The effect of degree of saturation and consolidation pressure on monotonic behavior of reinforced earth seawalls

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Abstract: Reinforced earth structures are usually in contact with water, especially if these structures are designed as waterfront structures such as a riverbank protection structure, an earth dam or a marine wall. In these cases, the effects of saturation must be considered in the design and analysis stages. For reinforced earth seawalls, which are located in a tidal environment and subjected to the dynamic loading of sea waves, the effects of saturation are of particular concern. From the early 1960's when reinforced earth was introduced by Henri Vidal, much research has been carried out with the aim of estimating the improvement in shear strength of reinforced earth compared to that of unreinforced soil. In these investigations the researchers tried to determine the ultimate shear strength of reinforced earth. This paper aims to examine the behavior of a saturated reinforced sand element (e.g. a reinforced sample in triaxial test) in an undrained fully saturated condition. The results of this study will be used later to describe the behavior of a fully saturated reinforced earth seawall under the effect of rapid impact loading due to sea wave or ship impact. Initially, triaxial tests were performed on dry and fully saturated reinforced and unreinforced beach sand. The results of saturated reinforced and unreinforced samples were compared with those of dry samples. In this comparison, different features such as the stress-strain relationship, failure mode and strength parameters Ø and c were considered.

[Farzad Daliri, Ali Karami Khaniki. **The effect of degree of saturation and consolidation pressure on monotonic behavior of reinforced earth seawalls.** Journal of American Science 2012; 8(2):349-356]. (ISSN: 1545-1003). http://www.americanscience.org. 50

Keywords: Earth seawalls, Reinforced soil, Triaxial test

1. Introduction

The frictional interaction between the soil and reinforcement is responsible for the greater strength of reinforced soil relative to unreinforced soil. This is also clearly supported by Hausmann (1976 & 1990), Chapuis (1977), Schlosser (1990), and Fukushima, Mochizuki and Kagawa (1988). This frictional interaction depends on three main groups of parameters such as reinforcement characteristics, soil properties and overburden pressure (vertical stress). Saturating the soil changes the soil properties and effective vertical stress on the reinforcement. Consequently, it can affect the frictional interaction between the soil and reinforcement, and finally the pullout resistance of the reinforcement.

According to Bowels (1979), the changes of soil properties due to saturation are considerable for cohesive soils, but are negligible for cohesion less materials, which are usually used for reinforced earth. Therefore, for reinforced earth seawalls of cohesion less soil (usually beach sand); it is not necessary to evaluate the saturation effects through changing the soil properties. For these structures the only way that saturation can affect the strength of the structure, is by changing the effective vertical stress on the reinforcement layers.

The change of effective vertical stress due to saturation must be observed in the pore water pressure generated in the soil mass. The value of pore water pressure generated in the sand during shearing is critically dependent on the void ratio (or density) of the sand (Bowels, 1979) and the degree of saturation. The generation of pore pressure in dense sand (with low void ratio) is different from that in loose sand (with high void ratio). Dense sand will have negative pore pressure induced in it because of the dilation phenomenon, while loose sand will have positive pore pressure induced due to volumetric compaction. The value of pore water pressure is also dependent on the degree of saturation. A decrease in the degree of saturation is associated with a decrease in the generated pore pressure. For the purpose of this study, the degree of saturation is considered to be close to 100% (fully saturated), which is critical.

Regarding the above discussion, pore water pressure is expected to be the main factor in evaluating the effect of saturation on the behavior of reinforced sand. This contribution can be observed in the different parameters of reinforced earth such as: shape of failure surface, shape of stress-strain curves, ultimate strength, and apparent shear strength parameters c and Ø. In continuation of this paper the effect of saturation on these parameters will be investigated with respect to changing pore water pressure in the soil.

2. Previous Studies on Reinforced Soils

The effect of saturation on reinforced earth has already been studied by Ashaari (1990), Ahmad (1990), and Elias et.al (1983). In 1990, Ashaari performed direct shear tests on dry and fully saturated reinforced sand using a large scale shear box, to evaluate the effect of reinforcement in submerged sand. The tests were carried out in an unconsolidated-undrained condition, while applied normal stress varied from 6.75 to 14.44 kPa. In these tests, pore water pressure was not directly measured. The conclusion from these tests was that the total shear strength parameters (Ø and c) of submerged reinforced sand in an undrained condition are higher than those of dry reinforced sand, but the effective strength parameters (Ø' and c') are the same for both of them.

In another investigation in 1990, Ahmad studied the effect of saturation and the water table location on the behavior of a reinforced soil wall, using a small scale model box. The fill material was beach sand, and aluminum strips were used for reinforcement. In this study four series of model walls were constructed with different water levels. From this investigation, it was concluded that raising the water level in the wall is associated with a reduction in the failure height or overall strength of the wall. In 1983, Elias et. al. investigated the effect of saturation and moisture content on the strength of a reinforced earth wall made from cohesive soil. In this study, he used fine-grained residual soils as reinforced earth backfill. He employed extensive laboratory testing on reinforced earth model walls with different fine and moisture content. The tests results demonstrated the reduction in strength with increasing fines and water content. According to his report, fines and moisture content caused reduction of strength, which resulted in wall deformations.

3. Investigation Method

Different experimental methods such as a triaxial test or direct shear test can be used to investigate the effect of saturation on shear strength of reinforced soil. For cohesionless soils, the direct shear test is easier. In comparison with the direct shear test, the triaxial test is more complicated and time consuming, but it presents more reliable values of soil parameters and stress-strain data (Bowels, 1979). The main problem in using both direct shear test and triaxial test is in the preparation of reinforced soil samples for the test. Preparing samples, especially for triaxial tests, is difficult and time consuming. Triaxial test was selected for this investigation because of its accuracy. The actual tests were performed on a computerized triaxial testing system, which provided accurate results.

Different types of triaxial tests such as UU, CD, and CU can be performed in the study. Since the permeability of cohesionless soils is too high, in normal conditions (under normal loading) it tends to drain. In this condition there is no advantage in using the undrained test. However, for special abrupt loadings occurring as a consequence of earthquake, blast and sea wave loading, it is necessary to use an undrained test (Bowels, 1978). In these cases, the loading process is so rapid that the soil actually remains undraind during the impact loading. Therefore, the UU test with pore pressure control was selected for saturated samples in this investigation. To provide similarity, the dry specimens were also tested in the same condition as the saturated samples (The back pressure valve in the triaxial machine was closed).

4. Laboratory Program and Material

To obtain good quality data, a computerized triaxial system (GDS Triaxial Testing System (John, 1986) was used in this investigation. The GDS Triaxial System consists of three main parts: a hydraulic triaxial cell, digital controllers, and a PC computer. Two different sizes of sample (38mm and 50mm in diameter) can be tested in the triaxial cell. The larger one was used for this investigation. In the GDS system the sample is loaded within a triaxial cell with the water pressure being applied by hydraulic jacks. Each hydraulic jack was controlled by a digital controller connected to a PC computer. All data were taken automatically and stored on the computer's hard disk. GDS Triaxial system is able to carry out various types of triaxial tests such as UU, CU, CD, K_0 consolidation, continues linear stress paths, and cyclic loading.

The soil used for the tests was medium-to-fine beach sand with rounded particles. The dry unit weight of the soil was 16.2 kN/m^3 at e=0.8 and 14.7 kN/m^3 at e=0.65. The saturated unit weight at 98 percent of saturation degree was 20.2 kN/m^3. The grain size varied from 0.1mm to 1.8mm with a median size of 0.4mm.

Aluminum foil disks were used as reinforcement. These aluminum disks were 45mm in diameter with a 6mm diameter hole in the center, and 0.018mm thick. This hole was used to facilitate the saturation of the sample. Figure 1 shows a reinforced earth element in triaxial test. The friction coefficient, "f", between the sand and aluminum foil was found to depend on the level of normal stress applied to the reinforcement. Table 1 shows a variation of "f" with normal stress. The ultimate tensile strength of aluminum foil was 96000kPa.

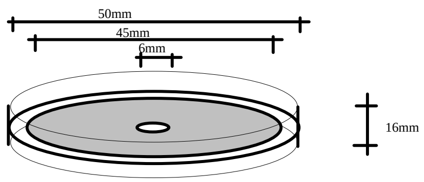


Figure 1. Reinforced earth element in triaxial test

Table 1. Variation of coefficient f with normal stress

Normal Stress (kPa)	Friction Coefficient f
28	0.31
56	0.327
70	0.335
155	0.404
436	0.49

To compare the behavior of reinforced sand with unreinforced sand in both dry and saturated conditions, the following four cases were considered:

- Unreinforced dry samples
- Unreinforced saturated samples
- Reinforced dry samples
- Reinforced saturated samples

For each of the above cases, nine samples were considered and tested at different nominal cell pressures: 10, 20, 30, 40, 50, 75, 100, 125 and 150 kPa. Each sample was 112 mm in height and 50mm in diameter. The spacing between the reinforcement layers was 16mm. The samples were prepared on the triaxial machine. Meanwhile, the rubber membrane was placed on the machine cap and then the layers of sand (7 layers, each layer 16mm thick) and aluminum foil (6 layers) were sequentially placed in the rubber membrane. For the saturated samples, the soil was saturated by injecting the water into the bottom of the sample. The air in the saturated samples was evacuated using a vacuum pump connected to the top of the sample. For unreinforced saturated samples a vacuum pump with a maximum negative pressure of 55kPa was used. For reinforced saturated samples evacuating the air from the sample was more difficult, so a more powerful vacuum pump with a maximum negative pressure of 95kPa was used for these samples. Each sample was vacuumed for an hour. After evacuating the air from the saturated sample, it was consolidated at zero back pressure by opening the back pressure valve connected to a de-aired water container. In the loading stage, the back pressure valve was closed and the tests were carried out in undrained condition. Each test continued until an axial strain of 20 percent was reached with a loading speed 50mm per hour.

5. Test Results

For each test, 27 different parameters were computed and stored on disk. Some of these parameters were: axial strain, axial stress, radial stress, effective axial stress, effective radial stress, deviator stress, stress ratio, pore water pressure.

Typical stress-strain curves (deviator stress versus axial strain) for 10, 30, 50 and 100kPa of lateral pressure are presented in Figure 2. The sample characteristics at failure (peak values) are tabulated in Table 2. In this table there are some small values of pore pressure reported for dry samples which are related to the air pressure inside the samples and recorded by the machine. These values caused small differences between the total and effective stresses for dry samples, which are not significant. In order to analyze the effects of saturation on the behavior of reinforced sand, the shape of the failure surface, the stress-strain curves, the ultimate strength line and the failure envelope of reinforced saturated samples have been compared with those of reinforced dry samples (Figures 2 to 5). Based on these figures, the effect of saturation on the different strength characteristics of reinforced sand is discussed.

The shape of the failure surface for the unreinforced dry samples under different cell pressures was an inclined plane with an angle of about 32.8 degree to the vertical. For the reinforced dry samples, the shape of the failure surface was a function of the cell pressure. Under high cell pressure (40kPa and more), the failure surface was a plane exactly like that for the unreinforced sample (see Figure 3a), but under low cell pressure (10kPa and smaller) the shape of the failure surface was completely different (See Figure 3b). Under high cell pressures some layers of reinforcement (2 layers) were torn when the sample failed. In this case failure of the sample was associated with rupture of the reinforcement. Under low pressure the reinforcement layers were not damaged but the sand layers expanded laterally (See Figure 3b), so in this case the failure of the sample was associated with failure of the bond between the soil and reinforcement (pull-out failure). Although the shape of the failure surfaces of dry reinforced samples is different under high and low cell pressure, the saturated reinforced samples exhibit the same shape of failure surface under all cell pressures. The shape of the failure surface for a saturated reinforced sample is an inclined plane under all cell pressures (Figure 3c and Figure 3d). The type of failure mode could be also understood by inspecting the shape of the stress-strain curve.

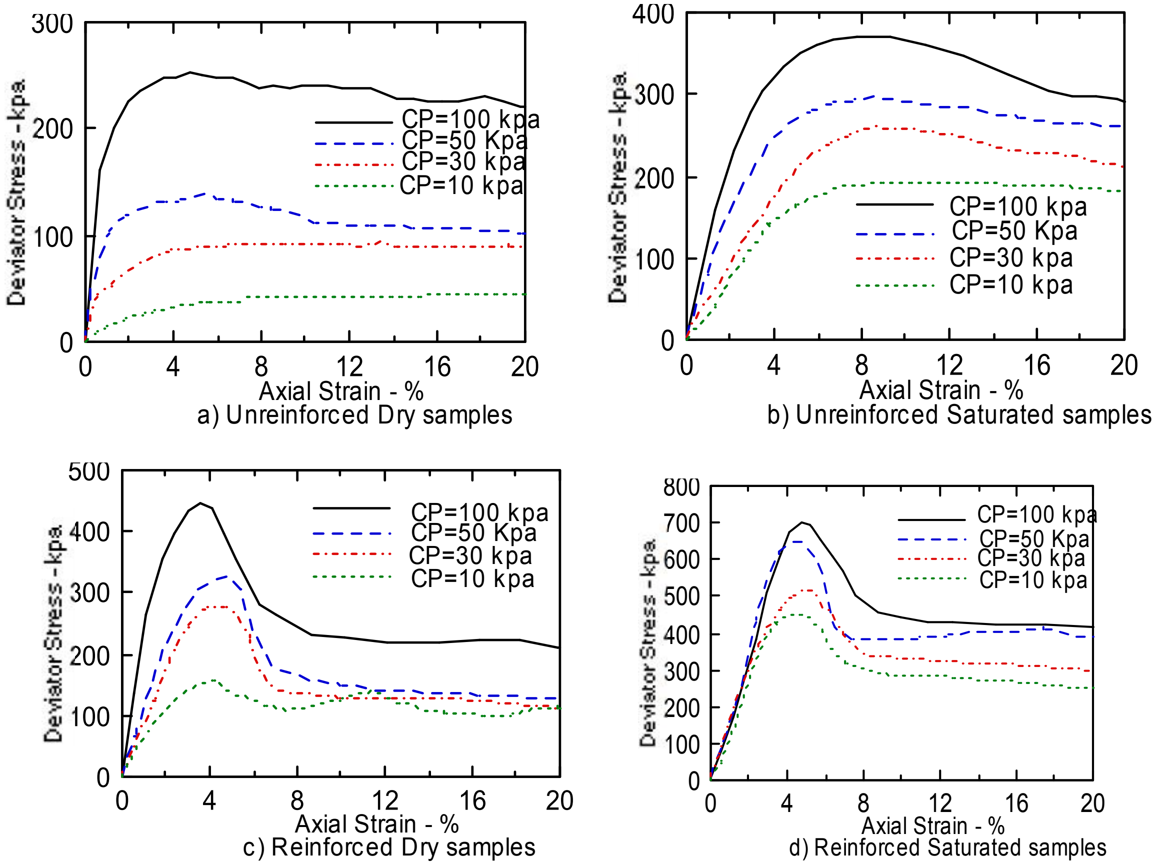
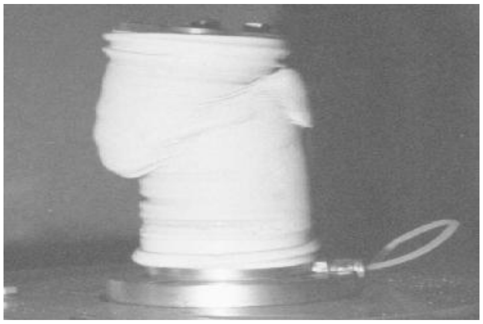


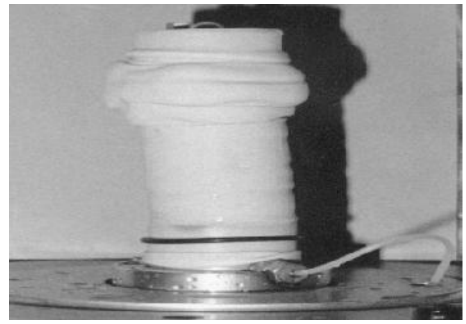
Figure 2. Typical stress-strain curves for reinforced/unreinforced dry/sat. Samples

Table 2. Strength characteristics of saturated samples at failure

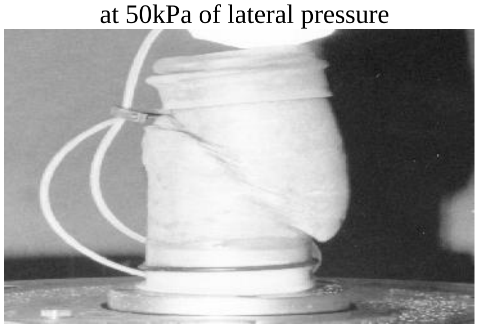
	Total	values	Effective	Values	pore pressure at failure
	$_{3}$ kPa	$_{1}$ kPa	$'_{3}$ kPa	$'_{1}$ kPa	kPa
Unreinforced Saturated Samples	10.9	203.5	79.5	272.1	-68.6
	21.1	238.5	83.7	301.1	-62.6
	31.5	289.3	94.4	352.2	-62.9
	41.4	287.6	97.1	343.3	-55.7
	50.7	344.9	119.7	413.9	-69.0
	76.1	451.2	139.1	514.2	-63.0
	100.0	481.4	156.8	538.2	-56.8
Reinforced Saturated Samples	11.5	460.0	99.3	547.8	-87.8
	20	462.2	87.0	529.2	-67.0
	31.5	546.7	116.9	632.1	-85.4
	40.6	632.3	121.5	713.2	-80.9
	51.1	700.0	142.1	791.0	-91.0
	70.0	703.4	148.5	781.9	-78.5
	75.0	775.0	-	-	-
	100.5	800.9	187.1	887.5	-86.6



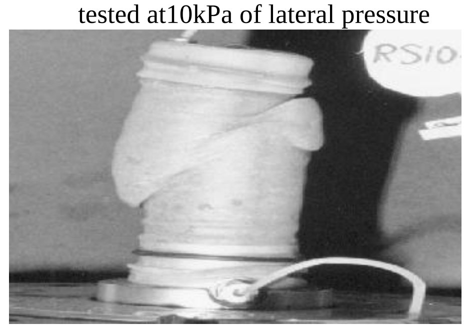
a) Reinforced-Dry sample at 50kPa of lateral pressure



b) Reinforced-Dry sample tested tested at10kPa of lateral pressure

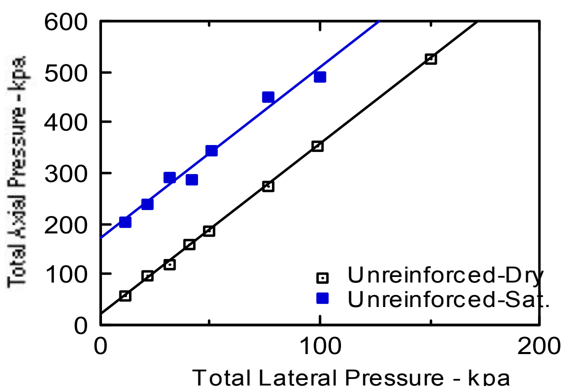


c) Reinforced-Saturated sample tested at 40kPa of lateral pressure

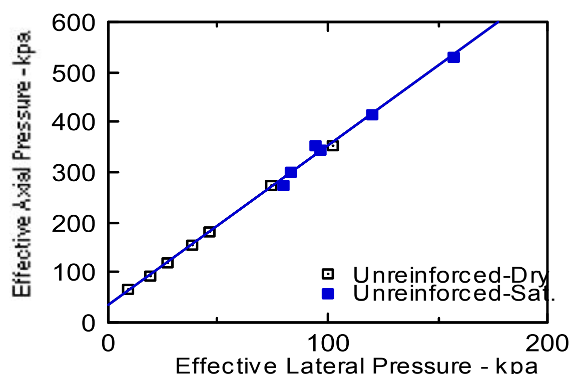


d) Reinforced-Saturated sample tested at 10kPa of lateral pressure

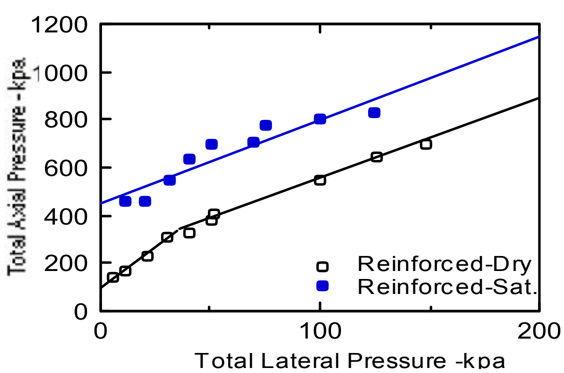
Figure 3. Effect of saturation on the shape of failure surface



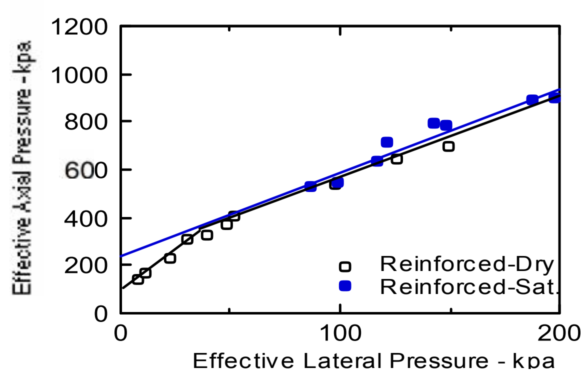
a) Unreinforced, Total values



b) Unreinforced, Effective values



c) Reinforced, Total values



d) Reinforced, Effective values

Figure 4. Effect of saturation on ultimate strength of reinforced/unreinforced sand

According to Figure 2c, it is clear that the stress-strain curve for the reinforced dry sample tested with 10kPa of cell pressure (low pressure) has more than one peak. It shows that the sample actually failed more than one time. At the first time one layer of soil (i.e. the layer between the two layers of reinforcement) expanded laterally. Further pressure resulted in the second layer starting to expand laterally and hence the second peak was generated on the stress-strain curve. Figure 2 shows that the stress-strain curves for saturated reinforced samples under different cell pressures are very similar, even under low pressure. Although dry reinforced samples under low cell pressure (e.g. 10 kPa) had a multi-peak stress-strain curve, this was not the same multi-peak as for the saturated reinforced sample under the same cell pressure. This clearly indicates that saturated reinforced samples failed by rupture of the reinforcement, even under low pressure. This fact is also confirmed by the shape of failure which explained already (Figure 3).

The strain at failure for reinforced saturated samples was about 4.5%, approximately the same as for reinforced dry samples. Therefore, it can be said that saturation has no significant effect on the position of the peak point (or strain at failure). The maximum axial stress of each sample versus the related lateral pressure is plotted for reinforced and unreinforced sand in Figure 4, respectively. As this figure shows, for unreinforced sand the total strength line is parallel to that for dry sand and its effective strength line coincides with that for dry sand. The same is not true for reinforced sand. In Figure 4c, the total strength line of saturated reinforced sand is parallel to that for dry reinforced sand only under high lateral pressures. This is because the failure mode of saturated reinforced samples under low cell pressure differs from the failure mode of the dry reinforced sample under the same cell pressure. According to Figure 4d, it is clear that the effective ultimate strength line of saturated reinforced samples does not completely coincide with that of the dry reinforced samples, and saturated samples exhibit higher effective strength than dry samples under the same cell pressures. Under low cell pressure this difference is due to the different failure modes, but under high cell pressure it is caused by increasing density in sand. A saturated dense sample produces a large negative pore pressure which actually increases both the lateral and axial stresses and finally causes a higher density of the soil. The strength parameters Ø and c, of reinforced and unreinforced saturated and dry samples had been tabulated in Table 3. Table 3a shows a small value of cohesion for unreinforced sand (c=5.45 kPa) and also for reinforced sand in low pressure (c=17.91 kPa). These values of cohesion are related to the effect of the rubber membrane used in the triaxial test. Table 3 also shows a relatively high value of cohesion (c=57.37 kPa) for reinforced dry sand under high cell pressure. A small part of this value (5.45 kPa) is due to the effect of the rubber membrane, but most of it (i.e. about 52 kPa) is related to the existence of the reinforcement layers in the sand samples. This apparent cohesion was caused by the additional lateral pressure generated by frictional interaction between the soil and reinforcement. In Figure 5 the failure envelope of unreinforced and reinforced saturated sand are compared with those for dry sand. Based on Table 3 and Figure 5, it is concluded that saturation has a considerable effect on the failure envelope of reinforced sand under low pressure, but under high pressure it has no significant effect. As a summary of this discussion, Figure 7 compares the behavior of reinforced saturated sand with that of reinforced dry sand.

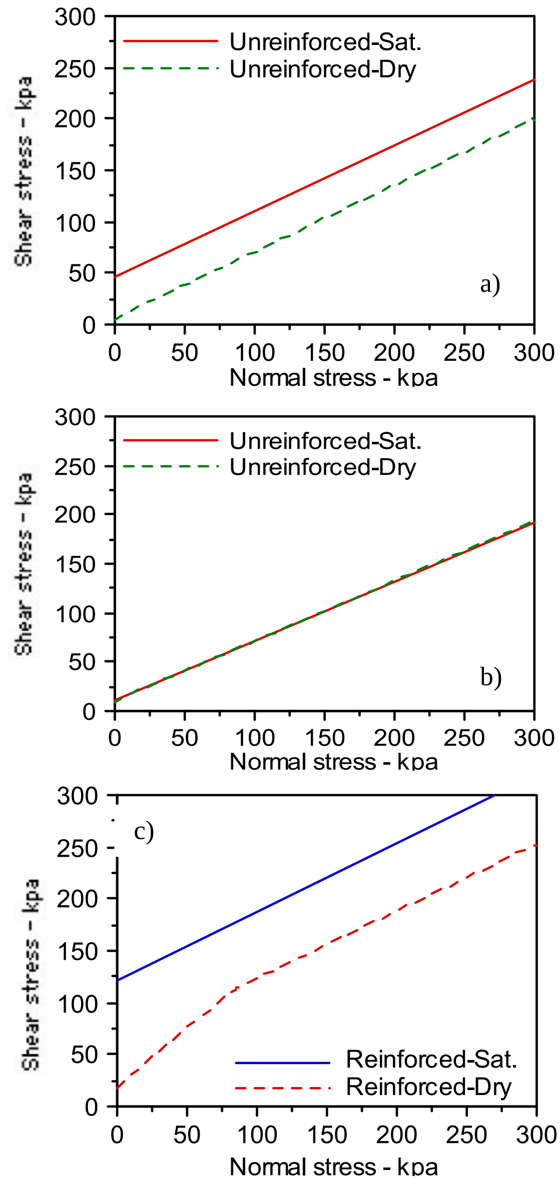


Figure 6. Effect of saturation on failure envelope of reinforced/unreinforced sand for a) unreinforced total values, b) unreinforced effective values, c) reinforced total values.

Table 3. Effect of saturation on strength parameters of unreinforced and reinforced sand

a) Dry

	unreinforced samples	reinforced samples	
	all pressures	low pressures	high pressures
c (kPa)	5.45	17.91	57.37
Ø(degree)	32.80	47.98	32.78
c' (kPa)	9.5	16.27	61.76
Ø'(degree)	31.41	48.3	30.93

b) Saturated

	unreinforced samples	reinforced samples
	all pressures	all pressures
c (kPa)	46.41	121.36
Ø (degree)	32.76	33.63
c' (kPa)	10.11	65.57
Ø' (degree)	31.29	33.74

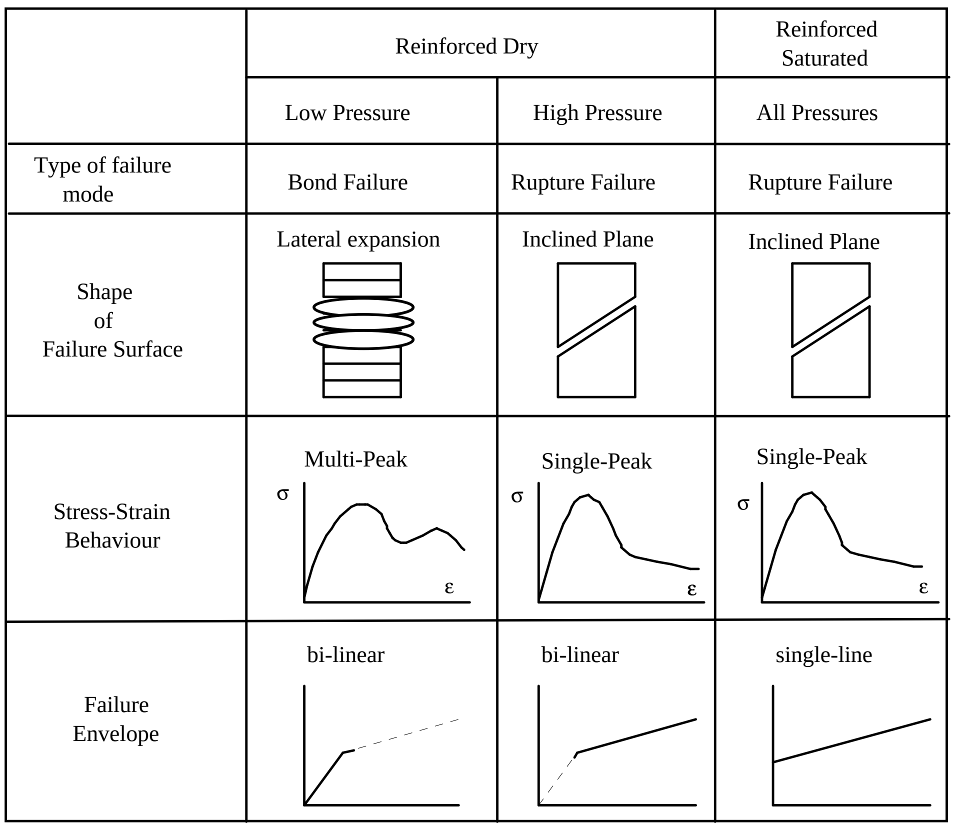


Figure 7. Summary of Effect of saturation on behaviour of reinforced sand in undrained triaxial test

6. Conclusion

The saturation effect on the strength of a reinforced earth element depends on three main factors comprising: backfill type (cohesionless, cohesive); saturation state (fully saturated, partially saturated); and draining condition during shearing (drained, undrained). Since the reinforced earth marine wall is mostly made from cohesionless soil, this type of soil was used exclusively in this investigation.

For cohesionless materials, if the soil can drain in site during shearing, saturation has no considerable effect on the strength, but this effect is considerable if the soil mass is fully saturated and draining prevented. The last case is like the condition of a fully saturated reinforced earth seawall under the rapid impact loading of sea wave or ship collision.

To model this condition on a reinforced earth seawall, some triaxial tests were conducted on dry and fully saturated reinforced and unreinforced sand. A comparison between the behavior of saturated reinforced sand in undrained triaxial test with that of dry reinforced sand gives following results: (Figure 7).

- The saturation has no considerable effect on the value of strain at failure.
- Under high pressures, the shape of the failure surface is the same as for both dry and saturated reinforced sand.
- Under low pressures, the shape of the failure surface for saturated reinforced sand is completely different from that of dry one.
- The ultimate strength of fully saturated reinforced sand in undrained condition is considerably higher than that of dry sand. This is because of negative pore pressure generated in the sand due to dilation of dense sand during shearing.
- While the dry reinforced sand shows a bi-linear failure envelope, the failure envelope of saturated reinforced sand is a straight line for both the total and the effective values of stresses.

It must be noted that the improvement of ultimate strength of reinforced sand due to saturation is only for an undrained condition (e.g. when the structure to be subjected to rapid shock loading). For the cases where the structure is subjected to normal loading when the loading time is too long, this improvement cannot be obtained.

It can be concluded that a saturated reinforced earth element built from cohesionless material generally exhibits an ultimate strength not less than that of a dry one. However in some cases, due to being subjected to a rapid shock loading, it exhibits higher strength than a dry reinforced earth element.

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