
Shell (3B)	22.9	23.9	1×10^{-2}	1×10^{-2}	94000	117234	285000	0	42	2	300	0.35	0.9
Shell (3C)	22.6	23.5	1×10^{-2}	1×10^{-2}	117000	116771	351000	0	45	15	1200	0.35	0.8

Table 2. Dam Foundation material properties

Material	γdry (kN/m^3)	γsat (kN/m^3)	k_x (cm/S)	k_y (cm/S)	υ	E (kPa)	c' (kPa)	Φ	Ψ
Found1	23	24	4×10^{-4}	4×10^{-4}	0.2	3872200	700	30	0
Found2	24	25	1×10^{-4}	1×10^{-4}	0.2	6776400	2000	45	12
Found3	24	25	2×10^{-5}	2×10^{-5}	0.2	6776400	2000	45	12

Fig. 4(b) compares 3D computed and measured settlements along the dam height in core centerline during construction at CH. 260. The results of corresponding 2D analyses were also presented in the Fig.4(b). As shown, reasonable agreements between the computed and measured settlements exist, especially 3D analyses. Reliable measured settlements for the lower mid-height of the dam were not acceptable.

Fig. 5(a) presents horizontal displacement contours at the end of construction using 3D analyses. . In addition, Fig. 5(b) illustrates distribution of horizontal displacement along longitudinal line at CH.260 and EI 230m after construction of dam. Approximately symmetrical distribution of displacements with respect to the core centerline can be observed.

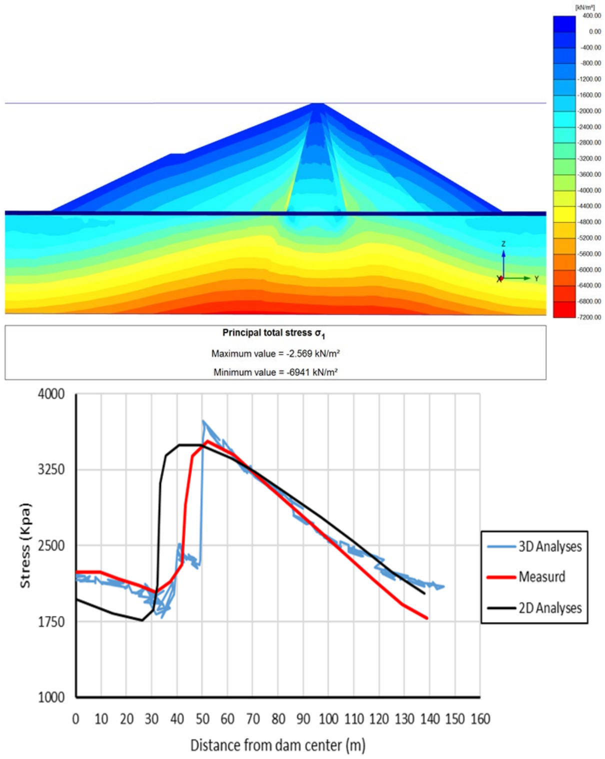


(a)

(b)

Fig. 5. (a). Contours of horizontal displacements at CH. 260 from 3D analyses at the end of construction phase, (b) distribution of horizontal displacement along longitudinal line at CH. 260 and EI 230 m

Fig. 6(a) illustrates contours of total vertical stresses at the end of construction at CH.260 resulted from 3D analyses. It can be seen that the stresses in the core are less than filter and shell, which means, arching phenomena have been occurred. Moreover, Fig. 6(b) compares 2D and 3D computed and measured total vertical stress throughout the dam's longitudinal direction at the end of construction phase. It can be seen that there is a fair agreement between the results of 3D analysis with the measured values. Furthermore, it is evident that there are some discrepancies between 2D results and measured values.

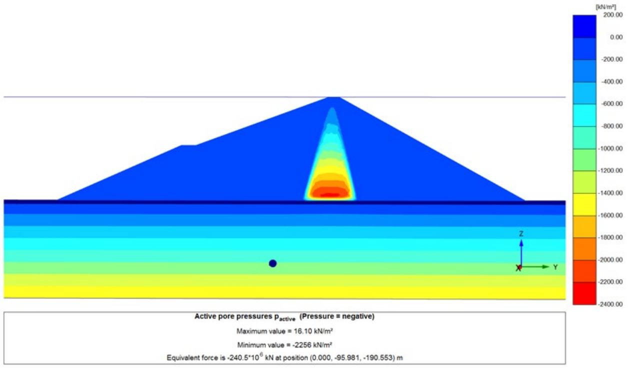


(a)

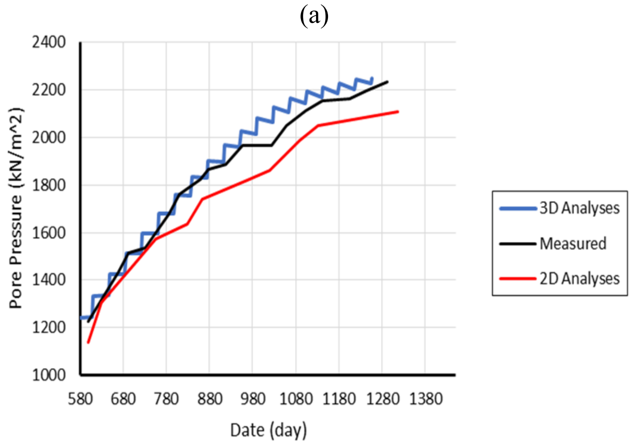
(b)

Fig. 6. (a) Contours of total vertical stress at CH. 260 using 3D analyses at the end of construction phase, (b) the comparison of 2D and 3D computed and measured values.

Pore water pressure contours at the end of construction at CH260 using 3D analyses have been presented in Fig. 7(a). There are several reasons which can describe the development of high pore water pressure in the core: (1) the width of the core is comparatively large, (2) the materials of the core are very fine and it has been classified in the CL group in unified soil classification; in addition, the plasticity index is about 19%, hence it has very low permeability, (3) moisture content of the core material is approximately 1.5% more than the optimum moisture content (Akhtarpour et al. 2014). The development of pore water pressures in the piezometer within the center of the core (PPE212), along with the history of the dam construction have been shown in Fig. 7(b); additionally, the corresponding 2D analyses results and measured values have been presented.



(a)



(b)

Fig. 7. (a). Contours of pore water pressures at CH. 260 at the end of construction phase, (b) the comparison of measured and computed (using 2D and 3D numerical analyses) pore water pressure at CH. 260 and EI 230 m (PPE 212)

3 CONCLUSION

In this research, results of 3D FEM analyses of Masjed-E-Soleyman clay core rockfill dam were presented. The main objective was to determine the behavior of the dam at the end of construction.

Main conclusions of this study are summarized, as follows;

- A favorable agreement exists between the measured and 3D analyses results.
- The results suggest that the dam should be considered as a 3D structure. For this dam, the cross-canyon 3D effects were not negligible and 2D analyses may not capture the 3D effects of the structure.
- Finally, the reasons for the development of high pore water pressures within the dam core were given special attention.

REFERENCES

Bui, Hong Ngoc, Robin Fell, and Chongmin Song. "Two and three dimensional numerical analysis of the potential for cracking of embankment dams during construction." University of New South Wales, School of Civil and Environmental Engineering, (2002).

Chen, Qun, et al. "Modelling the construction of a high embankment dam." KSCE Journal of Civil Engineering 18.1 (2014): 93-102.

Nonveiller, E., & Anagnosti, P. (1961). Stresses and deformations in cores of rockfill dams. In Proc. 5th Int. Conf. Soil Mech. & Foundn. Engng (Vol. 2, pp. 673-680).

Yu, Yuzhen, Liquan Xie, and Bingyin Zhang. "Stability of earth–rockfill dams: influence of geometry on the three-dimensional effect." Computers and Geotechnics 32.5 (2005): 326-339.

Pourakbar, M., Soroush, A., and Araei, A.A. " Low Stress Zones in Core of High Rockfill Dam Using 3D Analyses" 19 th international Conference on Soil Mechanics and Geotechnical Engineering, Seoul, Korea, September, 2017

Akhtarpour, A., and A. Soroush. "Numerical Study of Pore Pressure Development and Dissipation in Core of Masjed-Soleyman Rockfill Dam." (2014): 159-172.