

Research Article

Undrained Cyclic Response and Resistance of Saturated Calcareous Sand considering Initial Static Shear Effect

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Sand elements in the natural or manmade field have often undergone initial static shear stresses before suffering cyclic loading. To explore the effect of static shear stress, a series of undrained cyclic triaxial tests were performed on dense and loose calcareous sand under different initial and cyclic shear stresses. The triaxial test results are used to describe the effect of static shear stress on the cyclic response of the calcareous sand with different relative density. Cyclic mobility, flow deformation, and residual deformation accumulation are the three main failure modes under varying static and cyclic shear stress levels. The cyclic resistance of dense sand is greater than that of loose sand, but the initial static stress has different effects on the cyclic resistance of the two kinds of sand. The dense sand owns a higher cyclic resistance. The dense sand has more fast accumulation of dissipated energy, compared with loose sand. Additionally, an exponential relationship is established between static shear stress, relative density, and normalized energy density.

1. Introduction

With the implementation of the Belt and Road Initiative, calcareous sand, biogenic sediment and skeletal remain of marine organism, has been a topic of interest among geotechnical researchers recently [1, 2]. It is widely distributed in the continental shelf and coastline of tropical and subtropical climate between north and south latitude 30 degrees, such as the eastern and western of the Caribbean Sea, the Pacific Islands, the western of the Indian Ocean, and Nansha Islands and Xisha Islands in the South China Sea [3, 4]. Compared to terrigenous sand, the main composition is calcium carbonate [5, 6]. The characteristics of calcareous sand are high crushability, irregular particle shape, complex microstructure, and high intraparticle void [7, 8]. Therefore, the mechanical behaviors are quite different from those of silica sand [9– 11]. Over the past few years, calcareous sand has been used as a kind of filling material in geotechnical engineering, and the engineering challenges (e.g., embankment subsidence, retaining wall stability, and ground improvement) are becoming more and more complex. In order to promote the process of island and reef infrastructure construction, it is necessary to further study calcareous sand.

Many investigations have been carried out to explore the mechanical properties of calcareous sand. Using triaxial tests at high pressure to study uncemented Dog's Bay sand, the results showed that, despite particle breakage, its properties were still similar to those of the common soil observed [12]. And it was consistent with the principle of critical state soil mechanics. However, a series of static and dynamic experimental programs including direct shear tests, compression tests, triaxial tests, and resonant column tests were designed to reveal the difference between silica sand and Cabo Rojo sand with a similar grain size distribution [13, 14]. The

research claimed the latter expressed a more ductile and contractive behavior and had higher peak friction angles which is relative to the shear rate. Besides, liquefaction of calcareous sand has been an interested theme to examine mechanical properties among geotechnical scholars. It is a phenomenon that results from collapse deformation following the unstable behavior of saturated loose or dense sand at the state of low mean effective stress and shear strength [15, 16]. The liquefaction-type behavior, which may produce the most devastating effects of all catastrophic damage (e.g., the spreading of embankments and dams), can be induced under either monotonic or cyclic loading conditions [17, 18].

It is well known that sand elements in the natural or manmade field have often undergone an initial static shear stress prior to suffering from cyclic loading, which is caused by wave, traffic, wind, and earthquakes [19, 20]. Under the combined action of initial static and cyclic stress, the saturated sand foundation is prone to landslide, foundation instability, and subsidence, which is very harmful [21-23]. Therefore, the liquefaction behavior considering initial static shear stress has become one of challenging topics in geotechnical engineering [18, 24]. The results obtained by a lot of triaxial tests, taking into account initial static and cyclic deviatoric stress, proved that different stress conditions resulted in two types of cyclic behavior: CM and RDA [25]. Therefore, how to analyze the liquefaction is becoming more and more important. Since the pioneering work of David and Berrill [26], the dissipated energy concept was a convenient method. It was first introduced following the assumption of Nemat-Nasser and Shokooh [27] that the dissipated energy per unit volume resulting from the breakdown of soil skeleton was directly related to the pore pressure buildup. This could be an efficient way in evaluating the liquefaction potential of sand under both uniform and irregular cyclic stress conditions. In the last few decades, various studies have focused on establishing the relationship between the incremental pore pressure and dissipated energy obtained from stress-strain loops in undrained cyclic tests. As such, Kokusho and Pan and Yang [28, 29] further indicated that the energy dissipation correlated well not only with the generated pore pressure but also with the induced strain. The foregoing studies were mainly concerned with the energy-pore pressure or energy-strain relationship. Apart from these, the experimental work confirmed that the amount of energy dissipation that led to liquefaction failure (full pore pressure buildup or development of a specific strain) increased with soil density, confining pressure, and sustained shear stress level [30-32]. Although these previous studies have afforded valuable data for the energy-based evaluation of liquefaction potential, the validity of this method remains uncertain when it is applied to evaluate the cyclic resistance of calcareous sand under various initial and cyclic stress conditions.

In the present study, undrained cyclic triaxial tests were carried out. The results are composed of two parts: in the first part, through a comparison between loose and dense calcareous sand considering various initial static shear effect, cyclic



FIGURE 1: CKC automatic triaxial test system.

TABLE 1: Physical properties of calcareous sand.

Gs	<i>d</i> ₆₀ (mm)	$d_{30} ({\rm mm})$	$d_{10} ({\rm mm})$	$C_{\rm u}$	$C_{\rm c}$
2.79	2.60	0.88	0.38	6.84	0.78



FIGURE 2: Grain size distribution curves of calcareous sand.

shear responses of liquefaction are explored. On the other hand, through the energy-based liquefaction analysis, the dissipated energy could be uniquely correlated with cyclic resistance.

2. Laboratory Test Method

2.1. Apparatus and Material. An advanced system, CKC automatic triaxial test system shown in Figure 1, was used in this study to achieve the undrained circulation triaxial test. The system could convert the computer output digital signal into analog signal and then enter the electric-gas conversion system and control the air pressure amplifier to apply the air pressure. Thus, isotropic and anisotropic



FIGURE 3: Categories of stress conditions considered in this study: (a) stress reversal; (b) no stress reversal; (c, d) intermediate.

consolidation and applying various cyclic loading modes could be realized.

The test material used in this study, calcareous sand, is biogenic sediments and skeletal remains of marine organisms retrieved from the reef reclamation site in Nansha Island, South China Sea. A natural grading with a grain diameter less than 5.0 mm was retained for testing. The physical parameters are shown in Table 1. Figure 2 shows the particle size distribution curve of calcareous sand used in this study. The investigated materials have poor distribution, containing coarse and medium sand without fine particles.

2.2. Test Program. The specimens of 70 mm in diameter and 140 mm in height were used in this triaxial test, which were prepared by using the moist undercompaction method as stated by Kim et al. [33]. Before the triaxial sample was mounted on the loading frame, carbon dioxide and deaired water were circulated through the specimens successively. Subsequently, a backpressure of 300 kPa was applied to obtain a high degree of saturation. And finally, specimens can be considered to reach the saturation state with Skempton's *B*-values exceeding 0.95 for all of the samples presented in the study.

The saturated specimens were then isotropically consolidated to the mean effective stress $p_0' = 100$ kPa under drainage conditions and subsequently anisotropically consolidated to a desired q_s along a constant p' = 100 kPa path under drainage conditions likewise.

The specimens with various q_s were then loaded by the different q_{cvc} as follows:

$$q(t) = q_{\rm s} + q_{\rm cvc} \sin \left(2\pi ft\right),\tag{1}$$

where f = 1 Hz and t is the elapsed time. The cyclic stress paths are divided into "shear stress reversal," "no shear stress reversal," and "intermediate" [34], as shown in Figure 3.

As listed in Table 2, undrained cyclic tests were performed with dense calcareous sand samples ($D_r = 70\%$) and loose calcareous sand samples ($D_r = 30\%$) and were designed to consider various combinations of the static stress ratio (SSR = $q_s/2p_0'$) and cyclic stress ratio (CSR = $q_{cyc}/2p_0'$).

3. Cyclic Response and Failure Modes under Initial Shear Stress

Figures 4 and 5 show the typical response of saturated dense sand and loose calcareous sand under cyclic loading. Figures 4(a)-4(c) are the effective stress path (q-p') and stress-strain curve $(q-\varepsilon)$ relations of dense sand with $D_r =$ 70% under the condition of isotropic consolidation and initial static deviator-stress of compression and tension, respectively.

Figure 4(a) shows the typical response of saturated dense sand with isotropic consolidation suffering from symmetric cyclic load (SSR = 0, CSR = 0.125) under the condition of stress reversal. It can be seen from the effective stress path in the figure that, under the condition of being undrained, the effective stress of the test sample decreases continuously with the cyclic loading. At the end of the cycling stage, cyclic response is characterized by a "butterfly" effective stress path, which can be interpreted as the constant conversion between dilatancy and contraction of the sample throughout loading and unloading; the deviatoric stress of the sample approaches zero. The axial deformation develops slowly in the first 71 cycles and rapidly in the last 3 cycles at both the

Series	<i>D</i> _r (%)	$q_{\rm s}$ (kPa)	$q_{\rm cyc}$ (kPa)	SSR	CSR	Stress condition	N_{f}
		0	20	0	0.1	Reversal	232
		0	25	0	0.125	Reversal	74
		0	30	0	0.15	Reversal	17
		0	40	0	0.2	Reversal	6
		20	30	0.1	0.15	Reversal	168
		20	45	0.1	0.225	Reversal	19
		20	50	0.1	0.25	Reversal	3
		50	50	0.25	0.25	Intermediate	53
		50	60	0.25	0.3	Intermediate	11
	70	50	70	0.25	0.35	Reversal	6
Ι		80	70	0.4	0.35	Intermediate	14
		80	80	0.4	0.4	Intermediate	7
		-10	25	-0.05	0.125	Reversal	78
		-10	30	-0.05	0.15	Reversal	39
		-10	35	-0.05	0.175	Reversal	8
		-20	20	-0.1	0.1	Intermediate	210
		-20	25	-0.1	0.125	Intermediate	11
		-20	30	-0.1	0.15	Intermediate	8
		-40	20	-0.2	0.1	No reversal	57
		-40	25	-0.2	0.125	No reversal	16
		-40	30	-0.2	0.15	No reversal	8
ΙΙ	30	0	15	0	0.075	Reversal	943
		0	20	0	0.1	Reversal	120
		0	25	0	0.125	Reversal	37
		0	30	0	0.15	Reversal	18
		24	30	0.12	0.15	Intermediate	61
		24	35	0.12	0.175	Intermediate	16
		24	40	0.12	0.2	Intermediate	5
		40	15	0.2	0.075	No reversal	175
		40	20	0.2	0.1	No reversal	9
		50	12.5	0.25	0.0625	No reversal	17
		50	15	0.25	0.075	No reversal	2
		-10	12.5	-0.05	0.0625	Reversal	382
		-10	15	-0.05	0.075	Reversal	180
		-10	20	-0.05	0.1	Reversal	11
		-20	10	-0.1	0.05	No reversal	246
		-20	12.5	-0.1	0.0625	No reversal	202
		-20	15	-0.1	0.075	No reversal	12
		-40	5	-0.2	0.025	No reversal	104
		-40	7.5	-0.2	0.0375	No reversal	13
		-40	10	-0.2	0.05	No reversal	2

TABLE 2: Summary of undrained cyclic triaxial tests.

compression and tensile sides, thus forming an "S"-shaped stress-strain curve, and finally failure occurs at the tensile side, until the failure criterion of 5% double-amplitude (DA) axial strain has been satisfied [35]. Both the "butter-fly" stress path and the "S"-shaped stress-strain curves were the typical features of the "cyclic mobility" (CM) response [36].

Figure 4(b) shows the typical response of saturated dense sand, which is suffering from positive static deviatoric stress before undergoing undrained cyclic loading (SSR = 0.25, CSR = 0.25), under the condition of the "intermediate" state. It can be seen from the effective stress path in the figure that, in the early stage of cyclic loading, the effective stress decreases with cyclic loading,



FIGURE 4: Cyclic response of dense sand with different initial static deviatoric stresses.



(c) $D_r = 30\%$, SSR = -0.05, CSR = 0.1, $N_f = 12$, FD (intermediate)

FIGURE 5: Cyclic response of loose sand with different initial static deviatoric stresses.

while in the later stage of cyclic loading, the average effective stress tends to be stable and is always greater than 0. At the same time, due to the existence of static deviatoric stress, the axial strain only accumulates on the compression side, and the rate of strain accumulation is relatively stable until the failure criterion of 5% single-amplitude (SA) axial strain has been satisfied at $N_{\rm f}$ = 53. The above behavior type which is significantly different from the CM behavior type can be named "residual deformation accumulation" (RDA).

Figure 4(c) shows the typical response of saturated dense sand considering static negative deviatoric stress under undrained cyclic loading and no stress reversal conditions (SSR = -0.2, CSR = 0.125). The same response pattern of "residual deformation accumulation" as shown in Figure 4(b) can also be observed on the tensile side, and the rate of strain accumulation is relatively stable until the failure criterion of 5% single-amplitude (SA) axial strain has been satisfied at $N_f = 16$.

By comparing the effective stress path and stress-strain curve in Figures 4(a)-4(c), it can be seen that under the condition of stress reversal, the undrained cyclic response of saturated dense sand is mainly manifested as CM response. The saturated dense sand under the condition of no stress reversal in Figure 4(c) and the saturated dense sand under the condition of intermediate as shown in Figure 4(b) mainly present the behavior type of RDA. Due to the difference of static deviator stress, the effective stress paths of the two show "winglike" curves with different inclined directions in the later period of cyclic loading.

Figure 5(a) shows the typical response of saturated loose sand with isotropic consolidation suffering from symmetric cyclic load (SSR = 0, CSR = 0.15). It can be seen from the effective stress path in the figure that, under the condition of being undrained, the effective stress of the test sample decreases continuously with the cyclic loading. Eventually, failure occurs at the extension side, until the failure criterion of 5% double-amplitude (DA) axial strain has been satisfied at a number of cycles $N_{\rm f}$ = 16. This type of cyclic failure is classified as "flow deformation" (FD), manifested by a whole loss of strength and effective stress.

Figure 5(b) shows the typical response of saturated loose sand, which was suffering from positive static deviatoric stress before undergoing undrained cyclic loading (SSR = 0.25, CSR = 0.25). The same response pattern of "residual deformation accumulation" (RDA) as shown in Figure 3(b) can also be observed on the loose sand. And finally, the failure criterion of 5% axial strain has been satisfied at $N_f = 24$. Figure 5(c) shows the typical response of saturated loose sand considering static negative deviatoric stress under undrained cyclic loading. The same response pattern of "flow deformation" shown in Figure 5(a) can also be observed on the negative side. And the failure criterion of 5% axial strain has been satisfied at $N_f = 16$.

The above experimental results show that the behavior type of saturated sand under undrained cyclic load is not only related to the magnitude and direction of the initial stress state of the sample but also affected by the relative



FIGURE 6: Summary of dense sand behavior types under different stress conditions.



FIGURE 7: Summary of loose sand behavior types under different stress conditions.

density. Figures 6 and 7 show the distribution of dense and loose sand cyclic behavior types under different stress conditions, respectively. For dense sand as shown in Figure 6, the samples under the condition of stress reversal exhibit a "cyclic mobility" characterized by the "butterfly" stress path and the S-shaped stress-strain curves and the samples under the condition of no stress reversal or intermediate exhibit a "residual deformation accumulation" characterized by a stable effective path and axial strain on the initial deviatoric stress side. For loose sand as shown in Figure 7, there are mainly two types: "flow liquefaction" and "residual deformation accumulation." It is found that the former was presented when $q_s/q_{cyc} < 0.6$,



FIGURE 8: Relationship between CSR and N_f with various SSR.

characterized by complete loss of strength and effective stress, and the latter was presented when $q_s/q_{cyc} > 0.6$, indicating that the behavior types of loose sand have no obvious connection with stress reversal.

4. Cyclic Resistance

Figures 8(a) and 8(b), respectively, show the relationship between the number of cycles required to obtain axial strain of 5% $N_{\rm f}$ (DA or SA) and the cyclic stress ratio CSR required for saturated dense sand and saturated loose sand under different initial static deviatoric stress conditions. It can be seen from the single curve that the saturated dense sand and loose sand under anisotropic consolidation conditions $(SSR \neq 0)$ are consistent with those under the condition of isotropic consolidation (SSR = 0); that is, for a given initial deviatoric stress, $N_{\rm f}$ decreases monotonically with the increase in CSR, indicating that the increase in cyclic stress amplitude reduces the cyclic stability of soil. It can be seen from the positions between the curves that the N_f-CSR curves under different initial stress states (SSR $\neq 0$) may appear either above or below the condition of isotropic consolidation (SSR = 0), indicating that the existence of initial static shear stress can either promote or inhibit cyclic strength.

To compare the cyclic resistance of various samples effectively, the cyclic resistance ratio $CRR_{N=20}$ is introduced, which is defined as the required CSR to cause failure at $N_{\rm f} = 20$. It can be seen from Figure 9 that $CRR_{N=20}$ of dense sand increases monotonously with SSR, indicating that the initial deviatoric stress of compression has a promoting effect on the cyclic resistance of calcareous sand, while the initial deviatoric stress of tension has an inhibiting effect on the cyclic resistance of sand. The $CRR_{N=20}$ of



FIGURE 9: Relation curve between CRR for $N_f = 20$ and SSR.

loose sand first increased and then decreased with SSR and reached the peak strength at SSR = 0.12. In addition, for a given SSR, the cyclic resistance of dense sand is always above that of loose sand, indicating that the cyclic resistance of saturated sand increases with the increase in relative density $D_{\rm r}$.

5. Energy Dissipation

According to formula, the dissipated energy density value W of the sample during cyclic loading can be calculated. The



FIGURE 10: Relationship between dissipated energy and number of cycles required to cause liquefaction.





FIGURE 11: Relationship between the dissipated energy and static stress ratio.

FIGURE 12: Comparison of measured and predicted values of dissipated energy.

normalized energy $W_{n,f}$, that is, the dissipated energy density normalized by the minor principal effective stress σ_3' needed for the failures outlined by 5% strain criteria, is shown in Figures 10(a) and 10(b), versus the specified range of failure cycles N_f for loose and dense sand, severally. As shown in the figure, for a given SSR, the $W_{n,f}$, corresponding to different N_f , fluctuates up and down in a small range without an obvious rule; meanwhile, according to the previous textual intensity law, for a given SSR, the size of N_f is only related to the value of CSR, so the various CSR has a negligible effect on the amount of required energy, which is consistent with the

experimental phenomenon on isotropic consolidated sand; in their opinion, the dissipated energy was virtually unambiguously correlative with elicited strain no matter the cyclic stress ratio (CSR) within the reconstituted sands [37–41].

The required energy dissipation illustrated in Figure 10 can be versus the SSR, as shown in Figure 11. It can be seen from the figure that the dissipated energy required by both loose sand and dense sand reaching the 5% strain standard increases monotonically with the increase in SSR. For a given SSR, the dissipated energy required by dense sand is always greater than that of loose sand.

The above experimental results show that the dissipated energy of saturated calcareous sand under undrained cyclic load is mainly related to the state of SSR and D_r . According to the interpretation conducted by Yang and Pan [36], the relationship between $W_{n,f}$, SSR, and D_r can adopt the following expression:

$$W_{\rm n,f}^* = 10^{a(D_{\rm r} - 0.78)} \cdot 10^{b(\rm SSR-1.0)},\tag{2}$$

where *a* and *b* are empirical parameters. a = 0.65 and b = 1.5 are, respectively, recommended according to the data of this experiment. The dotted line in Figure 8 is the equation curve obtained by Equation (2), which can fit well with the experimental data. In addition, as shown in Figure 12, the measured value $(W_{n,f})$ and the predicted value $(W_{n,f}^*)$ of dissipated energy are compared, and it can be found that they basically fall on the diagonal with a slope of 1, indicating that Equation (2) can reasonably predict the dissipated energy.

6. Conclusions

A series of undrained cyclic triaxial tests were conducted on reconstituted samples and principally involved the static shear impact on the cyclic state change behavior of two totally different compactness of saturated calcareous sand below different initial deviatoric stress and cyclic stress. Through the definition of dissipated energy, the energy variation law of loose sand and dense sand under cyclic load is analyzed, and the prediction formula of dissipated energy is given. Here are the main conclusions of this study:

- (1) Calcareous sand exhibits three cyclic response modes under different initial deviatoric stresses and cyclic stress combinations: (a) cyclic mobility, (b) residual accumulated deformation, and (c) flow liquefaction. The "cyclic mobility" response is characterized by the "butterfly" stress path and the "S"-shaped stressstrain curves at the end of cyclic loading. The "residual deformation accumulated" response is characterized by unilateral "wing-like" effective stress path at the end of cyclic loading. The "flow deformation" response is characterized by complete loss of strength, and effective stress occurs at the end of the cycle. The dense sand is mainly manifested as "cyclic mobility" and "residual deformation accumulated." Loose sand is mainly manifested as "residual deformation accumulated" and "flow deformation." The cyclic response mode is affected not only by the relative density but also by the initial deviatoric stress and cyclic stress
- (2) The initial deviatoric stress of compression has a promoting effect on the cyclic resistance of dense calcareous sand, while the initial deviatoric stress of tension has an inhibiting effect on the cyclic resistance of dense sand. The cyclic resistance of loose sand first increased and then decreased with SSR and reached the peak strength at SSR = 0.12. For a given SSR,

the cyclic resistance of saturated sand increases with the increase in the density

- (3) The dissipated energy required by saturated calcareous sand reaching the 5% strain standard increases monotonically with the increase in SSR. For a given SSR, the dissipated energy required by dense sand is always greater than that of loose sand. By considering the initial static deviatoric stress ratio and relative compactness, the equation can be obtained to predict the dissipated energy variation law of saturated calcareous sand under undrained cyclic load, and the rationality of the equation is effectively verified
- (4) A systematic experimental study on calcareous sand with fine content concerning the effects of both compressional and extensional static stresses is potential directions for future research on this topic

Nomenclature

<i>a</i> , <i>b</i> :	Fitting parameters for the energy prediction model
C_c :	Coefficient of curvature
C_{u} :	Coefficient of uniformity
CSR:	Cyclic stress ratio
$CRR_{N=20}$:	Resistance ratio
d_{10}, d_{30}, d_{60} :	Effective, median, and limited particle size, respectively
DA:	Double-amplitude axial strain
D_r :	Relative density of sand
$G_{\rm S}$:	Specific gravity of sand
p':	Mean normal effective stress
$q_{\rm s}, q_{\rm cyc}$:	Static and cyclic deviatoric stress, respectively
SA:	Single-amplitude axial strain
SSR:	Static stress ratio cyclic
$N_{\rm f}$:	Number of cycles required to obtain axial strain of 5%
W:	Dissipated energy
$W_{n,f}$:	Required energy dissipation for failure (mea- sured value)
$W_{n,f}^*$:	Required energy dissipation for failure (pre- dicted value)
ε_{a} :	Axial strain.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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