Low Stress Zones in Core of High Rockfill Dam using 3D Analyses
Zones à faibles contraintes dans le noyau du barrage High Rockfill utilisant des analyses 3D

Mehran Pourakbar, *Dept. of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, MSc Student of Geotechnical Engineering, Iran, m.pourakbar@gmail.com*
Abbas Soroush. *Dept. of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Professor, Iran, soroush@aut.ac.ir*
Ata Aghaei Araei, *Geotechnical Engineering Department, BHRC, Assistant Professor, Iran, aghaeiaraei@bhrc.ac.ir*

ABSTRACT: The behavior of earth dams in narrow valleys, especially in the vicinity of abutments acquires a very high importance. This behavior is a matter of great concern in high dams as the consequences of their probable failure may be disastrous. Generally, the hydro-mechanical behavior of earth dams constructed in narrow canyons is affected by three dimensional geometric effects. Therefore, 3D analyses would be necessary for studying their behavior. In this paper, the behavior of Masjed-E-Soleyman high rockfill dam was investigated using the PLAXIS 3D software. The Hardening Soil Model has been employed for the dam body materials. Also, the effective stress parameters have been used for the core material in order to compute excess pore water pressures. The maximum depth of tensile zone in the dam crest and the q/p' ratio are used for determining low stress zones.

RÉSUMÉ : Le comportement des barrages en terre dans les vallées étroites, surtout au voisinage des butées, acquiert une très grande importance. Ce comportement est très préoccupant dans les grands barrages car les conséquences de leur probable défaillance peuvent être désastreuses. En général, le comportement hydro-mécanique d'un barrage en terre construit dans un étroit canyon est affecté par des effets géométriques tridimensionnels. Par conséquent, les analyses 3D seraient nécessaires pour étudier leur comportement. Dans cet article, le comportement du barrage de Masjed-E-Soleyman a été étudié à l'aide du logiciel PLAXIS 3D. Le modèle de sol durcissant a été utilisé pour les matériaux du corps du barrage. En outre, les paramètres de contraintes efficaces ont été utilisés pour le matériau de noyau afin de calculer des pressions d'eau de pores en excès. Pour la détermination des zones à faibles contraintes dans le noyau du barrage, on a utilisé certains critères tels que la profondeur maximale des zones de contrainte de traction dans le sol et le rapport q / p '.

KEYWORDS: Rockfill Dam, Low Stress Zones, 3D Analyses

1 INTRODUCTION

Construction of an embankment dam in a narrow valley may induce some particular structure and seepage problems, such as hydraulic fracturing and tension cracking of core, especially at abutments contact areas. Hydraulic fracturing may occur on the upstream face of clay core of a rockfill dam in the case that vertical effective stresses in the core are low enough to allow tension fracture to occur; this could even lead to failure of embankment dams. This problem originated from intense soil arching, and extension of low stress zones in transverse and longitudinal directions, respectively; the former results from material zoning, while the latter is caused by differential settlements.

A dam constructed in a narrow canyon with stepped valley profile experiences differential settlements due to different heights of embankment across the canyon. This is not a fortunate phenomenon as it can lead to low stress or tensile stress zones in which cracks may form. The reduction in the minor principal stress can give rise to hydraulic fracturing in combination with the influence of reservoir water pressure.

In this study, a finite element procedure has been developed to simulate the construction process of the Masjed-e-Soleyman dam. The Hardening Soil failure criterion has been employed for the material properties of the dam body. The step-by-step construction in effective stress conditions followed by subsequent impounding of the reservoir was simulated in the numerical simulation. Investigation about the low stress zones or tensile stress zones within the core is the main purpose of this study.

2 MASJED-E-SOLEYMAN DAM

2 .1 GENERAL FEATURES

The 177 m high MES clay core rockfill dam has been constructed between 1997 and 2000, and its impounding commenced in late 2000. 2000 MW of hydroelectric energy is produced annually by the dam, which is located on the Karun River. The dam crest is 490 m long and the reservoir volume is about 228×10^6 (m^3). The longitudinal and the highest cross sections of the dam are shown in Figures 1 and 2, respectively.

2 .2 MATERIAL PROPERTIES

The core materials (CL+GC) with about 80% fines and 20 % sand-gravel having optimum moisture content of 13.8 % were placed wet of optimum (w_{opt} +2%) and highly compacted (98% relative compaction) in layers of 20 cm final thickness. Quality control tests showed that the after-compaction degree of saturation of the core was about 95%. The filters with 5 m width were placed in 50 cm thick layers. The rockfills of the shell are conglomerates extracted from quarries, and sand-stone/clay-stone spoils from foundation and diversion tunnels excavation. These materials were compacted dry in layers of about 70-100 cm final thickness. The dam foundation is considerably stronger and stiffer than the embankment materials.

2 .3 INSTRUMENTATION

Pressure cells, piezometers, surface settlement marks, settlement gauges and inclinometers were placed in four sections of the dam (Ch160, CH260, CH360 and CH435 in Figure 2). A considerable number of the 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 Figure 2.

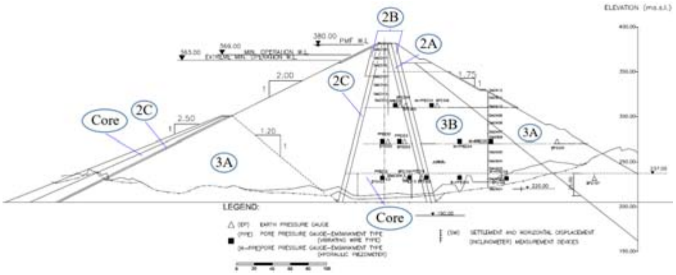

Figure 1. Highest cross-section of MES dam (CH. 260)

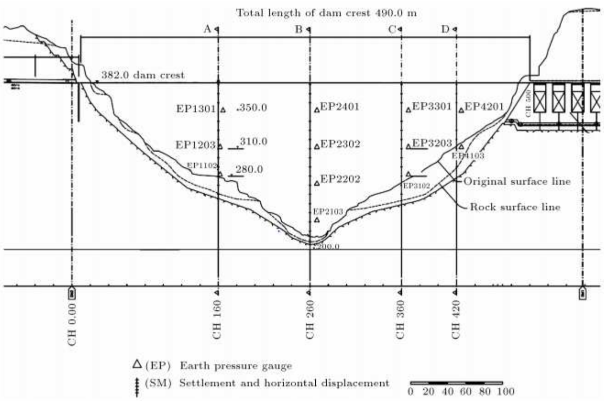

Figure 2. Central valley cross section of MES rockfill dam (dimensions and instrumentations)

3 PREVIOUS 2D AND 3D ANALYSES OF MES DAM

A total stress-strain analysis was performed by Madah et al. (2015) for the longitudinal section of the dam assuming rigid foundation and layered construction (17 layers). The stress criterion of $\sigma_3<0$ was applied for determination of low stress zones. Table 1 presents the total stress-strain parameters used in this analysis. The value of depth (D) and horizontal extension (L) of the tension zone is presented in Figure 3.

Table 1. Mohr-Coulomb constitutive model parameters used for sensitivity analyses (Madah et al. 2015)

Core	φ_{uu}	$cu\,(kPa)$	$E\,(MPa)$	ρ (kg/m^3)	υ
	3.7	85	36.6	2050	0.37

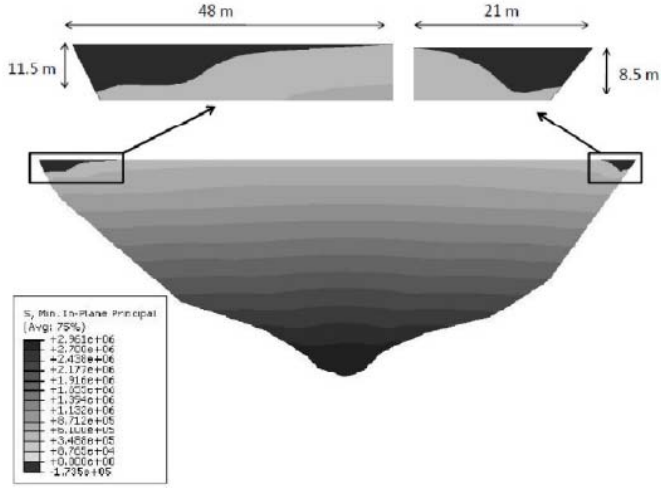

Figure 3. The value of D and L showing dimensions of the tensile zones (Madah et al. 2015)

Moreover, Porous Elastic and Cap Plasticity models were employed in order to investigate low stress zones (see Table 2). Figure 4 depicts the minimum principal stresses for the longitudinal section of the dam. It is shown that the depth of the tension zones increases while the horizontal extension of tensile zone decreased.

Table2. Porous Elastic and Cap Plasticity constitutive model parameters used for Masjed Soleyman dam (Madah et al. 2015)

d (kPa)	β	R	e_0	κ	λ	P_t^{el} (kPa)	$\varepsilon_{vol}^{in}\|_0$	k	α
173.4	7.5	0.2	0.47	0.0197	0.03	288	0	1	0.025

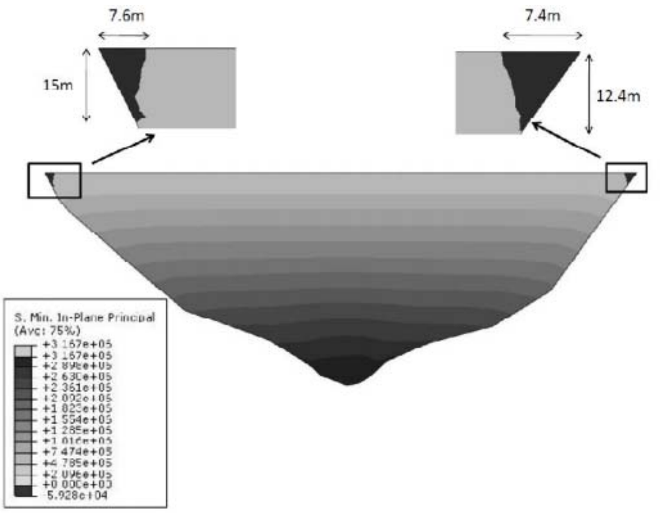

Figure 4. Extension of low stress zones using cap plasticity model (Madah et al. 2015)

It is concluded that tensile stress zones occur at the crest of the dam near the abutments, and these tensile stresses are mainly due to the lateral stresses as a result of the lateral displacements of embankment.

A 3D total stress analyses has been conducted by Ghafurian (2014) in order to investigate low stress zones in the core of MES rockfill dam. The Mohr-Coulomb model was employed for the material properties of the dam body (see Table 3). The general characteristics of the 3D model is shown in Figure 5.

Table3. Mohr Coulomb constitutive model parameters used for MES dam (Ghafurian. 2015)

Material	γ (kN/m3)	φ (°)	N	Ψ (°)	c (kPa)	E (MPa)
core	20.5	3.7	0.4	0	60	18
2A	21.7	33	0.36	5	0	107
2B	21.6	39	0.33	11	0	107
2C	23.5	39	0.3	11	0	185
3A	23.9	41	0.3	11	0	118
3C	24.6	41	0.3	15	0	118
3B	24	41	0.3	11	0	118

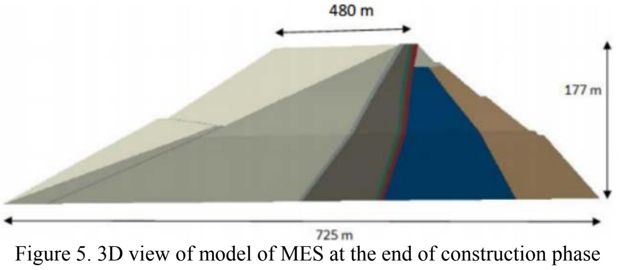

Figure 5. 3D view of model of MES at the end of construction phase (Ghafurian. 2015)

Figure 6 depicts the tensile stress zones in the core of the dam. The core has been separated from the whole model to provide better insight about development of low stress zones in the core. The tensile stresses remarkably developed close to sides of the valley near the abutments.

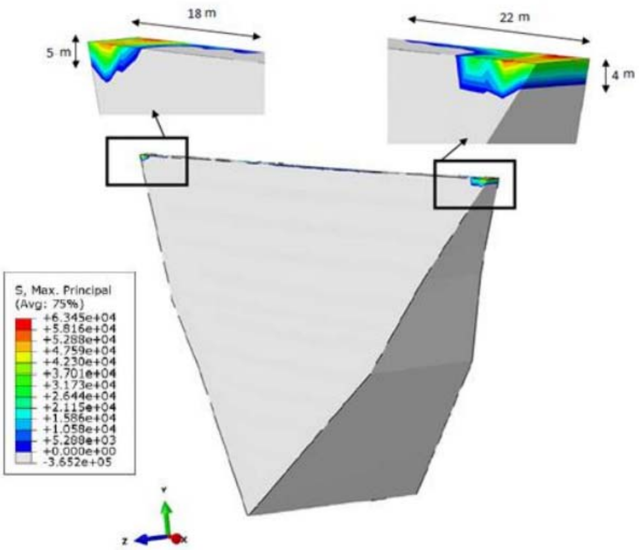

Figure 6. Extension of tensile stress zones (Ghafurian. 2015)

4 FEM ANALYSIS

In this study, the 3D FEM effective analysis for MES dam has been carried out by PLAXIS 3D. The basic soil elements of the 3D finite element mesh are the 10-node tetrahedral elements. The generated mesh of the model is presented in Figure 8.

The numerical analysis for the construction stage has been performed by dividing it into 35 stages (around 5 meters for each layer). The consolidation process has been included in the analyses for all layers. Furthermore, fully coupled deformation analyses have been selected to simulate impounding phases. To model initial impounding, the water level is raised in 5 stages (to 245 , 310, 355,372 and 382 masl, see Figure 8).

Summaries of the material properties of different zones within the dam body and foundation are presented in Tables 4 and 5, respectively. The Hardening Soil Failure Criterion has been employed for the materials of the dam body, based on the simulation of triaxial tests performed on the materials of the different zones of the dam during design phase of the project. Furthermore, the effective stress parameters have been utilized for the soil's strength to enable computing pore water pressures in the dam.

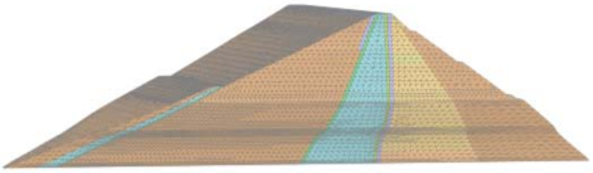

Figure 7. Generated mesh of dam body at the end of construction phase.

4 .1 Analyses results

Figure 9 shows development of low stress discretization in the core of the dam at the end of construction. The aforementioned stress criterion of $\sigma'_3<0$ was applied for determination of low stress zones or tensile stress zones.

Lateral displacements and differential settlements are responsible for the creation of these areas. Differential settlements are not favored as they induce tensile stresses in the contact areas of the core with the abutments and reduce minor principal stresses in these zones.

On the other hand, the arching between core and filters simultaneously reduces stresses in each elevation of the core in the cross valley section.

The two invariant stress parameters used in critical state soil mechanics are the mean normal effective stress, p' and the deviator stress q. A "no tension" or "limiting tensile strain" criterion is usually adopted to identify the initiation of tensile fracture (Schofield, 1980). Figure 10 illustrates the points which have the ratio of $q/p' > 3$ (red points). It is observed that the areas in the vicinity of the abutments and close to the crest of the dam are more affected by the evaluation of this criterion.

To assess whether this situation is changed during filling, the impounding phase was simulated. Table 6 presents the value of depth and horizontal extension of low stress zones for different phases of the model.

It has been observed that the low stress zones after impounding up to normal water level (372 m.a.s.l) are not significantly altered from those of the construction condition. Comparison of tension zones in last step of impounding and construction phase shows the values of depth and extension of low stress zones have been increased conspicuously. It is noticeable that upstream face of the core due to the deflection under the applied water load is more impressed. However, within the core, the minor principal stresses are not considerably changed as compared with the construction phases.

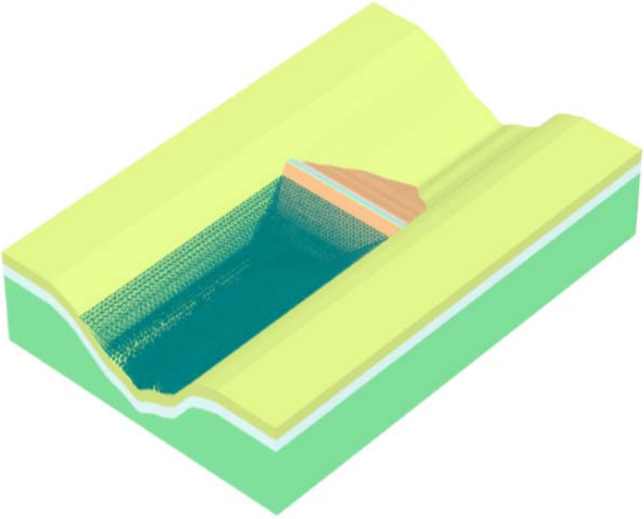

Figure 8. Overall 3D view of model at the end of construction phase

Table 4- 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□ (°)	Ψ (°)	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 5- Foundation material properties

Material	γ_{dry} (kN/m^3)	γ_{sat} (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

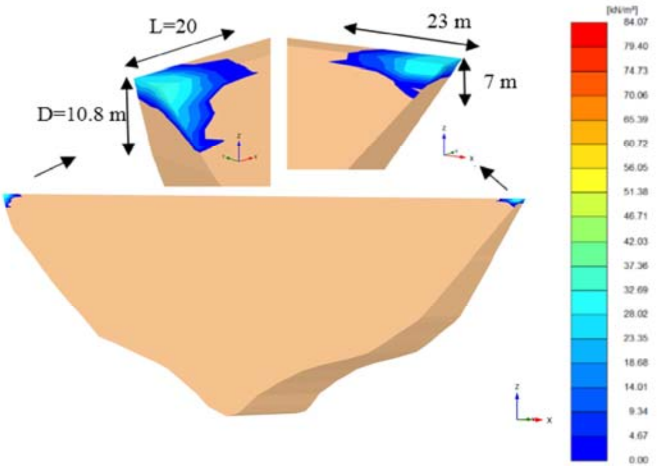

Figure 9. Dimension of the tensile stress zones at the end of construction phase.

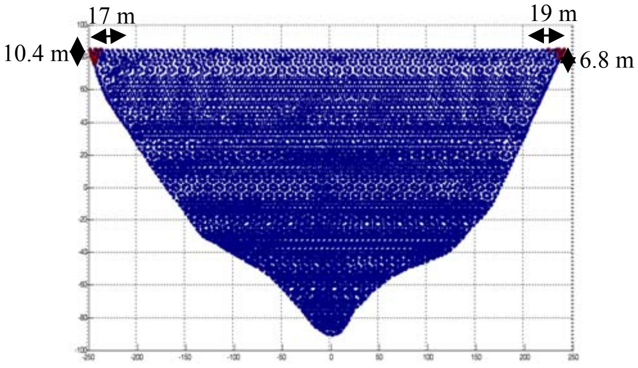

Figure 10. Dimensions of the areas with q/p'>3 (red points) at the end of construction phase.

Table 6- Variation of tensile zone (D and L) for different construction phases

	σ□$_3$<0				q/p' >3			
Time of construction	D (Left)	D (Right)	L (Left)	L (Right)	D (Left)	D (Right)	L (Left)	D (Right)
End of construction	10.8	7	20	23	10.4	6.8	17	19
Impounding (355 m.a.s.l)	11.5	7.9	26	28	12.2	7.9	21	22
Impounding (372 m.a.s.l)	11.8	8.3	27	28	12.3	8.1	21	23
Impounding (382 m.a.s.l)	13.7	10	37	42	14.6	10.5	35	43

4 CONCLUSIONS

The main results of this study can be summarized as follows:

- Low stress or tensile stress zones are created in vicinity of the abutments in narrow valleys.
- The 3D analyses would be necessary in order to consider the geometry effects of the valley.
- Depth and extension of low stress zones in core of the dam after impounding up to normal water level does not significantly differ from the depth and extension of low-stress zones at the end of construction.
- After impounding up to the flood water level, the upstream face of the dam are more affected than the – core due to low permeability of the core material and deflection of core due to applied water load.

4 REFERENCES

Maddah A., Soroush A., and Tabatabaie Shourijeh P. 2015. Effects of material properties on behavior of embankment dam clay cores in narrow valleys." *Scientia Iranica. Transaction A, Civil Engineering* 22.5, 1692.

Ghafurian Z. 2015. Assessing potential erodibility of the core of the earthfill dams in narrow valleys using 3D analyses. *Graduate Program in civil Engineering*. Amirkabir University of Iran.

He, Ke, Chongmin Song, and Robin Fell. 2014. Assessing potential cracking zones in embankment dams. 721.

Zhang, L. and Du, J. 1997. Effects of abutment slopes on the performance of high rockfill dams. *Canadian Geotechnical Journal*, 34, pp. 489-497.

Bui, H., Fell, R., Tandjiria, V., Song, C. and Khalili, N. 2005. Two and three dimensional numerical analysis of the potential for cracking of embankment dams. "*supplementary report*", UNICIV Report No. 438.