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Effects of material properties on behavior of embankment dam clay cores in narrow valleys

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Abstract. In this study, stress-strain analyses of embankment dams with clay core in narrow valleys are evaluated by means of numerical modeling, considering the longitudinal section along an embankment dam centerline. Emphasis is placed on effects of cross valley differential settlements, and the end of construction core load-settlement behavior, particularly in vicinity of abutments. The effects of core material type (mixed clayey sand material versus pure clay) on stress-strain behavior are examined. As a case study, the Masjed Soleyman clay core is analyzed considering different types of materials, and a range of core material deformation properties. A 70% reduction in depth of tensile zones near the core-abutment interface was achieved by inclusion of contact clay material at the core bottom. Comparison of analysis results with instrumentation data suggested a good agreement between results.

1. Introduction

Nowadays, with the increasing demand for dam construction, mainly for hydro-power generation and water storage purposes, construction of embankment dams in narrow valleys in lieu of flatter slope canyons is gaining widespread abundance. Geological and topographic conditions of a high rock fill dam erected in a narrow valley may give rise to some particular structural and seepage problems, such as hydraulic fracturing and tension cracking of core, especially at contact areas. Hydraulic fracturing results from pore water pressure increase caused by cracking, accompanied by sudden increase of water leakages in the soil, and accounts for one of the major reasons behind failure of embankment dams [1]. This problem stems 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. Shear localization is also likely to occur within rockfill dams, which is caused by irregular shape of abutment slopes as well as material zoning [2]. Although settlements and lateral movement of dams are somehow reduced by the three-dimensional effects of steep abutments in narrow valleys, differential settlement is not a favorable phenomenon as it induces tensile stresses in the contact areas of abutments and causes a reduction of minor principal stresses in the core [2]. This reduction of the minor principal stress can give rise to hydraulic fracturing in combination with the influence of reservoir water pressure. Little is available on effects of abutment slope and material type on the possibility of core cracking, and limited experience has been reported in construction of high rockfill dams in narrow valleys [3].

In case of a stepped valley profile, cf. Figure 1, different heights of embankment material cause differential settlements, which may result in tensile or low stress zones leading to cracking or hydraulic fracturing.

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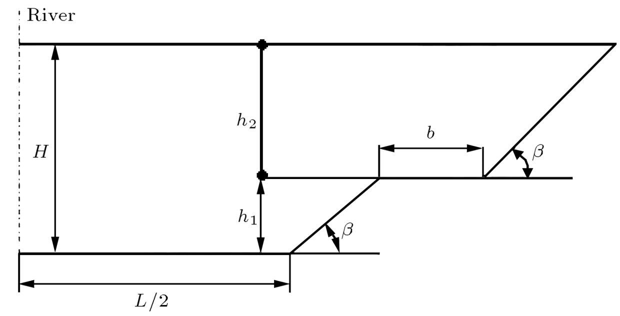

Figure 1. Cross valley profile used in numerical analyses [4].

On the other hand, arching between core and filters causes a constant simultaneous reduction of stress in each elevation of core cross valley section. However, as pointed out by Bui et al. [4], this effect is small compared to the effects of cross valley differential settlement provided the shoulders of the dam are well-compacted. Cracks associated with broad changes in valley profile are generally located in the upper 1/3 of the dam's height [5]. Weaver and Bruce [6] and Fell et al. [2] discussed the general principles of foundation preparation and choice of a proper abutment slope for several high rockfill dams. Core cracking is a major factor behind internal erosion "initiation", which may lead to dam breach and failure [7]. Bui et al. [4] carried out stress/deformation analysis on valley cross sections of Hyttejuvet, Viddlesvatn, Mud Mountain, and Buffalo dams, all with internal erosion experiences. The results suggested that zones affected by internal erosion were either cracked or had a low stress level (i.e. $\sigma_{\min} < 50$ kPa).

This study aims to investigate the effects of material properties and their interaction with canyon topographical conditions on the stress/deformation behavior of embankment dams. To this end, first a benchmark problem available in the literature is solved and the research technique employed is calibrated, then a real-case large rockfill dam is analyzed.

2. Analysis calibration

The results of modeling the longitudinal section of a hypothetical embankment dam (Figure 1) assuming a berm in the middle of 45° slope abutment [4] have been employed for calibration of ABAQUS software in this study. Total stress parameters (Table 1) in the Mohr-

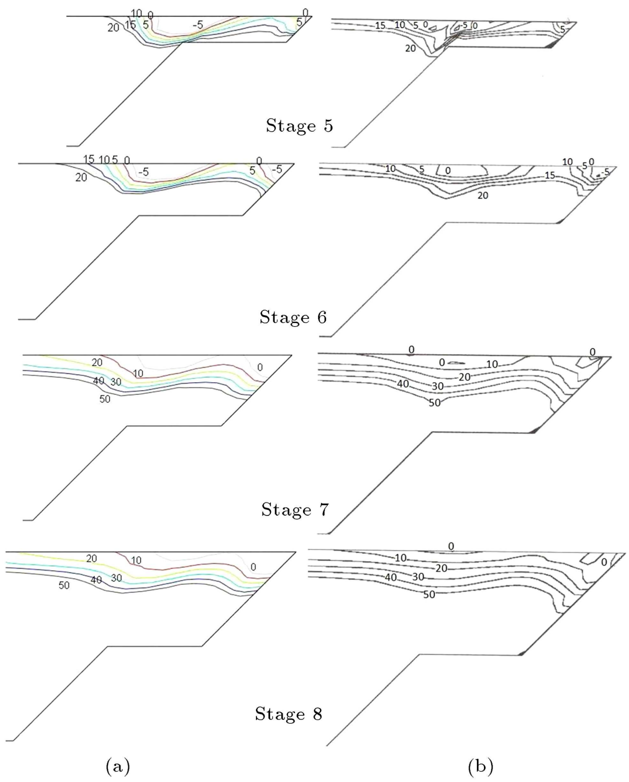

Figure 2. Low stress zones formed in an embankment dam during the last stages of construction (kPa): (a) This study; and b) Bui et al. [4].

Coulomb elasto-plastic constitutive model, and eight stages of core construction, each 5 m high, have been used. By considering symmetric section geometry, only half the berm is modeled on a rigid foundation. Zones with $\sigma_{\min}$ less than 50 kPa, known as cracked zones in the literature, are shown by contours in Figure 2.

Comparison of Figure 2(a) with Figure 2(b) indicates a logical modeling procedure in the current analysis. The cracked zones in Figure 2, resulting from a semi narrow valley, may extend deeper if the abutment slope increases. The behavior of different types of core materials will be compared clearly once we know the critical valley geometry which predominantly affects the extension of low stress zones, especially in vicinity of abutments. According to Fell et al. [5], for the most critical case, with the largest tension zone, the valley geometry (in accordance to Figure 1) should satisfy the following equations:

$$\beta \geq 60^{\circ}, \tag{1}$$

Table 1. Core material and dimensional parameters used for calibration modeling [4].

Total stress parameters of the core					Dimensional parameters of valley					
φ_{uu}	c_u (kPa)	E (MPa)	ρ (kg/m^3)	v	H^* (m)	h_1^* (m)	h_2^* (m)	L^* (m)	B^* (m)	$\beta^{\circ *}$
12	40	30	2038	0.3	50	20	30	100	20	45

* See Figure 1.

Table 2. Critical dimensional parameters for maximizing the extension of tensile zones.

H (m)	h_1 (m)	h_2 (m)	L (m)	b (m)	$\beta°$
50	40	10	100	15	60

$$b/h_2 \geq 1, \tag{2}$$

$$0 \leq h_2/h_1 \leq 0.5. \tag{3}$$

Hence, considering the above equations simultaneously, by presuming one parameter, other dimensional parameters of Figure 1 can be determined as shown in Table 2.

3. Material properties

Soroush and Soltani [8] performed monotonic and cyclic triaxial tests on mixed clay specimens with different percentages of granular materials. Two samples, i.e. T100 (pure kaolin clay) and ST40 (clayey sand with 40% kaolin clay) are of particular interest. Both specimens were compacted with +2% wet of optimum water content and to 98% of maximum standard Proctor dry density. Soroush et al. [9] offered strength and deformation parameters of T100 and ST40 materials by back analyzing laboratory test results in axisymmetric, plain strain and 3-dimensional numerical analyses conditions. As presented in Table 3, total stress and plain strain parameters determined through the mentioned analyses, are incorporated in this study. It is worthwhile noting that the Poisson's ratio (v) of 0.42 is typical for a well-compacted clayey soil (i.e. T100), compacted wet of optimum water content. In case of clayey sand, (i.e. ST40) however the high amount of granular particles restricts the increase in Poisson's ratio with increasing moisture content (i.e. wet of optimum water content).

Table 3. Strength and compressibility parameters of T100 and ST40 materials [9].

Soil	Clay (%)	Sand (%)	φ (°)	c (kPa)	E (MPa)	ρ (kg/m^3)	v
ST40	40	60	11	52	30	2000	0.3
T100	100	0	12	26	10	2000	0.42

4. Comparing clayey sand and clay as core materials

The berm, cf. Figure 1, incorporated in calibration (introduced by Bui et al. [4]) is analyzed numerically with dimensional parameters of Table 2, in order to compare stress/deformation behaviors of pure clay (i.e. T100) and mixed clay (i.e. ST40) materials. Contour lines of minimum principal stress ($\sigma_{\min} < 50$ kPa), shear stress (σ_s), settlement (S_v) and horizontal movement (S_h), at the end of construction are depicted in Figures 3 and 4. In these analyses, tension zones are considered as cracked zones, which satisfy the criterion of $\sigma_{\min} < 50$ kPa.

In Figure 3, tensile zones extension in abutments' vicinity (i.e. near the abutment and above the berms) is more widespread for ST40 in comparison to T100 material. Although tension zones and cracks are created in each stage of embankment construction, compression zones will develop once construction is continued in upper layers, forcing cracks to close. Consequently, top layers which are subjected to lower confining pressure are of more concern.

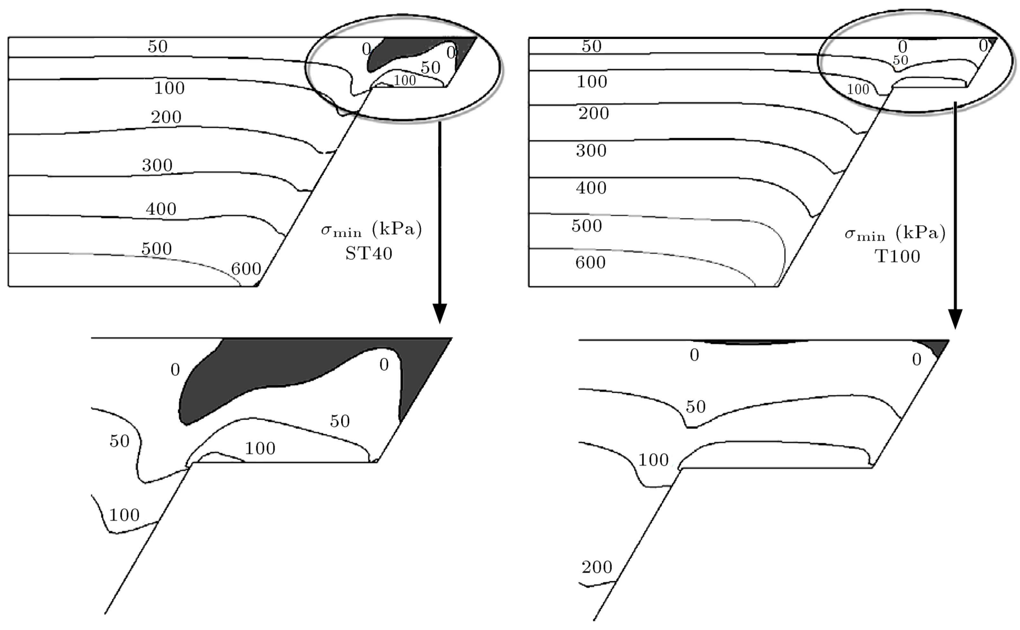

Figure 3. Valley cross section contours of minimum principal stress ($\sigma_{\min}$) for T100 and ST40 as core materials.

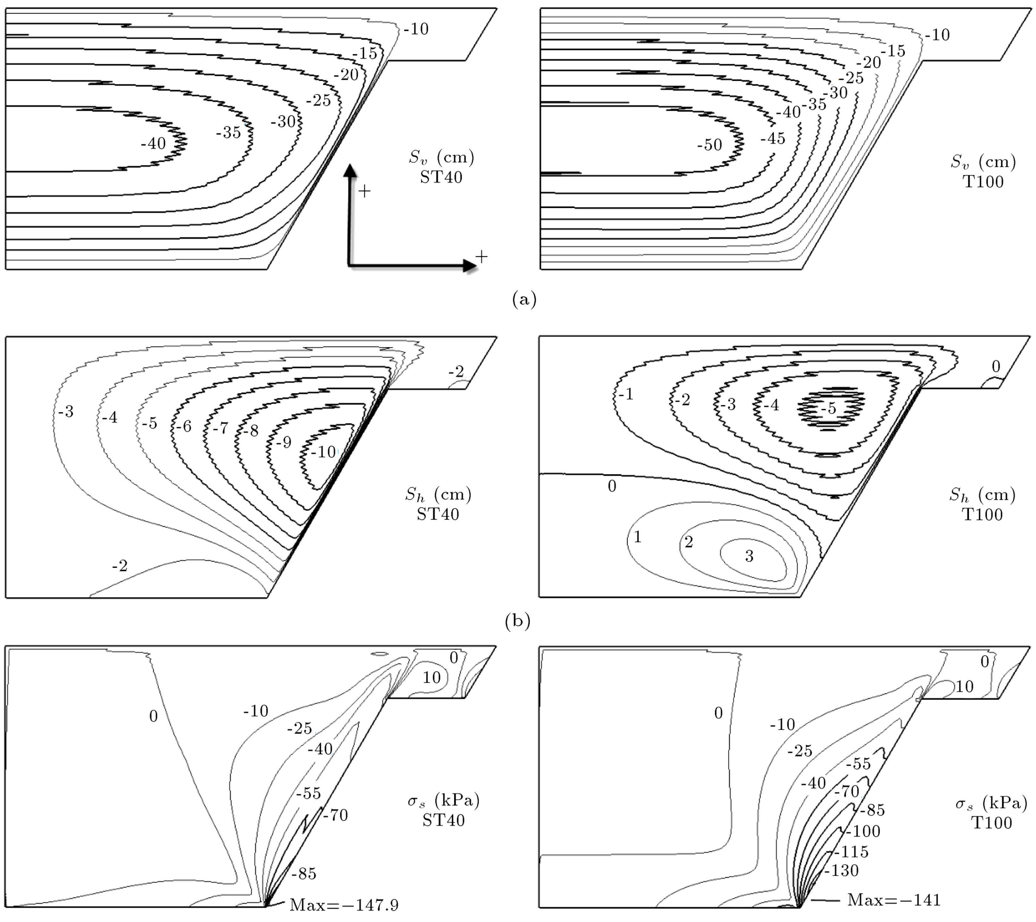

Figure 4. Valley cross section contours of settlement (S_v), horizontal movement (S_h), and shear stress (σ_s) for T100 and ST40 as core materials.

Settlement contour lines in Figure 4(a) indicate that maximum settlement ($S_{v,\max}$) occurs in the mid-height of the section, as a result of staged construction. For the clayey sand (ST40) and pure clay (T100), $S_{v,\max}$ is 37.8 cm and 51.1 cm, respectively. That is to say, by adding 60% granular material to pure clay, a 26% reduction in maximum settlement is achieved for the soils compacted to the same density ratio at the same moisture relative to optimum.

According to Figure 4(b), horizontal movements (S_h), toward the valley center, have occurred for both materials. Maximum horizontal movement ($S_{h,\max}$) for the clayey sand is 8.7 cm in the middle height, while it is 5.6 cm for the pure clay just above the middle section. Pure clay is comparatively more deformable with a lower elastic modulus, and thus expected to have more displacement, nonetheless a higher $S_{h,\max}$ is observed for the clayey sand material. The reason can be attributed to the tensile zones which are more extensive for ST40 materials, which are related to the lower Poisson's ratio of this soil. In other words, larger areas of tension strains in the abutment vicinity have driven the materials further toward the valley center. The upper part displacement toward the section center causes movement away from the center in the lower parts. Owing to high confining pressure, stress-strain variations of the lower parts are directly dependent on materials' compressibility. As shown in Figure 4(b), $S_{h,\max}$ of lower parts toward abutments for T100 is 3.8 cm which is greater than that of ST40 (i.e. 0.5 cm).

Finally, shear stress (σ_s) contours are shown in Figure 4(c). The maximum shear stress ($\sigma_{s,\max}$) for both materials is about 150 kPa which occurs in the section's base adjacent to abutments. It can be concluded that the valley cross section shear stresses have little dependency on core material type.

There is insufficient test data on real soils to confirm that clayey sands are likely to have lower Poisson's ratios than clays with low sand contents. However the testing by the authors indicates this may be the case, and while clayey sands may have somewhat higher effective strengths than clays, they may be more susceptible to low stress zones and hydraulic fracture.

In modern new dams, well designed and constructed filters will control internal erosion and piping which may initiate in cracks or hydraulic fractures.

5. Case study: Masjed Soleyman rockfill dam

The 187 m high Masjed Soleyman 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 (Southwest Iran), produces 1500 MW of hydroelectric energy annually. The crest length is 480 m and the reservoir volume is about 228×10^6 m^3. The longitudinal and highest cross sections of the dam are shown in Figures 5 and 6, respectively. 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 average, after-compaction degree of saturation of the core was about 95%. Filters with 5 meter width were placed in 50 cm thick layers. Quality control tests reported the relative density of 80% and 94% for filter materials in zones 2A and 2B, respectively (zones 2A and 2B are shown in Figure 5). The rockfill shell materials are conglomerates extracted from quarries, and sand-stone/clay-stone spoils from foundation and diversion tunnels excavations compacted dry in layers of about 70-100 cm final thickness. The dam foundation is considerably stronger and stiffer than the embankment materials [10]. The core material properties are shown in Table 4. The equivalent Young's modulus of the core can be estimated from the inclinometer settlement

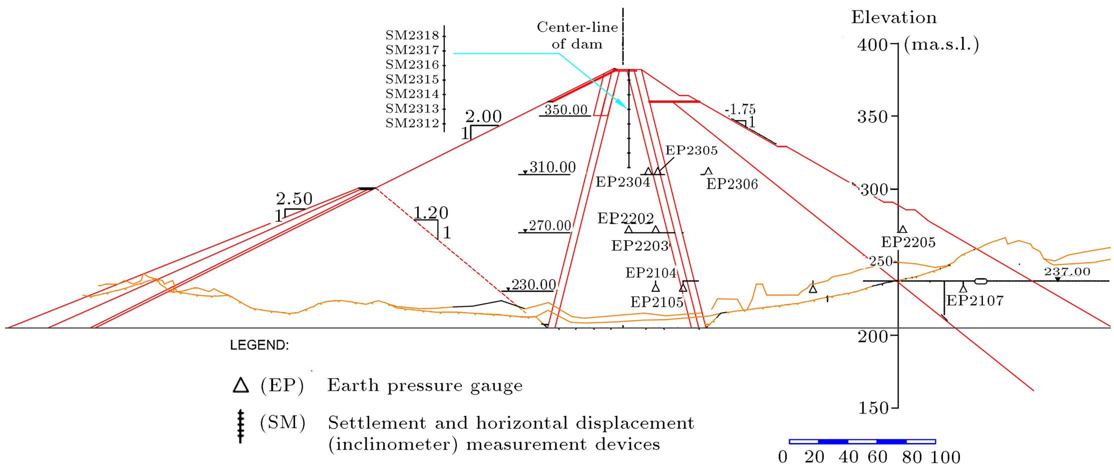

Figure 5. Highest cross section of Masjed Soleyman rockfill dam (CH 260) [11].

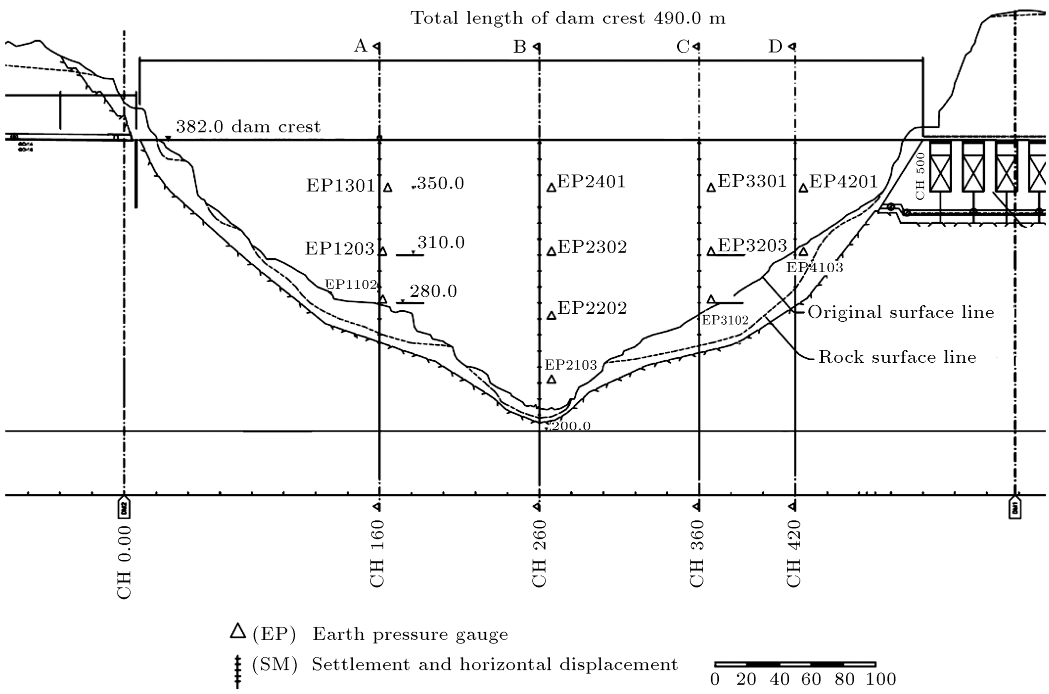

Figure 6. Central valley cross section of Masjed Soleyman rockfill dam (dimensions and instrumentations) [11].

Table 4. Material properties of core from laboratory and quality control tests [10].

MC (%)[a]	w_{opt} (%)	γ_d (kN/m^3)	γ_{wet} (kN/m^3)	RC (%)[b]	PI (%)[c]	c (kN/m^2)[d]	φ (°)[d]
15.2	13.8	18.2	21.0	100	18.7	85	3.7

[a] Moisture content; [b] Relative compaction; [c] Plasticity index;

[d] From unconsolidated undrained tests on saturated specimens.

data and construction history. When this is done for the upper 70 m height of the core elevation, and after extrapolation for the remaining lower 107 m of height, the range of moduli is 5 MPa to 31 MPa. Nonetheless, since monitoring data is insufficient, this extrapolation may not be very precise. Thus, it would be more certain to apply the parameters obtained from quality control tests [10].

6. Parametric study of Masjed Soleyman core behavior

A total stress-strain analysis was performed for the longitudinal section of Masjed Soleyman clay core assuming rigid foundation and layered construction (17 layers). The aforementioned stress criterion of $\sigma_{\min}$<50 kPa was applied for determination of cracked zones. Figure 7 shows model dimensions and mesh discretization. At first, development of low stress zones attributable to variations in strength and compressibility parameters were studied. For each model, selected parameters were based on variations of materials' compressibility. Table 5 presents the stress-strain parameters used in these analyses. From the results of each analysis, values of D and L (introduced in Figure 8) and maximum settlement ($S_{v,\max}$), which reflects section deformation, have been determined.

According to the analyses, φ_{uu} has a negligible effect on results, thus it has been assumed a constant value of 3.7°, i.e. equivalent to the original dam material, with no changes for sensitivity analyses. Variations of D and L with different Poisson's Ratio, near

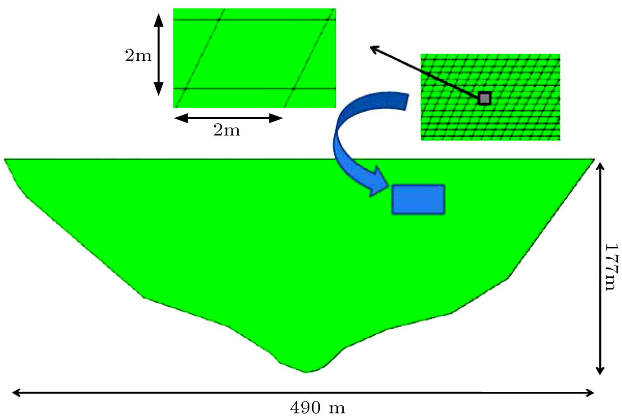

Figure 7. Dimensions of model and mesh discretization of valley cross section of Masjed Soleyman rockfill dam.

Table 5. Mohr-Coulomb constitutive model parameters used for sensitivity analyses.

Model number	C_u (kPa)	E (MPa)	v
1	50	10	0.28
2	50	10	0.3
3	50	10	0.35
4	50	10	0.4
5	50	10	0.42
6	50	10	0.45
7	60	18	0.28
8	60	18	0.3
9	60	18	0.35
10	60	18	0.4
11	60	18	0.42
12	60	18	0.45
13	85	36.6	0.28
14	85	36.6	0.3
15	85	36.6	0.35
16	85	36.6	0.4
17	85	36.6	0.42
18	85	36.6	0.45

both left and right abutments, are plotted in Figure 9. The wide range of Poisson's Ratio considered in Table 5 is logical recalling analogies presented for Table 3. From this, D in both abutments increases with increase of E (i.e. Elastic Modulus), and there is an overall trend of decreasing D with increase in v. Analogously, L follows a similar pattern with changes in v; however, for the left abutment, the effects of E on L do not present a clear trend. It is worthwhile noting that shoulders that are not well-compacted may settle and influence the extension of low stress zones in the core. A three-dimensional modeling is beneficial for tracing these effects, and is beyond the scope of this paper.

Variations of $S_{v,\max}$ with v are plotted in Figure 10. From this, $S_{v,\max}$ decreases with the increase of v, and this trend is more pronounced for lower elastic moduli. It can be concluded that a lower elastic modulus introduces softer clay which has higher flexibility and less cracked zones. Increase of Poisson's ratio decreases the cracked zone extensions.

Figure 10 shows the actual measured maximum

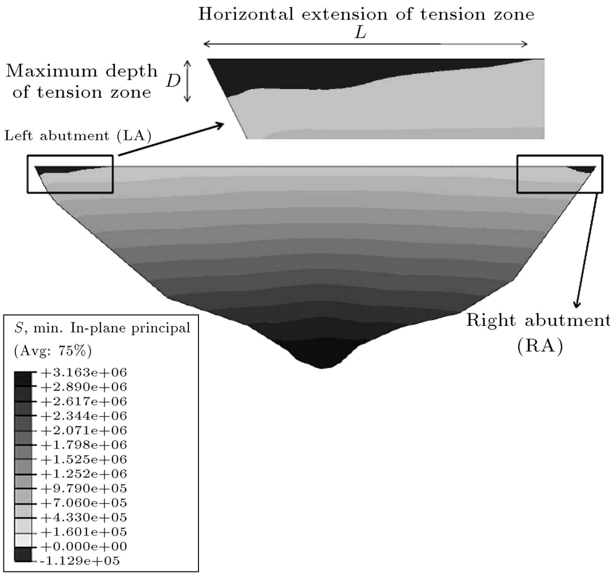

Figure 8. Schematics of D and L showing dimensions of the tensile zones.

settlement, $S_{v,\max}$, which is consistent with the highest modulus and undrained strength soil modelled. These are consistent with what would be expected for a well-compacted core, and indicate that the lower strengths and moduli modelled are unrealistically low.

7. Prevention of core cracking

Contact tension cracking is predominantly caused by changes in abutment slopes and poor cut-off trench design. The common practice is to excavate the shallow alluvial and weathered rock and place the core on the abutments. However, this has to be dealt with a lot of caution as very deep trenches, and steep batter slopes will be affected by the intense differential settlements effects. In addition to material type influence on core cracking which was explained in the previous sections, the following suggestions are made for preventing core cracking.

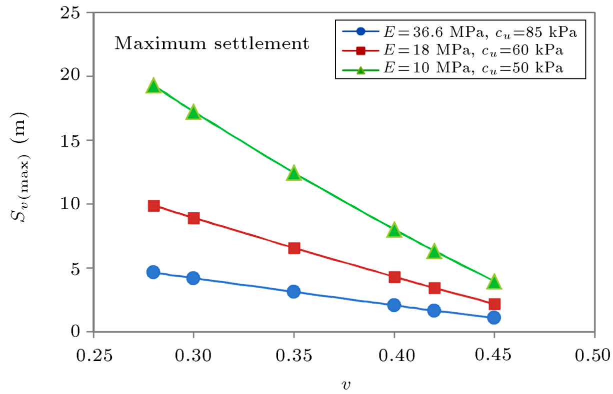

Figure 10. Variations of maximum settlement of Masjed Soleyman rockfill dam clay core with E and v.

7.1. *Application of high-plasticity clay in the core and filter contact areas*

The application of plastic contact clay material (at contact areas) can significantly decrease tensile stresses near core-abutment interfaces. Furthermore, the risk of contact clay cracking declines substantially due

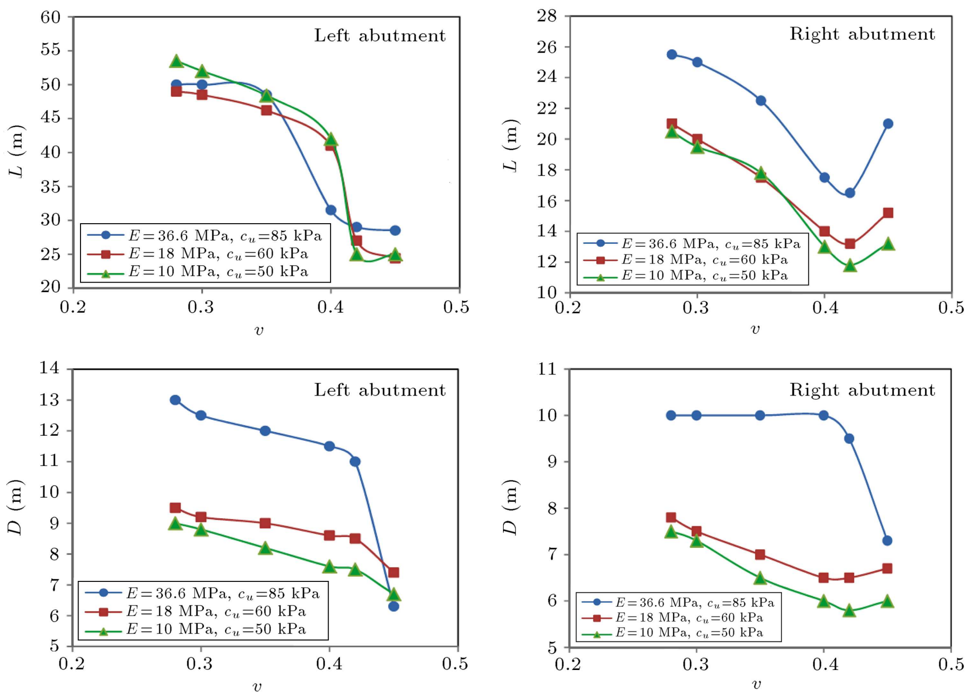

Figure 9. Variations of the tensile zone (D and L) with E and v in left and right abutments of Masjed Soleyman rockfill dam.

to the strain-hardening performance after yielding of clay [3].

7.2. Well-designed downstream filter

A well-designed filter will protect the core from piping or erosion failure and prevent clogging in the downstream shell. ICOLD [12] and USBR [13] emphasized the importance of the downstream filter. However, when the filter gradation is to fine or filter materials contain excessive fines, the permeability may not be enough to allow the passage of seeping water without build-up of extreme pore water pressure [14]. This in turn could result in mechanical instability, hydraulic fracturing, etc. Moreover, in case of cohesive filters with excessive fines, there is a risk that cracks through the core could propagate into the filter and alter its functionality [14]. Compaction of filters is also important, since filters compacted to very high densities contribute to arching related problems.

7.3. Proper compaction of the core

The compaction degree of core materials has prominent effect in improving the stress-strain behavior, and thus reducing the risk of hydraulic fracturing. Therefore, it is preferable to have a core material that is easily compacted [3,1].

7.4. Preparation of abutment for the core

Execution of a cutoff trench sometimes is necessary for slope stability, but it may increase the foundation permeability and erosion of contact areas. However, execution of a deep trench will decrease stresses, leading to arching across the narrow trench which in turn will increase likelihood of hydraulic fracturing. Cutoff trenches should be flattened as much as possible. According to Fell et al. [5], the slope should not be steeper than 0.5H: 1V to ensure the core material can be compacted against the sides of the trench, and 1H: 1V if the depth to width ratio of the trench is greater than 0.5 to avoid arching effects in the cutoff trench. Where excavations are required to be carried out in fissured or weathered rocks, it is preferable to make steeper abutments without sudden changes of slopes rather than execution of a deep cutoff trench. However, this preference is a factor of stress conditions and the excavation volume [3].

7.5. Proper core thickness

Obviously, a small core thickness will increase the soil arching onto the filters and shoulders of the dam resulting in more seepage stability problems [3].

8. Effects of contact clay

For the Masjed Soleyman dam, contact clay with a thickness of 1.5 to 2 m, perpendicular to the abutment

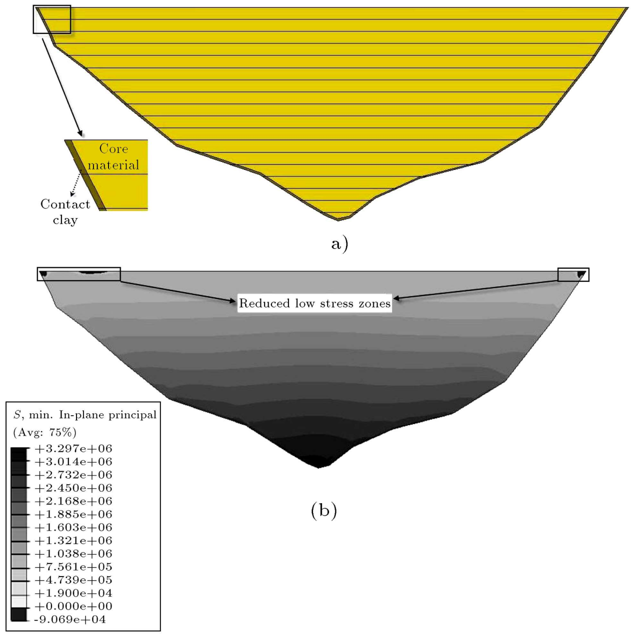

Figure 11. Numerical modeling of the contact clay: a) Definition of partitions; and b) diagram of the extension of low stress zones in presence of contact clay.

Table 6. Mohr Coulomb constitutive model parameters used for Masjed Soleyman rockfill dam clay core analyses [11].

	φ_{uu}	C_u (kPa)	E (MPa)	ρ (kg/m^3)	v
Core	3.7	85	36.6	2160	0.37
Contact clay	2	26	10	2000	0.42

surfaces, was executed during staged construction of the core. Two ad hoc models of Masjed Soleyman clay core longitudinal section, one with and the other without plastic contact clay, considering total stress-strain parameters (see Table 6) were analyzed. Figure 11 shows the model and reduced extent of low stress zones in presence of contact clay for Masjed Soleyman earth dam longitudinal section. The results are presented in Table 7. Modelling with a C_u of 50 kPa and the same modulus and Poisson's ratio gave similar results.

Apparently, contact clay placement reduces D by 62% and 74% in left and right abutments, respectively. Furthermore, maximum shear stress of the section ($\sigma_{s,\max}$) has increased up to 4 times, and there is a 11% increase in maximum vertical settlement ($S_{v,\max}$), with no significant changes in horizontal deformations (S_h). The results imply that tensile zones can be partly eliminated by applying a layer of high-plasticity clay on abutments' surfaces. This behavior is a result of plastic consistency of material which is able to flow under tensile stresses, without cracking.

Table 7. Extension of tensile zones and the stress strain results of Masjed Soleyman valley cross section analyses.

Model no.	Contact clay	D (m)		L (m)		$S_{v,\max}$ (m)	$\sigma_{s,\max}$ (kPa)	$S_{h,\max}$ (m)
		LA	RA	LA	RA			
1	×	11.5	8.5	48	21	2.76	130	0.53
2	√	3	3.2	64	7.5	3.07	479	0.46

Note: D, L, LA and RA are introduced in Figure 8.

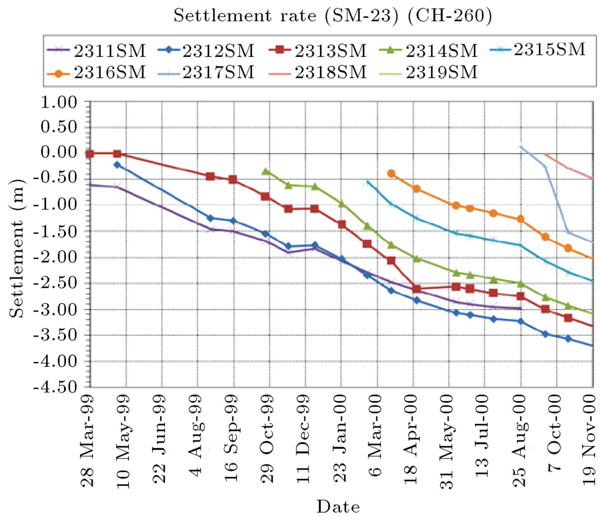

Figure 12. The recorded settlements of CH360 cross section inclinometers during construction [11].

9. Comparison of numerical analyses and instrumentations

Extensive instrumentation results are available in four cross sections, namely, CH160 (A), CH260 (B), CH360 (C) and CH420 (D) of Masjed Soleyman dam body. Vertical settlements (S_v) were recorded by inclinometers installed from the crest to the foundation in centerline of each section of longitudinal profile (see Figure 6). Recorded data up to maximum depth of 75 m were available for construction period of the dam. Thus, in Figure 5, only the inclinometers of upper 75 m dam elevation (i.e. SM) are illustrated. Figure 12 shows recorded settlements in cross section CH260 in each stage of embankment construction. Corresponding results of cross valley section numerical analysis, with and without contact clay application (with the same model used in Section 8), along with recorded values of settlements, at the end of construction for the instrumented cross sections, are shown in Figure 13.

The settlements increase by introducing contact clay to the bottom of the core, particularly in cross sections CH160 and CH420 which are closer to abutments and have a lower height of overburden soil. In other words, the ratio of soil elevation to contact clay elevation in these sections is lower. Comparison shows a somewhat acceptable agreement between computed and measured settlements. However, the fact that the dam was built in a steep-sided valley, along with

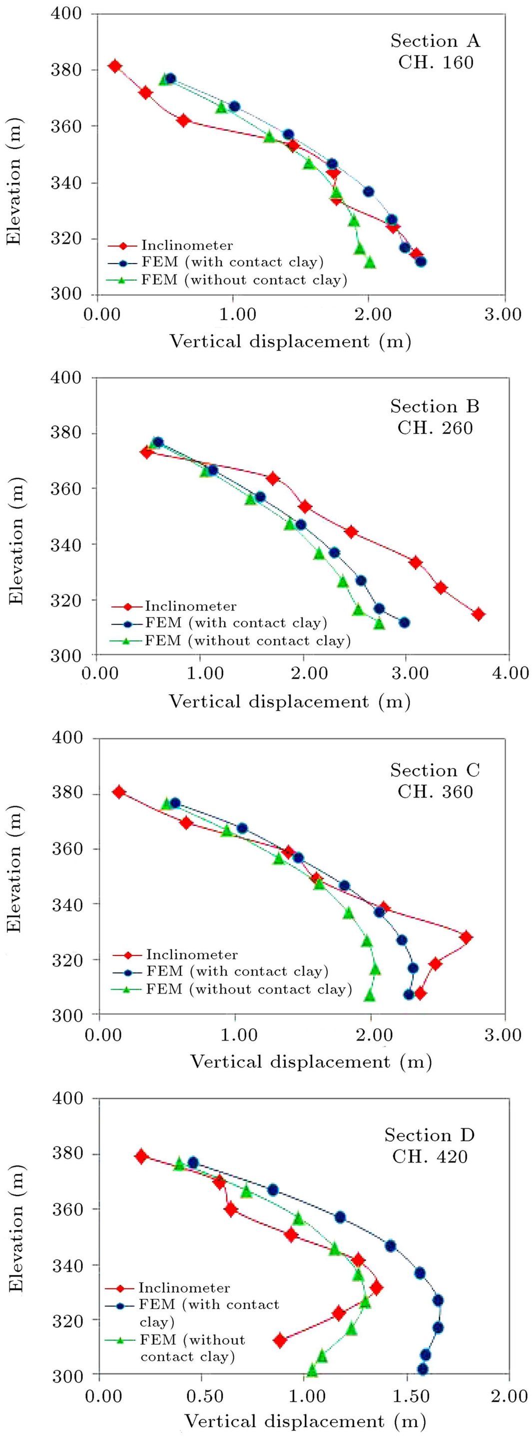

Figure 13. Comparison between maximum vertical settlements in section A (Ch.160) obtained from the numerical analyses and inclinometers records.

plain strain analyses assumptions of this study, may be responsible for some discrepancies.

10. Conclusions

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

- Low stress and tensile zones are created in vicinity of abutments and above berms in narrow valleys.
- Vertical and horizontal extensions of low stress zones, in cores with clayey sand materials, with the properties of ST40 and the lower Poisson's ratio, are more extensive than those with pure clay, with properties of T100. In the critical cross section of the hypothetical dam (Figure 3), this difference was about 35%. The most important difference in the properties of the two soils is the Poisson's ratio with larger tensile zones for the lower Poisson's ratio soil.
- By increasing the elastic modulus of core material, the depth of tensile zones increases in both abutments. This depth decreases when the Poisson's ratio increases.
- Execution of plastic contact clay, with a thickness of 1.5 to 2 m at the core bottom, significantly reduces the extension of tensile zones. These reductions in the left and right abutments were about 74% and 62%, respectively.
- The restraints of the narrow valley slopes significantly decrease movements of dams and vertical stresses in the lower parts of dams.
- Cross valley section shear stress is insensitive to core material type.

References

1. Ghanbari, A. and Rad, S.S. "Development of an empirical criterion for predicting the hydraulic fracturing in the core of earth dams", *Acta Geotechnica* (2013). DOI 10.1007/s11440-013-0263-2.
2. Fell, R., Macgregor, P., Stapledon, D. and Bell, G., *Geotechnical Engineering of Dams*, Taylor & Francis, pp. 359-376 (2005).
3. Zhang, L. and Du, J. "Effects of abutment slopes on the performance of high rockfill dams", *Canadian Geotechnical Journal*, **34**, pp. 489-497 (1997).
4. Bui, H., Fell, R., Tandjiria, V., Song, C. and Khalili, N. "Two and three dimensional numerical analysis of the potential for cracking of embankment dams - supplementary report", UNICIV Report No. 438, The School of civil and Environmental Engineering, The University of New South Wales Sydney (2005).
5. Fell, R., Foster, M.A. and Wan, C.F. "Assessment of the likelihood of initiation of erosion in embankment dams", *Internal Erosion of Dams and Their Foundation*, Fell & Fry Taylor & Francis Group, London, pp. 71-102 (2007).
6. Weaver, K. and Bruce, B., *Dam Foundation Grouting*, American Society of Civil Engineers; Rev Exp edition, 504 pages (2007)
7. Fell, R., Wan, C.F., Cyganiewicz, J. and Foster, M. "Time for development of internal erosion and piping in embankment dams", *Journal of Geotechnical and Geoenvironmental Engineering*, **129**(4), pp. 307-314 (2003).
8. Soroush, A. and Soltani Jigheh, H. "Pre- and post-cyclic behavior of mixed clayey soils", *Canadian geotechnical Journal*, **46**, pp. 1-14 (2009).
9. Soroush, A., Sasanian, S. and Soltani Jigheh, H. "Mixed versus clayey soils for the core of earth dams", *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering*, Egypt 5-9 October, pp. 1506-1509 (2009).
10. Soroush, A. and Aghaei Araei, A. "Analysis of Behavior of a High Rockfill Dam", *Proceedings of the Institution of Civil Engineers, ICE-Geotechnical Engineering*, 159 Issue GE1, pp. 49-59 (2006).
11. Niponkoei. *Supplementary Report of Masjed Soleyman Project*, technical report, Nipon Koei Co., LTD. (2004).
12. International Commission on Large Dams (ICOLD), "Bulletin 95, embankment dams granular filters and drains" (1994).
13. U.S. Bureau of Reclamation (USBR), "Protective Filters", Chapter 5, Design standards No.13-Embankment dams (2011).
14. Soroush, A., Tabatabaie Shourijeh, P., Farshbaf Aghajani H., Mohammadinia, A.R. and Aminzadeh, A.H. "A review of the sand castle test for assessing collapsibility of filters in dams", *Geotechnical Testing Journal (ASTM International)*, **35**(4), pp. 503-516 (2012).

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