Mixed versus clayey soils for the core of earth dams

Mixte versus argileux pour le coeur de barrages en terre

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ABSTRACT

There are interesting debates among the geotechnical engineers involved in the design and construction of earth dams, regarding the technical and practical advantages and disadvantages of using mixed soils (such as SC or GC) versus clayey soils (such as CL or CH) as materials for the dams core. Mixed soils are usually mixtures of clay and sand and (or) gravel. This paper presents the results of a series of numerical analyses carried out on a hypothetical earth dam with a vertical core and with two different types of materials: (i) pure clay and (ii) mixed clay. Regarding the consolidation conditions within the core during the dam construction, two types of analyses are performed: (a) fully undrained and (b) partially drained conditions. The results of the analyses show that for fully undrained analyses, excess pore water pressures developed within the core during construction are comparatively higher when the core comprises the pure clay. For the partially drained analyses, the values of excess pore water pressures in the two types of cores depend on the construction and consolidation rate. Settlements in the core consisting of the pure clay are comparatively higher if drainage of the core is impeded. When consolidation of the core is permitted, the settlements of the core comprising of the pure clay and the mixed clay are not much different. Horizontal displacement values of the core consisted of the pure clay material are higher than their corresponding values of the core consisted of the mixed clay.

RÉSUMÉ

Il y a des débats intéressants entre géotechniques ingénieurs impliqués dans la conception et la construction de barrages en terre, en ce qui concerne la technique et les avantages concrets et inconvénients de l'utilisation mixte sols (tels que SC ou GC) versus argileux (tels que CL ou CH) comme matériaux pour la construction de barrages core. Mixte sols sont habituellement les mélanges d'argile et du sable et (ou) gravier. Ce document présente les résultats d'une série de les analyses quantitatives effectuées sur un hypothétique barrages en terre avec une base verticale et avec deux différents types de matériaux: (i) pure clay, et (ii) mélangé clay. En ce qui concerne la consolidation conditions au sein de la base au cours de la construction du barrage, deux types d'analyses sont effectuées: (a) pleinement non égouttées et (b) partiellement drainé conditions. Les résultats des analyses montrent que, pour pleinement non égouttées analyses, l'excédent l'eau interstitielle pressions développé dans le coeur pendant la construction sont relativement plus élevé lorsque les ressources de base comprend la pure clay. Pour la partiellement drainé analyses, les valeurs de l'excédent l'eau interstitielle pressions dans les deux types de mandrins dépendent de la construction et la consolidation taux. Colonies au programme principal consistant de la pure argile sont relativement plus élevé si le drainage de la core est entravée. Lorsque la consolidation de la base n'est permise, les colonies de la core comprenant de la pure argile et mixtes argile ne diffèrent pas beaucoup. Déplacement Horizontal valeurs de base se composait de la pure argile matériel sont plus élevés que leurs valeurs correspondantes de la base se composait de mélange clay.

Keywords: Numerical analyses, earth dam core, pore water pressure, mixed clayey soil.

1 INTRODUCTION

The core materials of earth dams are usually selected on the basis of available borrow areas and usually from low-permeable geomaterials. Moreover, these materials should have enough strength and stiffness in order to be able to withstand against different loading conditions, such as construction, first impounding, steady state seepage, rapid drawdown, and earthquake shaking. Depending on the availability of borrow area, different types of soils may be used for the core. These soils could be categorized as (i) clayey soils, such as CL or CH, with relatively high percentage of clay, and (ii) mixed soils, with proportions of clay, silt, sand and gravel (e.g., glacial tills).

In practice, both of the above soil types are used worldwide for the core of earth dams.

Each of the above soil types has their own advantages and disadvantages. For example, mixed soils have higher shear strength (at least under monotonic loading) and higher permeability; they are also more liquefiable when subjected to rapid monotonic and cyclic loading. Also, the potential of cracking is less in mixed clayey soils.

On the other hand, clayey soils have lower strength, lower permeability, higher compressibility, and higher cracking potential; they are apparently less susceptible to liquefaction.

In this paper, the results of numerical analyses carried on a cylindrical specimen (on which triaxial compression tests had been carried out) and a hypothetical earth dam with a central core are presented. The materials for the specimen and the core are considered once (i) a clayey soil and once (ii) a mixed clayey soil. Regarding the consolidation conditions within the core during the dam construction, two types of analyses are

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performed: (a) fully undrained and (b) partially drained conditions. The analyses results are presented and compared.

2 EXPERIMENTAL TESTS

Soltani (2006) carried out a series of consolidated-undrained monotonic, cyclic, and post-cyclic monotonic strain-controlled triaxial compression tests on specimens of clay and mixed clayey soils. The mixed specimens contained 20%, 40%, and 60% granular material (sand or gravel). The pure clay was Turkey ball-clay with specific gravity (G_s) of 2.72 and plasticity index (*PI*) of 19. The sand and gravel with a specific gravity of 2.64 were provided from vicinity of Tehran. The tests were carried out under effective confining pressures of 100, 200 and 350 kPa.

In general, the results of the triaxial tests showed that excess pore water pressures, generated during strain-controlled monotonic loading, increase when the granular material content of the specimens increases. Also, in the specimens with the same granular material content, when the grain size decreases (i.e., sand versus gravel), the shear strength decreases but pore water pressure increases. In equal stress levels, pore water pressures generated during monotonic loading decrease by the increase of granular material content. This trend is opposite to the trend observed in strain-controlled loading conditions. The details of the results of the tests are given in Soltani (2006), Soltani and Soroush (2007), and Soroush and Soltani (2008).

3 NUMERICAL MODELING

3.1. Software and constitutive models

ABAQUS 6.7 finite element software was employed for performing the numerical analyses. In order to select an appropriate constitutive model for the soils' behavior, the triaxial specimens were analyzed by the Mohr-Coulomb, Drucker-Prager, and Cam-Clay elasto-plastic models and their results were compared with the results of the tests. From the above comparison we found that the Cam-Clay model better represents the soil behavior.

The shear strength parameters of the soils were determined from the results of the tests according to Equations 1 and 2.

$$\tau = c' + \sigma'_n . \tan\phi' \tag{1}$$

$$\sin\phi' = \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3 + 2c' \cot\phi' - 2\Delta u} \tag{2}$$

where, σ_1 and σ_3 are major and minor principal stresses; Δu is excess pore water pressure; τ, σ'_n, c, and ϕ' are shear strength, effective normal stress, effective cohesion, and effective friction angle, respectively.

The Cam-Clay model includes main parameters of M, κ, and λ, which are respectively the stress ratio at critical state, the plastic slope, and the elastic slope. These parameters are obtained from the following theoretical and empirical equations:

$$\lambda = (G_s . PI)/461 \tag{3}$$

$$\kappa = P/E \tag{4}$$

$$M = \frac{6\sin\phi'}{3 - \sin\phi'} \tag{5}$$

where, P, E, and PI are respectively confining stress, Young's modulus, and plasticity index.

The material characteristics for the analyses of the triaxial specimens with the Cam-Clay model for the specimens T100 and ST40 are presented in Table 1.

Table 1. Material characteristics for the analyses on the triaxial specimens with the Cam-Clay model

Specimen	σ'_c (kPa)	Cam-Clay Parameters λ	κ	M	Permeability, k (cm/s)	Void Ratio, e_0
T100	100	0.09	0.075	0.9	6.07E-10	0.708
	200		0.065	0.8576		
	350		0.061	0.8523		
ST40	100	0.075	0.045	1.448	6.76E-09	0.412
	200		0.04	1.347		
	350		0.025	1.252		
Pore water bulk modulus = 2e+6 (kPa) and Saturation ratio = 1						

3.2. Analysis of the triaxial tests

The triaxial tests were modeled and analyzed in 3D conditions using the parameters presented in Table 1. The loading condition was strain-controlled with a final strain of 16%. The variations of deviatoric stress and pore water pressure versus axial strain obtained from the analyses are compared with the tests results in Figures 1 and 2. It can be observed that the ultimate values of deviatoric stresses and pore water pressures resulted from the numerical analyses and the tests are in reasonable agreements for both T100 and ST40 specimens.

The final pore water pressure values (at the strain of 16%) obtained from the analyses and the tests for the T100 and ST40 specimen, for the tests with σ'_c =100, 200, and 350 kPa, are presented in Table 2. It is seen that both the experimental and computed pore water pressures are comparatively higher in the ST40 specimen.

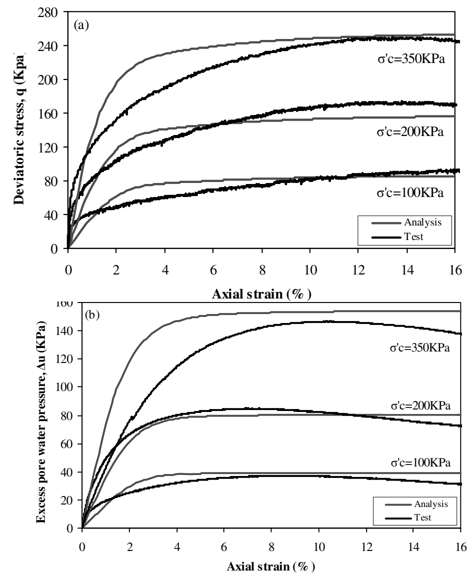

Figure 1. Tests and analyses results of T100 specimen: (a) deviatoric stress, and (b) excess pore water pressure.

3.3. Analysis of the hypothetical earth dam

In order to compare the behavior of earth dams with the core comprising clayey soils versus mixed soils, a hypothetical earth dam was numerically modeled and analyzed. Once, the core material was considered as the T100 material and then, it was considered as the ST40 materials. The average parameters used in the analyses with the Cam-Clay and Mohr-Coulomb models are presented in Table 3.

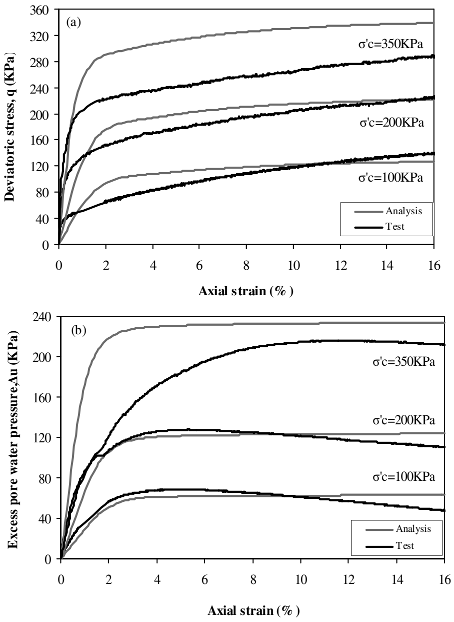

Figure 2. Tests and analyses results of ST40 specimen: (a) deviatoric stress, and (b) excess pore water pressure.

Table 2. Final pore water pressure values from the numerical analyses and the triaxial tests.

Specimen	T100		ST40	
σ'$_c$ (kPa)	Test	Analysis	Test	Analysis
100	31	39.28	47.39	62.84
200	71.87	80.51	110.19	123.82
350	136.87	154.07	211.69	233.91

The dam construction stages were modeled in five layers. Figure 3 shows the geometry and finite element mesh of the dam. The Mohr-Coulomb elasto-plastic model was used for modeling of the behavior of the dam shell.

In order to evaluate values of pore water pressure, pore water pressure ratio, settlement, and horizontal displacement in the dam, the middle nodes along the layers boundaries on the center line of the dam were selected as the target points.

Table 3. Parameters of Cam-Clay and Mohr-Coulomb models used for the earth dam materials.

	Cam-Clay parameters			Young modulus	Poisson's
	λ	κ	M	E (kPa)	ratio, ν
T100	0.09	0.067	0.87		
ST40	0.075	0.037	1.349		
	Mohr-Coulomb parameters				
	c' (kPa)	ϕ' (°)	ψ (°)		
T100	18.8	18.7	0	10000	0.3
ST40	25	26	0	50000	0.3
Shell	1	36	5	50000	0.25

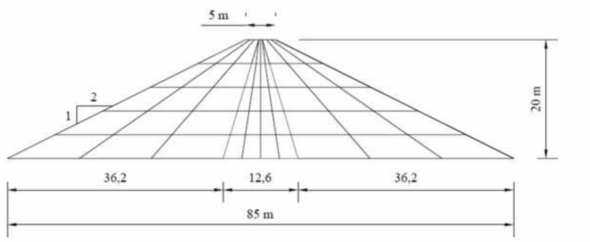

Figure 3. Geometrical characteristics and finite element mesh of the dam.

In order to allow the completion of pore water pressure redistribution within the dam core during the fully undrained analysis, sufficient time was considered for the construction of each layer. In the numerical analysis of the dam with consolidation of the core layers, about 30 days were considered for the construction of each layer.

Contours of construction-induced excess pore water pressures and settlements resulted from the analyses of the dam with the pure clay core, when the core is considered to partially consolidate during construction, are shown in Figures 4a and 4b, respectively. This figure is typical of the results, which are not all presented in this paper due to the limitation of pages numbers.

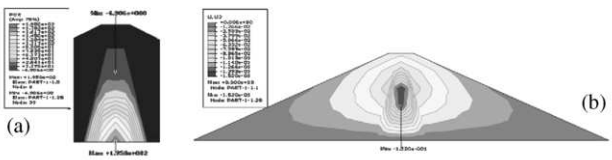

Figure 4. Contours of construction-induced (a) excess pore water pressure and (b) settlement of the earth dam with pure clay core, when core consolidation is allowed.

Table 4 summarizes the maximum values of excess pore water pressure and settlement for both analysis methods (with and without consolidation of the core) for the dam with two core materials (T100 and ST40). It is evident that the maximum pore water pressures and settlements in the core with pure clay (T100) (with only one exception for the settlement) are higher than their corresponding values in the core with mixed clay (ST40).

Table 4. Comparison of the maximum values of excess pore water pressure and settlement in the core.

	Fully undrained analysis		Consolidation analysis	
	Cam-Clay	Mohr-Coulomb	Cam-Clay	Mohr-Coulomb
Excess pore water pressure, Δu (kPa)				
T100	222.56	245.4	195.01	170.1
ST40	205.3	238.5	57.01	42.39
Settlement, δ_y (cm)				
T100	27.27	15.93	15.2	9.837
ST40	16.46	11.63	17.41	5.645

Figure 5 presents variations of excess pore water pressure, pore water pressure ratio (u/σ_v), settlement, and horizontal displacement in six locations along the centerline of the dam. These results correspond to the analyses with the Cam-Clay model for the core materials behavior.

The maximum values of excess pore water pressure, vertical settlement, pore water pressure ratio, and horizontal displacement for both the cores obtained form the analyses with Cam-Clay model are presented in Table 5. Irrespective of analysis method, the maximum excess pore water pressure induced within the mixed clay core is lower than the corresponding values of pure clay core.

Figure 5a shows that pore water pressures in the core made of pure clay are comparatively higher and that the fully undrained analyses (as expected) induce higher pore pressures in the core. Figure 5b indicates that pore water pressure ratios as high as about unity may be induced in the core of T100 material if consolidation of the core is impeded. Figure 5c shows that maximum settlements occur in the dam when the core comprises T100 material and behaves in fully undrained

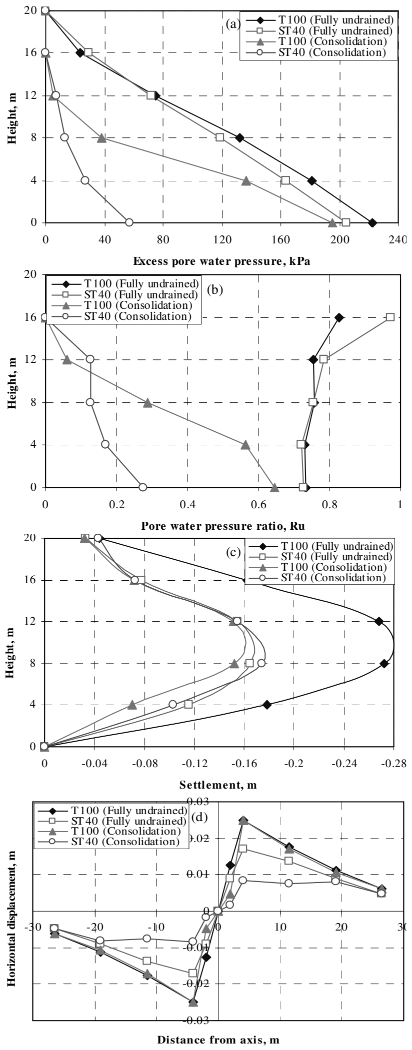

Figure 5. Variations of: (a) excess pore water pressure, (b) pore water pressure ratio, (c) settlement, and (d) horizontal displacement along the core height

Table 5. Comparison of the results of typical earth dam analyses for both types of analysis methods.

	Excess pore water pressure, Δu (kPa)	Pore water pressure ratio, R_u	Vertical Settlement, δ_y (cm)	Horizontal displacement, δ_x (cm)
Fully Undrained condition				
T100	222.56	0.76	27.27	2.482
ST40	205.08	0.78	16.46	1.711
Consolidation condition				
T100	195	0.65	15.2	2.494
ST40	57.01	0.28	17.41	0.834

conditions during construction. Figure 5d indicates that maximum horizontal displacements in the core occur if the core material is T100, for both undrained and partially drained conditions.

4. CONCLUSIONS

The following major conclusions may be made from this research:

- By using the mixed clayey soil, ST40, (as opposed to pure clay, T100) for the core materials, irrespective of drainage conditions, pore water pressures in the core induced during construction of the dam comparatively decreases. This decrease is more pronounced if consolidation of the core is allowed during construction (Figure 5a).
- In the analyses with the consolidation of the core, for a major height of the dam, especially lower elevations, pore water pressure ratio is comparatively higher in the core made of T100 (Figure 5b).
- Settlements in the core made of T100 are comparatively higher if drainage of the core is impeded. When consolidation of the core is permitted, the settlements of the core comprising of T100 and ST40 are not much different (Figure 5c).
- Horizontal displacement values of the core consisted of the T100 material are higher than their corresponding values of the core consisted of ST40 (Figure 5d).
- A comparison between the pore water pressure results of the triaxial tests and the hypothetical earth dam indicates that within the core of earth dams, equal stress level (i.e., stress controlled, versus strain controlled, loading) conditions dominate.

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