Evaluation of Collapse Deformation Behavior of a Rockfill Material Using Large Scale Triaxial Tests

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Abstract

An experimental program including dry-saturated large-scale triaxial tests was conducted in order to investigate the effects of gradation curve and dry density on the saturation-induced collapse deformation behavior of a rockfill material. Two large scale triaxial equipments with three different sample diameters of 20, 30 and 80cm were employed and a set of dry-saturated tests were conducted. Specimens with different gradation curves and various initial dry densities were tested. The results indicate that in all of the dry-saturated tests, sudden reductions in the shear strengths and volumes of the specimens were observed during the submerging process. The effects of material maximum particle size, fines content and initial dry density on the value of sudden shear strength reduction, internal friction angle reduction caused by saturation ($\Delta\varphi_c$), the change in elasticity modulus of the material due to submerging, i.e., (E_{wet}/E_{dry}), and also the saturation-induced sudden volumetric strain (ε_{vc}) were evaluated and discussed. Based on the results of dry-saturated tests, the intensity of collapse deformation behavior of the rockfill material increases as the material maximum particle size and fines content increases. However, increasing the initial dry density of the material decreases the intensity of collapse deformation phenomenon.

Keywords: Rockfill, Collapse Deformation, Large Scale Triaxial Test.

1. INTRODUCTION

The extensive application of rockfill materials in geotechnical structures, specially in rockfill dams during recent decades, makes the precise recognition of different aspects of the behavior of these materials ineluctable. Rockfill material such as other coarse grained materials undergoes rapid or sudden settlemnts, that could have relatively large values, without any changes in the applied loads and only because of submerging (or wetting) ([1],[2],[3],[4],[5],[6]). This phenomenon is called collapse deformation ([2],[7]). Intesification of particle breakage and crack propagation, particles rearangement and facilitation of particles displacement because of lubrication effects of water are among major events that were found responsible for this phenomenon ([8],[9],[10]).

Rapid settlemets cuased by saturation that are reported in the litrature for different rockfill dams and also for other rockfill embankments (such as railway embankments), are the main examples of this phenomenon ([2],[7],[11]). This event is frequently reported in the upstream shell of rockfill dams during first impounding of the reservior or in other rockfill structuers because of heavy rains ([12],[13],[14]). Although some valuable investigations have been carried out to recognize the principles and mechanism of collapse deformation, some aspects of this phenomenon are still unkown.

Because of the large size of the particles, testing of the prototype rockfill materials is almost imposible and the grain sizes are usually scaled down for laboratory testing. However, since the scaled materials are still relatively coarse grained, large scale laboratory tests such as triaxial, direct shear and odometer tests have been employed for studying the behavior of rockfill materials ([15],[16],[17],[18],[19]). However because the large scale laboratory tests are usually expensive and difficult to perform the number of these researches are relatively limited.

Duo to the quarry properties and the mineralogy of the rockfill materials and also because of technical considerations, the materials could have different gradation curve envelopes. In addition, various rockfill structures were constructed with different dry densities of rockfill materials. therefore, evaluation of the effects of grain size distribution curve and the initial dry density of the rockfill materials on the pattern and intensity of the saturation-induced collapse deformations could be useful.

The main purpose of this study is to evaluate the effects of gradation curve and initial dry density on the collapse settlement behavior of rockfill materials and to determine the changes in the strength and deformeability parameters of this material caused by submerging. To this end, two large scale triaxial equipments with different sample diameters were employed and a set of dry-saturated tests were conducted on the specimens of a rockfill material. In these dry-saturated tests, the specimens were first sheared (in dry conditions) up to a specified shear stress level; then the axial loading was stopped, the specimen was gradually and fully submerged with de-aired water and then axial loading was continued until the failure of the specimen. The effect of materials gradation curve was evaluated by testing specimens with three different material fines contents (percent passing #200 sieve) and three maximum particle sizes. Testing materials with different maximum particle sizes could be helpful in exploring the effects of unavoidable scaling down of the particle sizes that should be performed when the laboratory tests are used to estimate the behavior of prototype rockfill materials. Moreover, three different initial dry densities were used for reconstitution of the specimens in order to probe the influence of the materials dry density. Finally the results of the tests were analyzed and interpreated to study the effects of these factors on the collapse settlement behavior of the rockfill materials.

2. EXPERIMENTAL PROGRAM

Two large scale triaxial apparatuses with maximum sample diameters of 800mm and 300mm were used in this study. The smaller equipment was used for testing specimens with diameters of 200mm and 300mm. The samples were sheared strain-controlled by the moving down of the top cap at a constant rate. LVDT sensors were used to measure the vertical displacement of the samples. Vertical load was also measured by means of sensors installed inside and outside the cell.

In this study rockfill material were obtained from the shell borrow area of a rockfill dam. Characteristics of the material along with the standards employed for their determination are presented in table 1.

Table 1: Rockfill Material Characteristics

Mineralogy	Shape	Water Absorption	Gs	Los Angeles Abrasion (500 cycles)
Limestone	Subrounded to Subangular	1% ASTM (C127-128)	2.7 ASTM (C127-128)	28% ASTM (C131)

The prototype rockfill material has a maximum particle size of 700 mm. It is obvious that testing the prototype material was almost impossible because of its coarseness and the limitations of the triaxial cell dimensions. Therefore, the material particle sizes for laboratory test specimens were scaled down by some degrees. The ratio of specimen diameter to material maximum particle size was selected to be about six or less. Specimens with three diameters of 200mm, 300mm and 800mm were used and the maximum particle sizes of the testing materials were selected equal to 19.1mm, 50mm and 150mm respectively. Gradation curves of these materials are shown in figure 1a; these materials have a fine content (percent passing #200 sieve) of 8%. Materials with three fines contents of 2, 8 and 15% were also tested. Fines content is defined as the percent (by weight) of the material passing sieve # 200. Gradation curves of these materials are illustrated in figure 1b; these materials have a maximum particle size of 50mm.

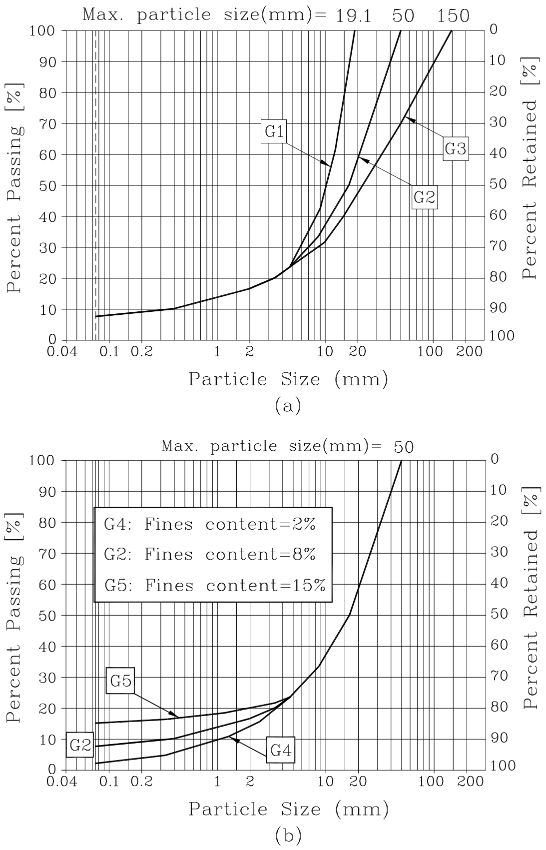

Figure 1. Gradation curve of testing materials a) Different maximum particle sizes b) Different fines contents

3. TESTING PROCEDURE

In order to prepare specimens with specified dry densities and gradation curves, the quantity of various sizes of the material was determined by weight. The individual fractions were mixed thoroughly in order to achieve a more homogenous sample. The produced material was compacted in six layers in accordance with the ASTM D7181 proposed "tamping method" to achieve the required density. The strain-controlled axial loading of the specimens was applied with a rate of 1mm/min based on the method proposed by the same standard (ASTM D7181) because of the relatively high permeability of the tested material.

The experimental program consisted of twenty-four large scale strain-controlled triaxial tests that were conducted on the specimens with diameters of 200, 300 and 800mm in three confining pressures of 100, 500 and 1000 kPa. In the dry-saturated tests, the specimens were first sheared (in dry condition) up to a specified shear stress level, then the axial loading (monotonic movement of the top cap) was stopped, the specimen was gradually and fully submerged from bottom to the top under very low head of de-aired water and then axial loading was continued.

Shear stress level (SSL) is defined by the ratio of shear stress at the moment of saturation to the maximum shear strength of the specimen in dry condition. According to the current design criteria of rockfill embankments, the minimum allowable safety factor for long-term stability of rockfill slopes in static loading conditions is around 1.5. Therefore the shear stress level that regarding to its definition could be considered as the inverse of the safety factor (at the moment of saturation) was selected equal to 0.7 ($\cong 1/1.5$). This shear stress level could represent the static stability conditions of properly designed slopes before getting submerged. Each specimen was first sheared in dry condition to determine its maximum shear strength required for performing tests in SSL of 0.7. As mentioned before, two series of tests were conducted in order to explore the effects of fines content and dry density. In these two series, the specimens were submerged in two shear stress levels (SSL) of 0.7 and 1.0. Table 2 shows the experimental program of this study.

Table 2- Experimental program

Test series name & purposes	Name of Gradation curve	Specimen Diameter (mm)	Max. Particle Size (mm)	Dry Density (gr/cm^3)	Fines Content (%)	Confining Pressure (kPa)	SSL	Test Name
Series A: Effect of maximum particle size	G1	200	19.1	2.15	8	100	Dry	100D-DI200
							0.7	100D0.7S-DI200
						1000	Dry	1000D-DI200
							0.7	1000D0.7S-DI200
	G2	300	50			100	Dry	100D-DI300
							0.7	100D0.7S-DI300
						1000	Dry	1000D-DI300
							0.7	1000D0.7S-DI300
	G3	800	150			100	Dry	100D-DI800
							0.7	100D0.7S-DI800
						1000	Dry	1000D-DI800
							0.7	1000D0.7S-DI800
Series B: Effect of fines content	G4	300	50	2.15	2	500	1.0	500D1.0S-F2
							0.7	500D0.7S-F2
	G2				8		1.0	500D1.0S-F8
							0.7	500D0.7S-F8
	G5				15		1.0	500D1.0S-F15
							0.7	500D0.7S-F15
Series C: Effect of dry density	G2	300	50	1.7	8	500	1.0	500D1.0S-DD1.7
							0.7	500D0.7S-DD1.7
				1.9			1.0	500D1.0S-DD1.9
							0.7	500D0.7S-DD1.9
				2.15			1.0	500D1.0S-DD2.15
							0.7	500D0.7S-DD2.15

4. RESULTS

4.1. STRESS-STRAIN BEHAVIOR

Figures 2 and 3 present the axial stress-axial strain and the volumetric strain-axial strain behavior of the tests of series A. Figures 4 and 5 indicates the axial stress-axial strain and the volumetric strain-axial strain behavior of the tests of series B and C respectively. In these figures the first number (three to four digits) represents the confining pressure value in kPa, “D” stands for dry condition, “S” refers to saturated condition and the number between “D” and “S” represents the shear stress level in which the specimen was submerged. The last part coming after “S” in series A is the specimen diameter in millimeters (that comes along with DI), in series B it is the material fines content in percent (coming along with F) and in series C it is the dry density in gr/cm3 (that comes along with DD). In these figures the dilation is considered positive.

For each confining pressure first the maximum shear strength of the material (in dry condition) was identified by performing tests in dry condition or by conducting dry-saturated tests at the shear stress level (SSL) of 1.0. Then the other d-s tests were conducted at the shear stress level of 0.7, i.e., specimens were submerged in 70% of their identified maximum dry shear strength.

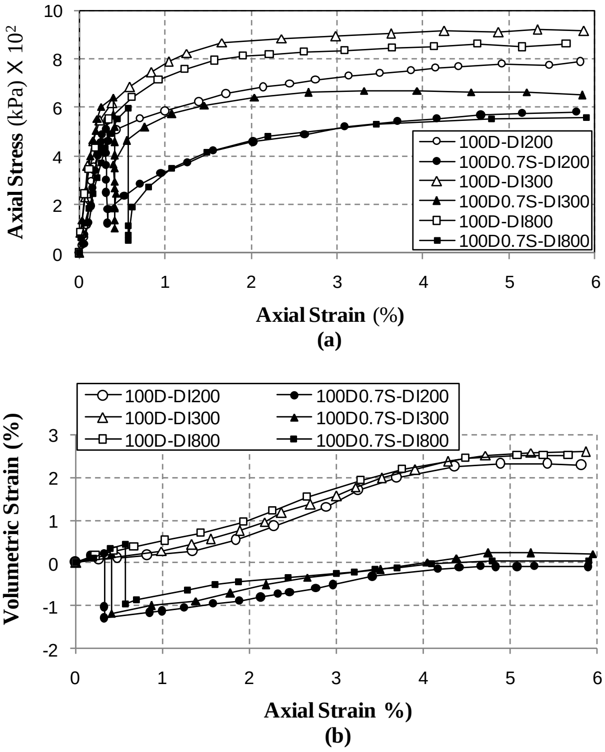

Figure 2. a) Axial stress-axial strain b) volumetric strain-axial strain behavior of series A tests performed in confining pressure of 100 kPa, Effect of materials maximum particle size

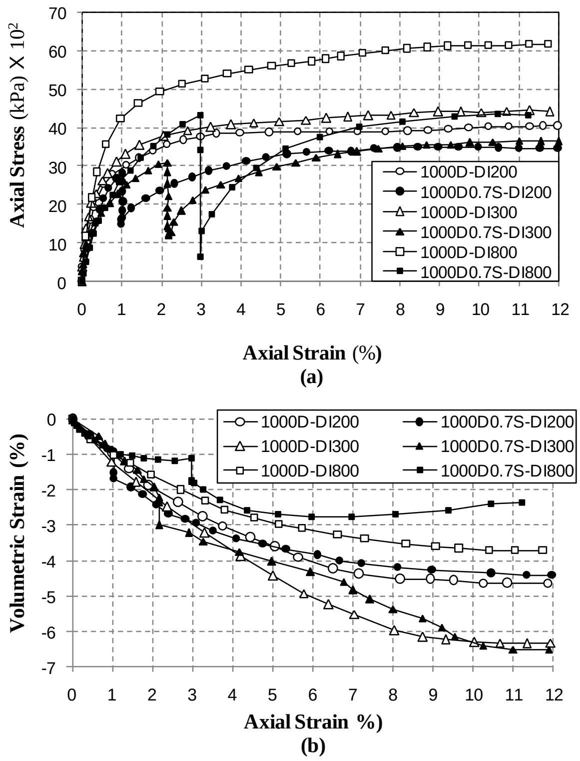

Figure 3. a) Axial stress-axial strain b) volumetric strain-axial strain behavior of series A tests performed in confining pressure of 1000 kPa, Effect of materials maximum particle size

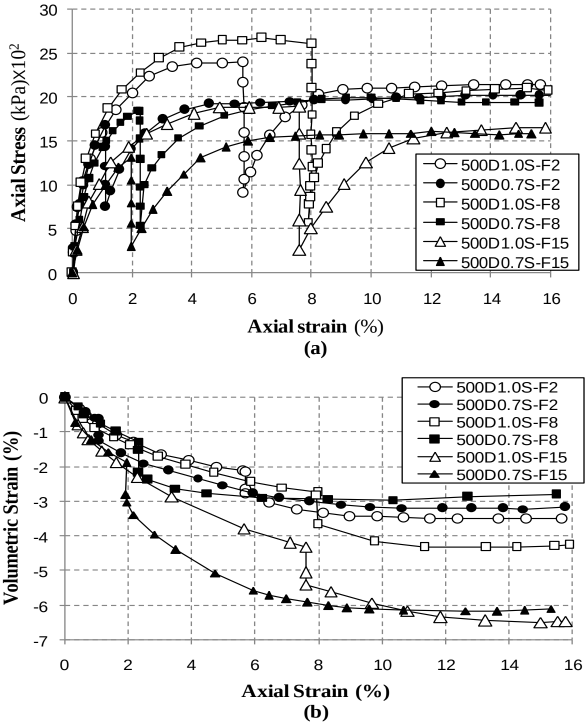

Figure 4. a) Axial stress-axial strain b) volumetric strain-axial strain behavior of series B tests, Effect of materials fines content

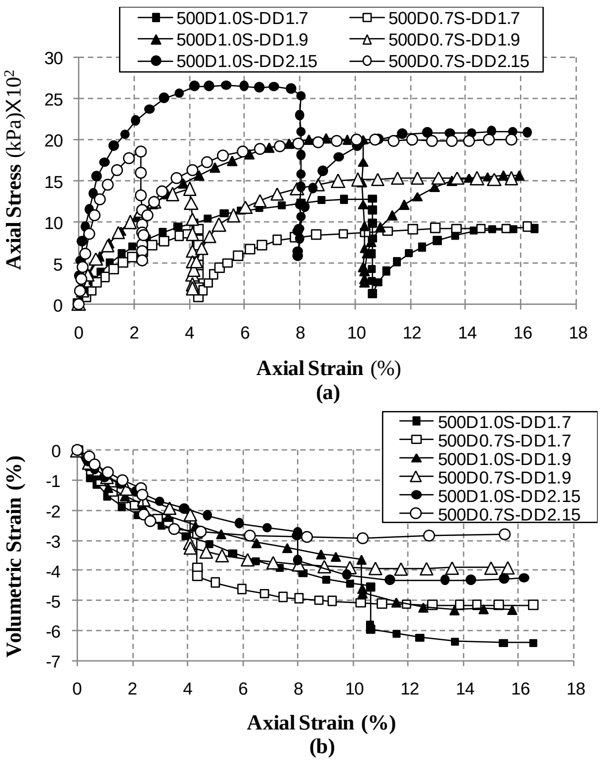

Figure 5. a) Axial stress-axial strain b) volumetric strain-axial strain behavior of series C tests, Effect of initial dry density

As seen in figures 2 to 5, in all of the dry-saturated tests saturation caused a sudden reduction of axial stress (representing shear strength of the specimens) in a constant axial strain. These behaviors were expected ([20], [21]); however, one of the purposes of this study was to estimate the value of this reduction and to find out its dependence (if any) to the fines content, maximum particle size and initial dry density of the material. When the specimens were completely submerged with water, the axial stress reached its minimum value and remained constant. Then the monotonic movement of the top cap restarted and the axial stress increased to a maximum value and stayed approximately constant to the end of the test.

The ratio of the minimum axial strength (deviatoric stress) of a submerged specimen at the end of the saturation process to the shear strength of the specimen before saturation is defined as the coefficient of stress recovery, C_{sr} and referring to figure 6, could be calculated by the following equation.

$$C_{sr} = \frac{\sigma_{d2}}{\sigma_{d1}} \tag{1}$$

Where σ_{d1} and σ_{d2} represent the deviatoric stresses before saturation and at the end of saturation process, respectively.

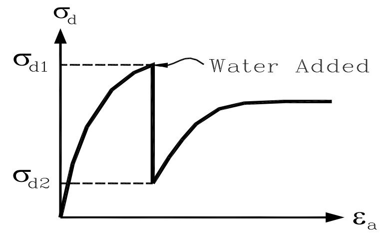

Figure 6. Typical behavior of dry-saturated specimens

The values of C_{sr} were calculated for all of the dry-saturated tests by applying equation 1. Figure 7 presents the variation of C_{sr} values versus materials maximum particle size (obtained from series A tests).

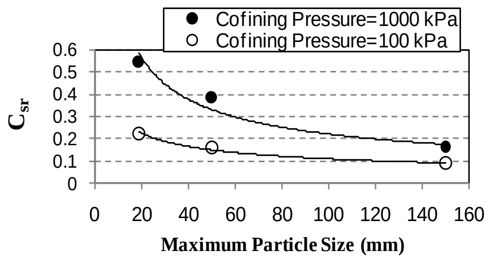

Fig 7. Coefficient of stress recovery (Csr) versus materials maximum particle size

Figure 7 shows that by increasing materials maximum particle size the coefficient of stress recovery (C_{sr}) decreases by a decreasing rate. This evidences that performing laboratory tests on the materials with limited particle sizes may underestimate the intensity of saturation-induced stress relaxation of the prototype materials. However greater accuracy may be achieved by employing large scale equipments with larger sample diameters (bigger maximum particle sizes). In the tests performed on the initially dry specimens in a specific dry density (and therefore in a constant void ratio), when the maximum particle size of the material increases or, in the other words, as the gravelly part of the material becomes coarser, the sizes of the solid particles and also the sizes of the voids increase. Therefore, the number of the contact points between rockfill particles per unit area decreases and accordingly the stress values at these contact points increase. This stress concentration could intensify the above-mentioned events that were found responsible for the collapse deformation phenomenon. Also according to figure 7, in a specified maximum particle size the tests performed in confining pressure of 1000 kPa show higher values of C_{sr} compared to the tests conducted in the confining pressure of 100 kPa. This was expected since the materials that experienced higher confining pressures become denser and more compressed before wetting. Therefore, during submerging the specimens tested in higher confining pressures will undergo smaller values of deformation and so their stress relaxation will be smaller.

The variation of C_{sr} values against materials fines content (obtained from series B tests) is presented in figure 8. Here increasing materials fines content decreases the coefficient of stress recovery (C_{sr}) at a decreasing rate. Also it could be seen that the value of shear stress level (SSL) in the moment of saturation does not have a significant effect on the variation of (C_{sr}).

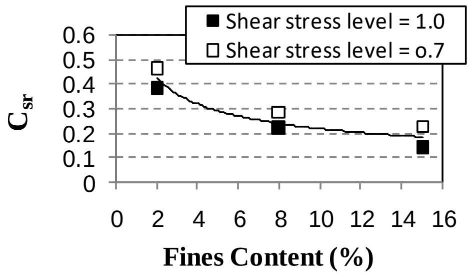

Figure 8. Coefficient of stress recovery (Csr) versus materials fines content

Plots of C_{sr} values versus initial dry density of the material (obtained from series C tests) are shown in figure 9. The coefficient of stress recovery (C_{sr}) increases as the initial dry density of the material increases. This could be explained considering the fact that the materials with higher values of dry density are denser, less deformable and therefore will undergo smaller values of strength sudden reduction caused by saturation. Figure 9 also indicates that the value of shear stress level (SSL) in the moment of saturation does not have a meaningful effect on the values of (C_{sr}) and the results obtained for two shear stress levels of 1.0 and 0.7 are pretty close to each other.

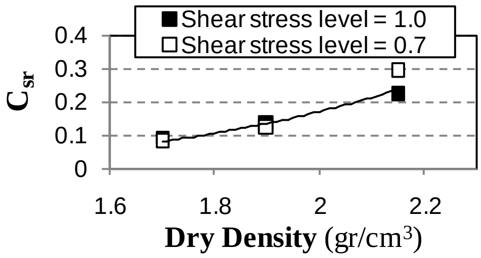

Figure 9. Coefficient of stress recovery (Csr) versus initial dry density

Making acceptable estimations of the values of collapse deformation of rockfill materials requires the development of a precise numerical modeling of this phenomenon ([22], [23]). Since the explained results were obtained using a limited number of tests for specific materials and for particular stress range applied in this study, therefore no equations are presented for the variations of C_{sr} against the aforementioned parameters. Nevertheless, finding out and using the C_{sr} coefficient could be an applicable approach to estimating the post saturation shear stresses, *e.g.* in a numerical analysis to specify the values of shear stresses in the elements one cycle after submerging.

4.2. INTERNAL FRICTION ANGLE

According to the literature saturation degrades the strength parameters of rockfill materials ([1],[4],[24],[25]). The results of dry-saturated tests were analyzed to probe the effects of materials maximum particle size, fines content and initial dry density on the intensity of this degradation. Figure 11 shows that the internal friction angles of the specimens in dry condition decrease when the materials become saturated.

Based on the results (figures 2a to 5a) for each specimen values of the maximum principle stresses, *i.e.* σ_1, could be obtained in dry condition. Therefore, considering no cohesion for the rockfill material the values of internal friction angles of the specimens in dry condition for each confining pressure are calculated. On the other hand, in dry-saturated tests and after submerging, for each confining pressure the final maximum shear strengths, the related values of σ_1 and therefore the internal friction angles of the specimens in saturated condition could be specified. Then the values of the reductions of the internal friction angles ($\Delta\phi_c$) due to saturation could be calculated for each specimen. Variation of these reductions (values of $\Delta\phi_c$) versus materials maximum particle size, fines content and initial dry density are presented in figures 10a to 10c, respectively.

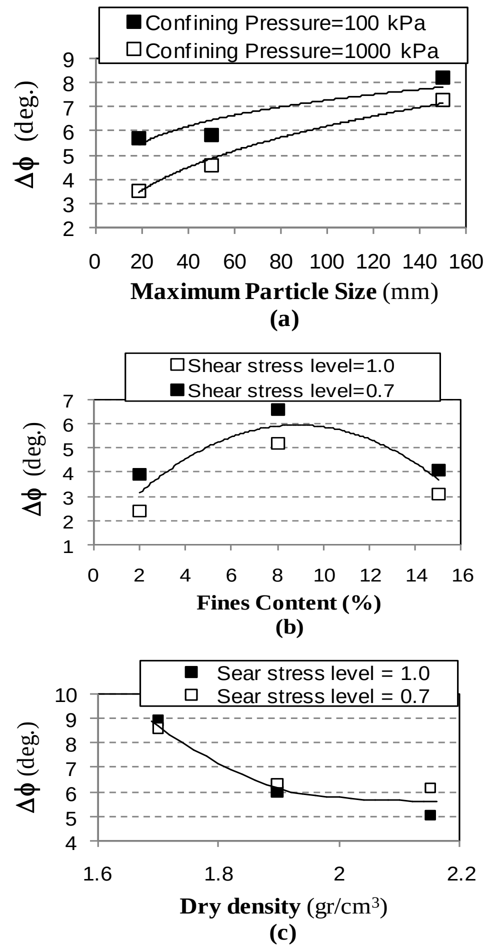

Figure 10. Reduction of internal friction angle due to saturation ($\Delta\phi_c$), a) versus material maximum particle size, b) versus fines content, c) versus initial dry density

Figure 10a indicates that the values of $\Delta\phi_c$ (reduction of the internal friction angle caused by saturation) increase as the material maximum particle size increases. The explanation for the variation of C_{sr} against maximum particle size offered above could also be applied here. It is also clear that the values of $\Delta\phi_c$ for tests performed in confining pressure of 1000 kPa are smaller than those obtained from tests carried out in confining pressure of 100 kPa. However, the values of $\Delta\phi_c$ obtained from tests performed in confining pressures of 100 kPa and 1000 kPa get closer to each other as the material maximum particle size increases.

According to figure 10b, increasing the material fines content from 2% to 8% increases the value of $\Delta\phi_c$ however more increase of the fines content from 8% to 15% decreases the value of $\Delta\phi_c$. therefore the values of $\Delta\phi_c$ for fines contents of 2% and 15% are pretty close to each other. Meanwhile the value of shear stress level (SSL) in the moment of saturation does not have a significant effect on the value of $\Delta\phi_c$.

Figure 10c indicates that increasing the initial dry density of the materials decreases the values of $\Delta\phi_c$ by a decreasing rate. This was expected because the materials with smaller initial dry densities are looser and will undergo more degradation of strength parameters due to submerging. However, the value of shear stress level (SSL) does not have a meaningful effect on the value of $\Delta\phi_c$.

4.3. DEFORMATION BEHAVIOR AND PARAMETERS

Turning to figures 2b to 5b, it can be seen that in comparatively low confining pressure of 100 kPa (related to series A tests with initial dry density of 2.15 gr/cm^3) dilation governs the deformation behavior of the material and a general trend of volume increase (positive values of volumetric strain) is observed during deviatoric loading due to relatively high dry density of the specimens. As confining pressure increases to higher values (*i.e.* 500 and 1000 kPa) the volume of the specimens decreases during deviatoric loading and the effect of dilation is not considerable. Figures 2b to 5b also shows that during the submerging process a sudden reduction in the volume of the specimens was observed in all of the dry-saturated tests (in a constant axial strain). This observation is compatible with the saturation-induced sudden settlements reported in the literature for odometer or direct shear tests on rockfill materials ([1], [3], [26]).

In order to evaluate the changes in the deformation parameters of the materials due to saturation, elasticity modulus of the specimens in dry condition and after submerging are specified. The initial elasticity modulus of the specimens in dry condition (E_{dry}) and the elasticity modulus of the material after submerging (E_{wet}) are calculated considering the axial stress-axial strain curves ($\square_a$-$\square_a$) obtained from the triaxial tests ([27]). The ratios of the elasticity modulus of the material after saturation to their elasticity modulus in dry condition, *i.e.*, (E_{wet}/E_{dry}), are calculated and the variation of this ratio (E_{wet}/E_{dry}) versus materials maximum particle size, fines content and initial dry density are illustrated in figures 11a to 11c, respectively.

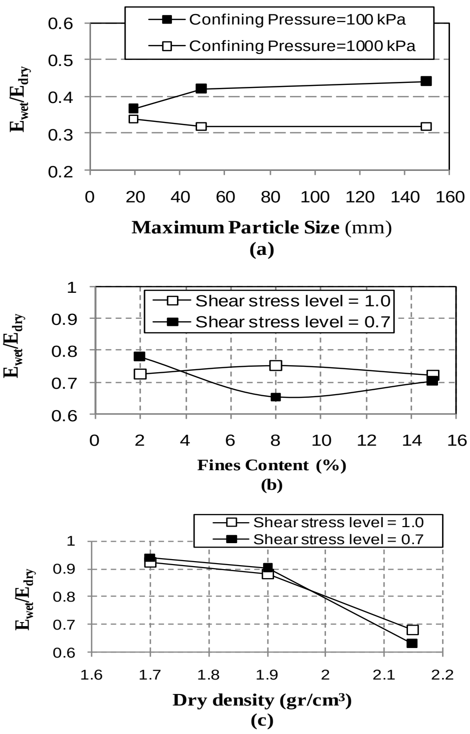

Fig. 11 Ratio of the saturated to dry elasticity modulus of the material (E_{wet}/E_{dry}), a) versus material maximum particle size, b) versus fines content, c) versus initial dry density

These figures show that the ratio of E_{wet}/E_{dry} is not affected by the material fines content and there is also no clear trend for the variation of this ratio (E_{wet}/E_{dry}) against material maximum particle size. However, the ratio of E_{wet}/E_{dry} decreases as the initial dry density increases. For the specimens with relatively low dry densities the material is initially loose and it has a relatively low value of elasticity modulus before submerging. Therefore, saturation could not cause a major reduction on its initially low elasticity modulus. So that the ratio of E_{wet}/E_{dry} increases to more than 0.9 for the materials with the dry density of 1.7 gr/cm^3 (figure 11c of series C tests).

5. CONCLUSIONS

A set of large-scale triaxial tests have been conducted to investigate the saturation-induced collapse settlement behavior of a rockfill material. Specimens were tested in dry-saturated conditions with three different material fines contents (percent passing #200 sieve), three maximum particle sizes and three different initial dry densities. The effects of gradation curve and initial dry density on the collapse settlement behavior of rockfill material were explored and the changes in the strength and deformeability parameters of these materials caused by submerging were evaluated.

According to the results of all of the dry-saturated tests a sudden reduction of axial stress (representing shear strength of the specimens) in a constant axial strain was observed due to saturation.

The ratio of the minimum axial strength (deviatoric stress) of a submerged specimen (at the end of the saturation process) to the shear strength of the specimen before saturation is defined as coefficient of stress recovery, C_{sr}. Results of dry-saturated tests showed that increasing materials maximum particle size decreases the coefficient of stress recovery (C_{sr}) by a decreasing rate. This evidences that performing laboratory tests on the materials with limited particle sizes may underestimate the intensity of saturation induced stress relaxation of the prototype materials. However, the value of this underestimation will reduce when large scale equipments with larger sample diameters (bigger maximum particle sizes) are employed. Based on the results, as the materials fines content increases, the coefficient of stress recovery (C_{sr}) decreases by a decreasing rate. In addition, the coefficient of stress recovery (C_{sr}) increases as the initial dry density of the material increases. Also it is obvious that the value of shear stress level (SSL) in the moment of saturation does not have a considerable effect on the variation of C_{sr}.

The results indicated that saturation degrades the strength and deformability parameters of the rockfill material. Results of dry-saturated tests showed that the values of internal friction angle reduction caused by saturation (□□$_c$) increase as the material maximum particle size increases. Furthermore, increasing the material fines content from 2% to 8% increases the values of □□$_c$ however then decreases as the material fines content increases from 8 to 15%. In addition, as the initial dry density of the material increases, the values of □□$_c$ decrease by a decreasing rate.

The results indicated that the ratios of the elasticity modulus of the material after saturation to their elasticity modulus in dry condition, *i.e.*, E_{wet}/E_{dry}, decreases as the initial dry density increases; however, the values of this ratio are not affected by the material fines content and there is also no clear trend for variation of this ratio (E_{wet}/E_{dry}) against material maximum particle size.

In all of the dry-saturated tests a sudden reduction in the volume of the specimens was observed during the submerging process (in a constant axial strain). This observation is compatible with the saturation induced sudden settlements reported in the literature for oedometer or direct shear tests on rockfill materials.

6. ACKNOWLEDGMENT

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