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Post-cyclic behavior of carbonate sand with anisotropic consolidation

S. H. R. Kargar[1], H. Shahnazari[2,]*, H. Salehzadeh[2]

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Abstract

In this study, a researching program is conducted by cyclic triaxial test to determine the post-cyclic behavior of Bushehr carbonate sand retrieved from the north of the Persian Gulf, under anisotropic consolidation at 200 kPa confining pressure. The article compares the post-cyclic monotonic strength and excess pore water pressures generated after the test with the pre-cyclic monotonic results. The results attest to the existence of a relationship between CSR (Cyclic Stress Ratio) and the frequency of failure cycles. The article also investigates the relationship between the amount of excess pore pressures generated during both the cyclic and post-cyclic loading, revealing an increase in the post-cyclic strength and stiffness of sand retrieved from Bushehr. Also the effect of multi stages cyclic loading, density, pore pressure and stain history in post cyclic strength and stiffness is evaluated. The increasing in post cyclic strength and stiffness depends on excess pore pressure generated during cyclic loading and stain history. This article also reveals that a distinct trend in the relation between post cyclic behavior and crushing value does not exist at lower confining pressure.

Keywords: *Anisotropic consolidation, Bushehr sand, Carbonate sand, Crushing, Post-cyclic, Strain history.*

1. Introduction

The majority of oil reserves of the world, such as the Persian Gulf, are located in certain fields in which carbonate/calcareous soils are abundant [32]. Due to these soils skeletal structures, which are comprised of marine organic compounds, the carbonate/calcareous particles are weaker and their behavior is more volatile under monotonic and cyclic loading conditions in comparison with conventional soils [36]. However, carbonate sand exhibits all other features of conventional soils [10]. This fact is significant because oil platforms are often constructed on the seabed, which comprises carbonate soils. These structures are subject to frequent rough sea waves during their lifespan. Successive monotonic-cyclic-monotonic loading on carbonate soil has undesirable consequences

Soil response to monotonic loading, under conditions when the soil has already experienced cyclic loading, in geotechnical literature is termed as surveying post-cyclic behavior of soil imposing post-cyclic loading on soil has several consequences such as: particle crushing [10 and13], changing in shear strength, fluctuating stiffness pattern [38],toleration capacity reduction, changing behavior of soil-structure interaction model, potential enhancement of soil settlement, changing over-consolidation pressure of the soil, altering soil yield point, modifying particles distribution, loss of contact between the cemented grains [4], changes in the soil response to the next cyclic loading, asymmetric foundation settlement of oil and gas platforms, risk of oil diffusion and pollution due to platform collapse.

The elastic modulus of carbonate soils and confining pressure effect on it were estimated before by Airey [4 and2]. Lade and Nelson [26] also developed a model that relates Young's modulus to the confining stress.

In the literature it was found that post-cyclic laboratory tests on silica sands or cohesive soils were conducted by some scientists and reported in the following articles[8,11,16,18, 31,37,43,45,52,54,56,53 and 57]. Afterwards, cyclic triaxial and hallow cylinder testing or direct shear tests were also performed on specimens. Extensive research on the drained and undrained monotonic shear response and cyclic behavior of carbonate sands have been carried out by other researchers in the following articles [1, 3, 10, 8,14,23,24, 25,32,33,36, and 38].

Consequently, the post-cyclic behavior of carbonate soil is important, but extensive research in this field is lacking. As a result, experiments were carried out to investigate this partly ignored aspect of oil platforms behavior. To this aim, the post-cyclic behavior of Bushehr carbonate sand was examined by exposing it to multistage cyclic loadings at different confining pressures and cyclic stress levels, gradually increasing the frequency of the cycles and repeating the cyclic-monotonic loading.

In recent decades, studying the behavior of sand in anisotropic consolidation condition has been of significant

* *Corresponding author: hshahnazari@iust.ac.ir*
1 Ph.D Candidate, Iran University of Science and Technology and Islamic Azad University-Kermanshah Branch
2 Assistant Professor, Collage of Civil Engineering, Iran University of Science and Technology

importance among researchers. Normally, sand is consolidated under anisotropic conditions and its anisotropy can be either inherent or induced. Inherent anisotropy is a physical property of sand and entirely independent of the applied strains [5]. On the other side, induced anisotropy occurs due to applied loading on sand [50]. The degree of anisotropic consolidation equals to a significant parameter such as void ratio [46]. So the counteractive or dilative behavior of sand is totally affected by initial stress ratio (K_0) [27, 42 and 47]. Increased anisotropic consolidation ratio causes an increase of cyclic strength in loose sand and even a decreases of cyclic strength in loose sand [20 and 21]; moreover, increased initial sustained deviator stress ratio for silt leads to a decrease in post-cyclic strength [19]. However due to the fact that anisotropic consolidation is closer to the existing realities of oil platforms loading, the behavior of soil in anisotropic conditions is investigated in this study.

In the present study, according to the soil drainage potential in Bushehr sand due to its high permeability and to investigate the long-term behavior of sand, the samples were subjected to post- cyclic loading with suitable time interval after cyclic loading applied, and during the process with drainage possibility for soil. It was possible of complete elimination of generated excess pore pressure during cyclic loading and practically a reconsolidation of the soil was allowed, similar to the applied mechanism in studies such as: [9, 49, 55 and 28].

2. Materials Tested

The sand used in this research was retrieved from the northern coast of the Persian Gulf in the west of Bushehr (a southern city in Iran); with calcium carbonate content of 45%. This medium carbonate sand has an average particle size (D_{50}) of 0.43mm, uniformity coefficient (Cu) of 7.87, curvature coefficient (Cc) of 0.84 and specific gravity (Gs) of 2.7. The minimum and maximum void ratios of the sand are 0.726 and 1.051, respectively. Figure 1 illustrates the sharp-edged particles of Bushehr sand in microscopic dimensions. In this picture, some shells and other marine animal and plant skeletons are also visible. Figure 2 illustrates the grain size distribution of Bushehr sand. An analysis was also performed at the end of each test to determine the amount of grain susceptibility to crushing.

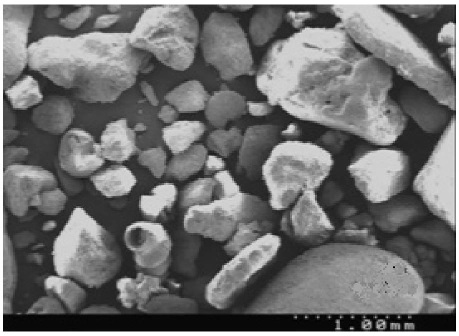


Fig. 1 Microscopic picture of Bushehr sand

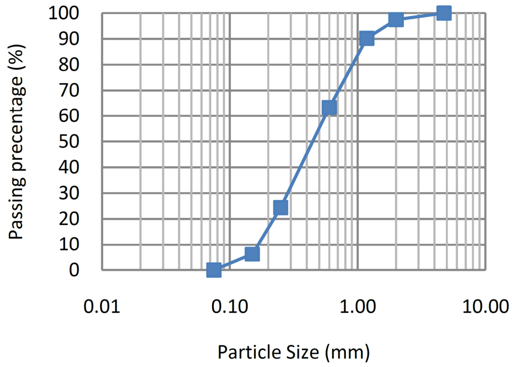


Fig. 2 Grain size distribution

2.1. Test Apparatus and Procedure

A CBEL cyclic triaxial test apparatus in Iran University of Science and Technology was developed and used for this study. Bushehr calcareous sand was used for all the tests. Specimens with 50% of the average relative density with 7 cm diameter and 14 cm height were prepared using a preliminary air-pluviation method with CO2 gas and then de-aired water was flushed through the samples from bottom to top. A minimum B value of 0.97 was achieved under 200 kPa back pressure during the saturation process of all the tests. Then, the specimens were consolidated under effective confining pressure of 200 kPa and their relative densities were measured after consolidation. Overall, three patterns of loading were used in this study to investigate the post-cyclic behavior of Bushehr sand:

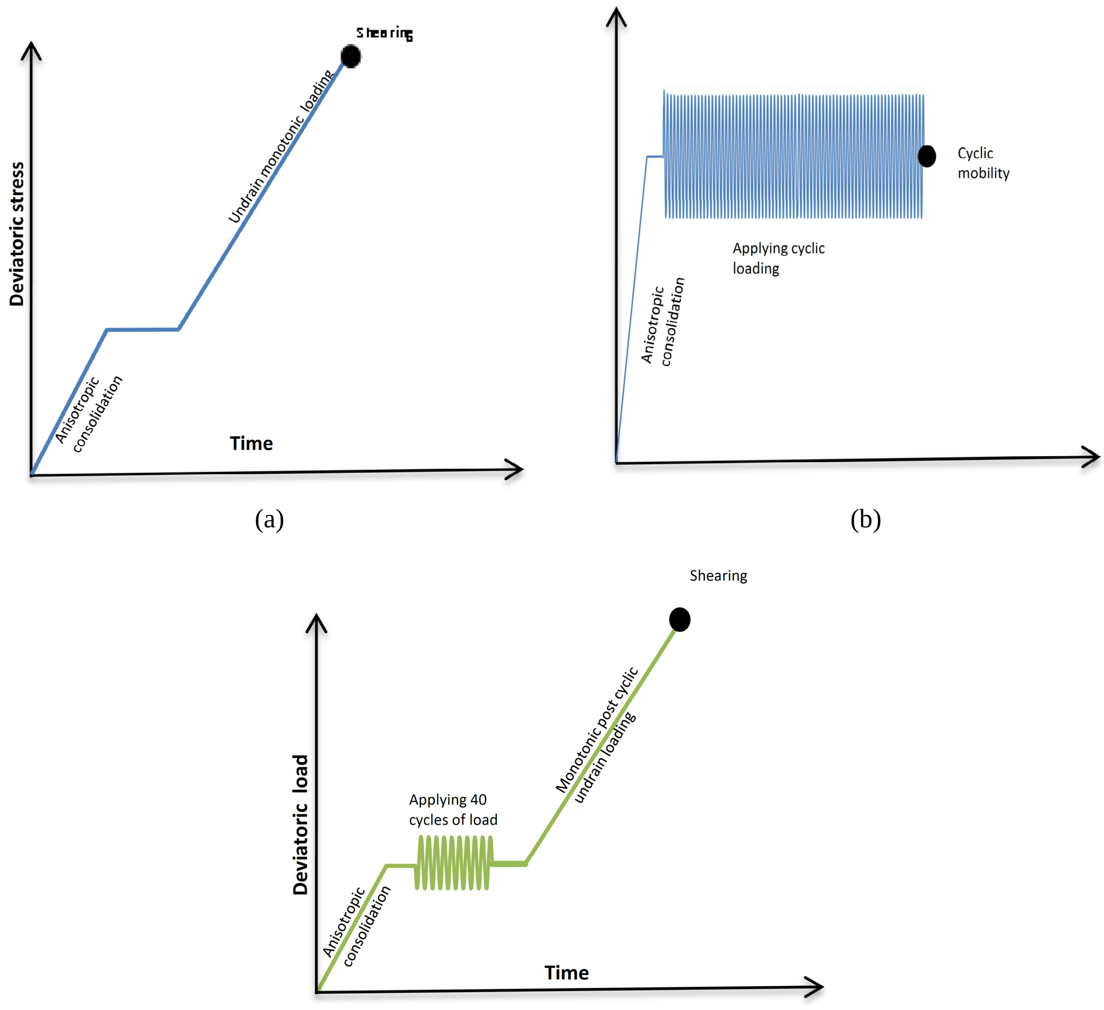
I: Undrained monotonic triaxial shearing (Figure 3a)

II: Undrained cyclic loading after anisotropic consolidation (Figure 3b)

III: Undrained cyclic loading followed by post-cyclic monotonic shearing (Figure 3c)

In pattern III, after anisotropically consolited, all specimens were subjected to sinusoidal cyclic loading by 40 uniform cycles. The stress-controlled method was applied with a frequency of 0.1*Hz*. The cyclic stress ratios were 0.2, 0.4 and 0.8 as listed in Table 1. The cyclic loading step followed by draining and the samples were also reconsolidated. Finally they were sheared monotonically in undrained condition. Another set of post cyclic tests were also carried out followed by multistage cyclic loadings (each one of was 40 cycles) with a csr of 0.2., and the samples were reconsolidated in the interval between the stages. The multistage cyclic loading followed by monotonic shearing loads.

In this research program, a total number of 92 tests were carried out. From among them, some representative tests were selected the specifications of which are summarized in Table 1.



(c)

Fig. 3 a: Undrained monotonic loading; b: Cyclic loading; c: Monotonic post-cyclic loading

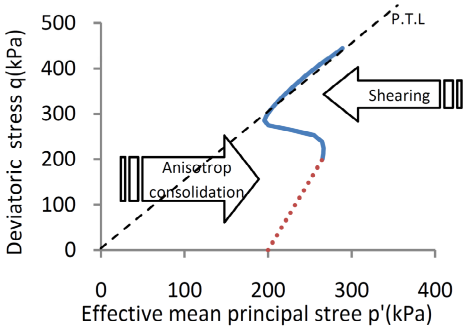
Table 1 Summary of triaxial tests

Test no	P'_0(KPa)	q_{cyc}/P'_0	K_0	No. of Load cycles	Test definition
M1	267	---	0.5	-	Monotonic
C1	267	0.75	0.5	336	Cyclic
C2	267	0.85	0.5	196	Cyclic
C3	267	0.95	0.5	147	Cyclic
C4	267	1.2	0.5	70	Cyclic
C5	267	1.5	0.5	25	Cyclic
P1	267	0.2	0.5	40	Post Cyclic
P2	267	0.4	0.5	40	Post cyclic
P3	267	0.8	0.5	40	Post cyclic
P4	267	0.2	0.5	80[1]	Post cyclic
P5	267	0.2	0.5	200[2]	Post cyclic

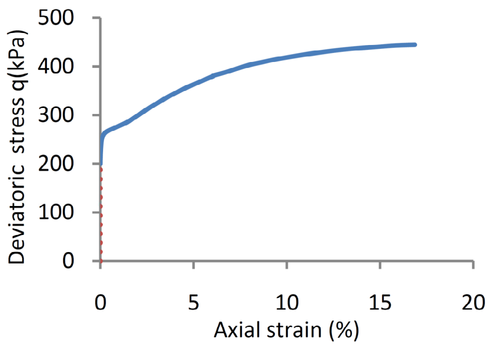
1: Two stages of loading, each one 40 cycles.
2: Five stages of loading, each one 40 cycles.

3. Undrained Monotonic Shearing Response

Figure 4 illustrates the stress path, stress-strain relation and excess pore water pressure-axial strain curves of the samples. The specimens were first subjected to anisotropic consolidation (K_0=0.5) and then to an undrained loading condition. Finally, post-cyclic shearing response was compared with the results of pre-cyclic monotonic test. Due to the use of the stress control method in this research, no critical stress parameters could be obtained from the tests.



(a)



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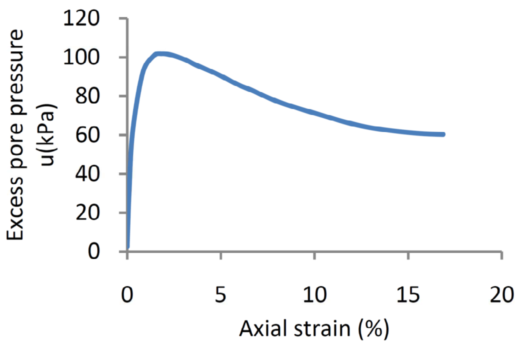


(c)

Fig. 4 Undrained monotonic triaxial test results: a: effective stress path; b: deviatoric stress vs. axial strain; c: excess pore pressure vs. axial strain

4. Undrained Cyclic Behavior

In this study, a series of cyclic triaxial tests with different cyclic stress ratios were performed under one-way cyclic loading and anisotropic consolidation condition (K_0=0.5). The typical response of the undrained cyclic test results is shown in Figure5. Generally, the samples demonstrated cyclic mobility (as shown in Figure5) under high cyclic stress ratio (CSR about 0.4 and higher).

Cyclic mobility, triggered by cyclic loading, occurs in sand deposits with shear stresses higher than the soil strength. Deformations due to cyclic mobility develop incrementally due to an increase in the generated pore water pressure and consequently the effective stresses that exist during the cyclic loading decrease. Since the samples are subject to one-way cyclic loading, cyclic mobility compressive failure takes place due to the accumulation of large residual strains (greater than about 30 percent of axial strain, as shown in Figure 5).

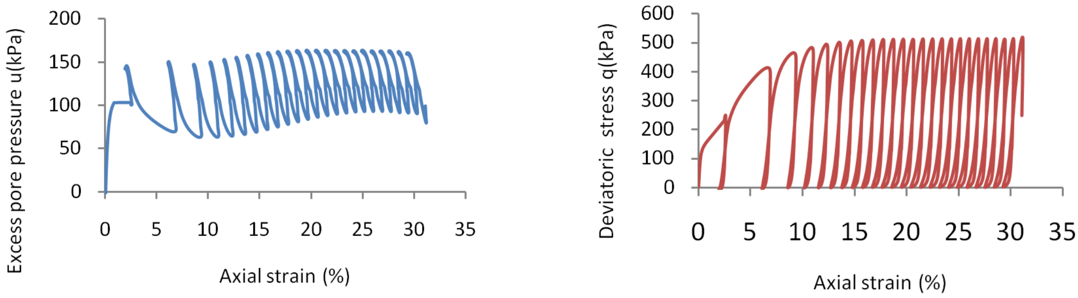


Fig. 5 Cyclic triaxial undrained test result (Compression cyclic loading) a: deviatoric stress vs. axial strain; b: excess pore pressure vs. axial strain

The interaction between cyclic stress ratio (CSR) and the number of cycles leads to a large residual strain accumulation (about 25%) plotted in Figure 6. The following equation, suggested by Seed [35], was used to calculate Bushehr test results:

$$\mathrm{CSR} = \mathrm{A} * (\mathrm{No.\,of.\,cycles})^{-\mathrm{B}} \qquad (1)$$

Based on the best-fit value of the data set, a value of 0.274 for (B) parameter and a value of 3.6992 for (A) parameter were selected. Many other researchers applied Equation (1) under isotropic consolidation condition, but it is the first time this equation is employed for carbonate sand under anisotropic consolidation condition.

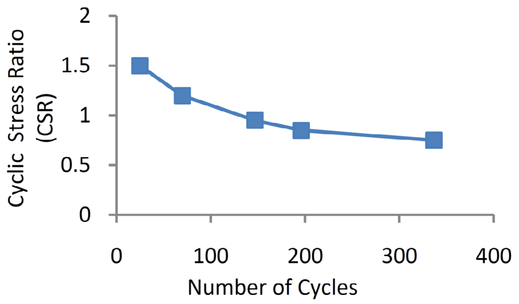


Fig. 6 Number of cycles necessary to reach large residual cyclic strain accumulation

5. Monotonic Post Cyclic Shearing

Monotonic post-cyclic behavior of Bushehr sand was investigated by conducting monotonic triaxial tests after the samples experienced cyclic loading. The effect of cyclic stress ratio (CSR) on post-cyclic resistance was evaluated by testing samples with values of 0.2, 0.4 and 0.8 of CSR. Monotonic post-cyclic stress-strain relation, excess pore water pressure versus axial strain and stress-path curves are presented in Figure7, which shows monotonic post-cyclic strength increases as the magnitude of cyclic stress ratio increases. The increase in post-cyclic strength can be affected by an increasing relative density, crushing, cyclic strain or residual cyclic strain.

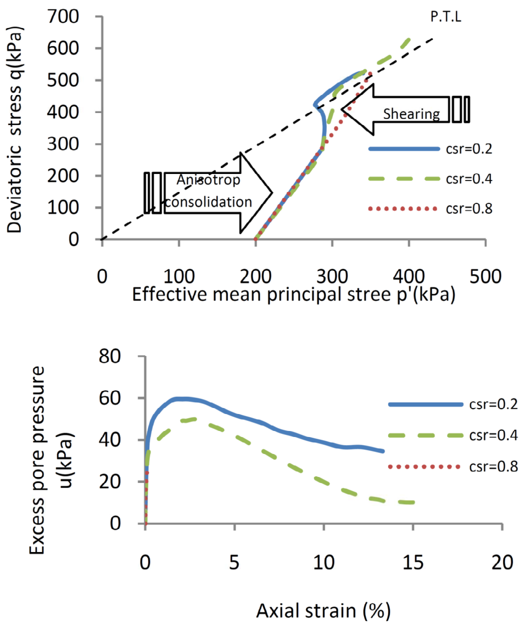


Figure 7: Undrained post-cyclic triaxial test result (CSR effect under K0=0.5, one-way cyclic loading) a: effective stress path; b: excess pore pressure vs. axial strain

5.1. Effect of CSR on post cyclic responses

As mentioned earlier and as shown in figure 7, almost all the samples indicated a significant improve in post-cyclic strength. This strength growth along with an increase in CSR had a stronger intensity. It is precisely contradictory to those results obtained by researchers not allowing reconsolidation of the soil, which is quite obvious according to the innate difference in loading mechanism in those studies compared to the present one. In this section, we are going to address possible factors of increasing the above strength. No doubt that CSR parameter cannot directly and independently overshadow the post-cyclic response of the soil, a result acknowledge by many other researchers [9]. Now, knowing about the lack of direct impact of cyclic stress ratio, we are going to address the impacts of cyclic loading on other parameters and the possibility of taking influence from post cyclic behavior in each one of them.

5.2. Effect of D_r on post cyclic responses

Post-cyclic behavior of soil can be affected by changing in relative density [49]. Due to possibility of draining between cyclic and post-cyclic loading and reconsolidation of soil, there can be an increase in relative density of sand at the beginning of post-cyclic loading [55], [28] This process highly corresponds with the result of the study performed by Chern and Lin [9]. An important point that should not be missed is the reason of such increase in density level. Given the evidence, increase of density parameter is due to increase in pore pressure. Therefore, it is more logical to look for the reason of post-cyclic behavior being overshadowed in the main factor of cyclic pore water pressure instead of surveying impacts of density on post-cyclic strength and stiffness.

No significant differences in volume change was observed due to drainage, between the two stages of cyclic and post-cyclic loading, and therefore changing in relative density, as reported below, was not noticeable. The maximum changing value of relative density when the cyclic loading applied under anisotropic consolidation condition, 200 kPa of confining pressure and 0.4 of CSR was about 4.35 percent. In conclusion, the study showed a slight modification (about 5.7 percent as shown in Figure 8) in the strength of Bushehr sand caused by the changing value of relative density.

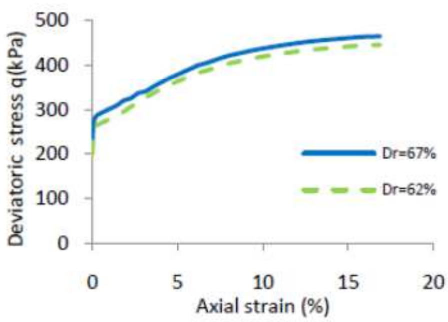


Fig. 8 Deviatoric stress vs. axial strain

5.3. Effect of crushing parameter on post cyclic responses

Two reasonable factors are responsible for crushing in carbonate sand: high intergranular pressure and moving grains on top of each other [10]. The impact of the first factor in this research was quite negligible due to the relatively low confining pressure applied on the samples. Furthermore, measuring crushing parameter at the end of sand consolidation proved this fact. Moving grains on top of each other, more precisely the formation of shear planes [10], in the sample can be regarded as a second factor intensifying the process of particle breakage. The increase of accumulative cyclic strain is a significant reason of moving grains on top of each other. However, this claim that grain crushing is due to grain movement, compared to the pre- and post-cyclic loading was not substantiated (as noted in Table 2). Non-intensification of particle breakage during cyclic loading can be due to lack of synchronous presence of the conditions namely inter granular movement and high inter granular pressure. Grain movement alone cannot intensify crushing parameter. On the other hand, according to the relatively low amount of strain in each cycle, no suitable continues was seen in inter granular movement. In other words, accumulative cyclic strain is in no way a suitable parameter for evaluating crushing; however, the maximum cyclic strain and more importantly the mean cyclic strain can be regarded as significant parameters influential in grain crushing. Perhaps, accumulative strain overshadows grain abrasion (as shown in figure 9) and grain crushing requires a bigger cyclic strain under a bigger confining pressure. Grading analyzes results and a considerable percent of the soil passing through the sieve 200 confirm this fact as well. The percent of passing through sieve number 200 increased due to an increase in accumulative cyclic strain implying an intensification of grain abrasion. The significant point is the insignificant impact of abrasion on crushing parameter compared to grain fracture [12].

When the sand particles are sheared, they break down and show the greatest crushing value. Nonetheless, this fact may be obscured when the samples develop rupture planes (see Table 2). Regarding post-cyclic resistance, the results show the effect of breakage value is not very significant for this crushable sand. Test results also do not exhibit a clear trend between cyclic stress ratio and crushing value.

Table 2 Hardin's relative breakage factor Br [12] and some factor affecting it

Test no	B_r	q_{cyc}/P_0	N	Monotonic shearing	Cyclic Mobility
M1	0.06735	---	-	√	---
C1	0.06281	0.75	336	---	√
C2	0.05447	0.85	196	---	√
C3	0.03825	0.95	147	---	√
C4	0.03100	1.2	70	---	√
C5	0.08096	1.5	25	---	√
P1	0.08151	0.2	40	√	---
P2	0.08104	0.4	40	√	---
P3	0.08625	0.8	40	√	---
P4	0.09657	0.2	80[1]	√	---
P5	0.06735	0.2	200[2]	√	---

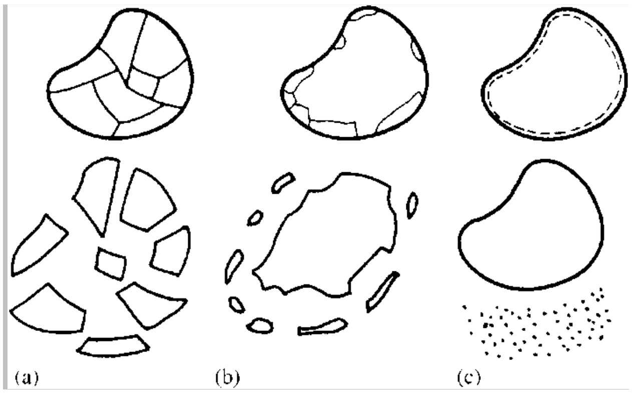


Fig. 9 Different Mechanisms of Grain Crushing: a) fracture, b) attrition, and c) abrasion [12]

5.4. Effect of Strain history on post cyclic responses

Seed in 1979 [34] introduced strain history as an effective parameter in behavior of granular soils. The impact of this parameter on behavior of soil is far more important than void ratio and stress level [34]. Studying the effect of strain history on soil responses is difficult, so instead of that we use maximum shear strain index before post-cycling loading [49]. In this study, according to the nature of one-way cyclic loading we have used maximum cyclic strain and accumulative cyclic strain as good substitutes for strain history. The impact of accumulative cyclic strain and maximum cyclic strain on post-cyclic behavior of soil has been frequently studied by several researchers such as [30, 43 and 45]. Singh et al. [40], through pre-drained loading and without any change in void ratio (density), observed a 30-40% increase in cyclic strength. As the test results show (see table 3 and figure 10), the increase in cyclic strain and accumulative cyclic strain highly affects post-cyclic behavior of Bushehr sand and causes an increase in post-cyclic strength and stiffness of Bushehr sand. Grain movement in the sand and occurrence of more suitable arrangement of the grains under applied strains (according to the irregular structure of grains of granular sand) improve strength and stiffness [29 and 41]. Increase in accumulative cyclic strain indicates the increase of induced anisotropic in sand [41]. Due to increase of induce anisotropy, the post-cyclic strength of Bushehr sand will also increase.

The importance of replacing cyclic stress with cyclic strain on post-cyclic behavior researching is due to consolidation and certainty of strain effect. Stress value can be varied by time or its effects can be changed by changing in pore pressure. However, strain is an obvious expression of certain recent events in soil. Based on the data from the table 3 we can see that along with the increase in cyclic stress ratio both parameters maximum cyclic strain and accumulative cyclic strain almost increase in form of a linear relationship and following this increase, the post-cyclic strength of Bushehr sand will also increase.

Maximum value of cyclic shear strain during the cyclic loading, and accumulative cyclic shear strain were the fundamental factors in increasing the post-cyclic strength in comparison with the monotonic results (see Table 3).

Table 3 Values of accumulative cyclic shear strain in N cycles of loading and the maximum cyclic shear strain during the cycle of N.

q_{cyc}/P'_0	$\varepsilon_s^*(\%)$	$\varepsilon_{speak}(\%)$	N	Test definition
0.2	1.62	0.17	11	Post Cyclic
0.4	4.03	0.39	7	Post cyclic
0.8	13.93	0.98	3	Post cyclic
0.2	1.67	0.5	80	Post cyclic
0.2	1.69	0.5	120	Post cyclic
0.2	1.70	0.5	160	Post cyclic
0.2	1.70	0.5	200	Post cyclic

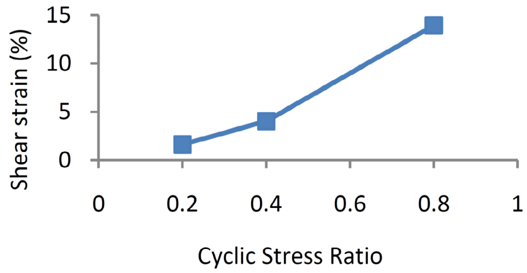


Fig. 10 Residual shear strain versus cyclic stress ratio

5.5. Effect of excess pore water pressure on post cyclic responses

As shown in figure 11, generated excess pore pressure during cyclic loading increases with increasing in CSR. In other word, post cyclic strength and stiffness increase with increasing in CSR and consequently post cyclic strength and stiffness increase with increasing in pore pressure generated during cyclic loading. The increase in excess pore water pressure during cyclic loading is one of the most important parameters affected post-cyclic behavior of soil in both drainage and non-drainage manners between cyclic and post-cyclic loading stages [7, 51, 56 and 57]. Without reconsolidation before the post-cyclic loading, the presence of pore pressure along with reducing effective stress gets obtain condition for decreasing in strength and stiffness of the soil [44, 56 and 57]. On the other side, when there is the possibility of drainage between cyclic and post-cyclic loading stages, the increase in excess pore pressure usually through intensifying reconsolidation of the sand and it causes an increase in relative density parameter [49]. The increase in strength and stiffness of any soil such as Bushehr carbonate sand following the increase in density is a quite clear fact. In Bushehr sand, we can claim that part of this increase in strength and stiffness is due to increase of density.

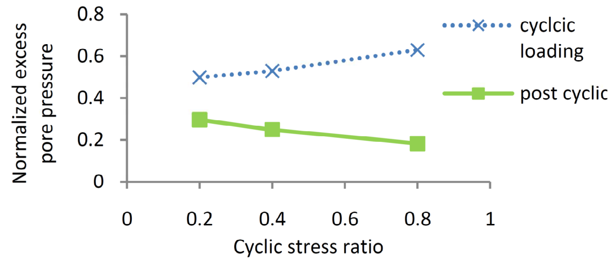


Fig. 11 Normalized generated excess pore water pressure during the cyclic loading and post-cyclic loading versus cyclic stress ratio

Post-cyclic tests showed lower generated excess pore water pressure than monotonic tests during compression loading. It is interesting to note that generated excess pore pressure during monotonic post-cyclic loading tended to decrease when excess pore pressure increased during cyclic loading (Figure 11). The values of generated excess pore pressures during the cyclic and post-cyclic loading, under anisotropic consolidation condition and 200 kPa of confining pressure and a relative density of fifty percent, can be calculated by the following equation:

$$\frac{\Delta u}{\sigma_3})_{cyclic} + \frac{\Delta u}{\sigma_3})_{postcyclic} = 0.795 \tag{2}$$

By using empirical models, the generated excess pore water pressure trend during cyclic loading was established [13, 15, 22, and 35] and finally the excess pore water pressure during post-cyclic loading was calculated by the equation (2).Therefore if one determines excess pore water pressure, one can easily predict a part of the post-cyclic behavior of Bushehr sand.

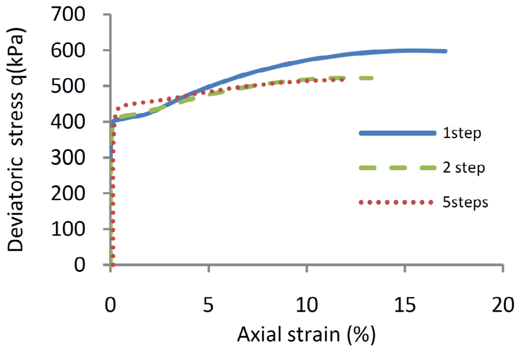
In this study, it was found that all post-cyclic tests subjected to one-way cyclic loading and anisotropic consolidation condition demonstrated a constant trend for CSR higher than 0.75, normalized by excess pore water pressure during the cyclic loading of 0.65.

Now, the question raised is which parameter plays the main and final role in increasing post-cyclic strength. The key to answer this question is the diagram of changes in pore pressure and strain in different cycles. As it can be seen in figure 7 and table 3, there is no cyclic adaptation in occurrence of these parameters. In other words, when the maximum cyclic strain is obtained, development and increasing in pore pressure and accumulative cyclic strain parameters has still persisted. The issue regarding continuation of increase in accumulative strain is also true when increase growth of cyclic pore pressure is slow. For example, regarding the sample that was tested under cyclic ratio of 0.8, the maximum cyclic strain has been recorded in the third cycle with amount of 0.98%; while with the increase in accumulative cyclic strain parameters and the pore pressure growth, a far slower growth compared to the initial cycles, has continued until the last loading cycle.

6. Post-Cyclic Monotonic Shearing in Multistage Loading

A second series of post-cyclic tests were also carried out followed by multistage cyclic loadings, and the samples were allowed to drain in the interval between the stages. The number of each cyclic loading stage was 40. All stages and all the samples were tested under a CSR of 0.2. This process was carried out for the first, second and fifth stages of cyclic loading as presented in Figure 12.

The greatest effect on post-cyclic behavior of Bushehr sand is detectable in the first stage as compared with the second and fifth stages of cyclic loading, plotted in Figs. 13 and 14. The post-cyclic behavior of the fifth cyclic stage, with an axial strain greater than 3.8%, resembles that of the second cyclic stage.



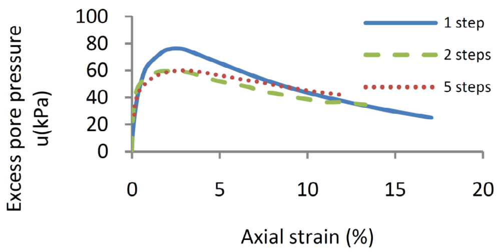


Fig. 12 Undrained post-Cyclic triaxial test result (Multistage cyclic loading effect) a: deviatoric stress vs. axial strain; b: excess pore pressure vs. axial strain

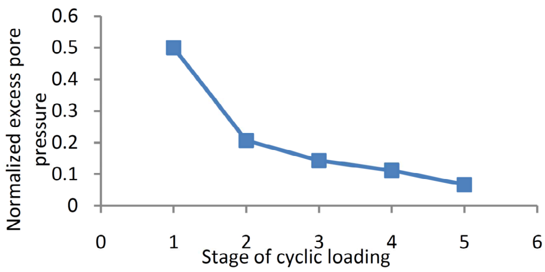


Fig. 13 Normalized generated excess pore water pressure during the cyclic loading versus stages of loading

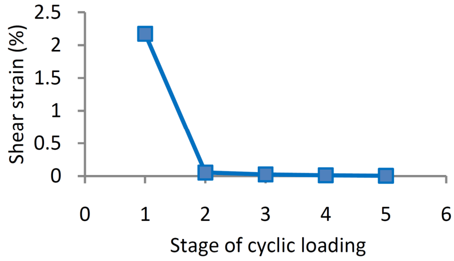


Fig. 14 Residual shear strain versus stage of loading

Post-cycling strength and stiffness of Bushehr sand in multistage cycling loading confirms the certain effects of pore water pressure and accumulative cyclic strain parameters. Interestingly, no further increase of accumulative cyclic strain occurs from the second stage onward (as shown in figure 14); however, pore water pressure still goes on until the fifth stage of cyclic loading (figure 13) and more interesting is the fact that the impact of the fifth stage of cyclic loading on post-cyclic behavior is typically similar to the impact of the second stage on post-cyclic strength (the same result as Vaid and Thomas article [48]). Therefore, we can conclude that normalized excess pore pressure lower that 10% has no impact on post-cyclic behavior of Bushehr sand under anisotropic consolidation and 200 kPa pore pressure.

7. Conclusion

- From this research, the following results are obtained:
- Based on the results of this research, increased strength in samples influenced by post-cyclic loading compared to other samples was observed, similar to the results obtained in other researchers [39 and 49].
- These results contradict other studies performed by some researchers [7, 43, 45, 56 and 57]. However, this is obvious since these researchers imposed post-cyclic load just after tolerating cyclic load by sample (with no drainage between the cyclic and post-cyclic loading stages). The apparent result of such loading mechanism is remaining pore pressure on samples hence decreasing effective stress at the beginning of cyclic loading compared to pre-cyclic monotonic loading.
- Regarding all the above mentioned matters we can consider the combination of pore water pressure and accumulative cyclic strain as two bases of post-cyclic strength growth of Bushehr sand which through accelerating the process of consolidation and the movement of grains Bushehr granular sand predisposes increasing density on one hand and occurrence of more suitable arrangement of grains on the other. Higher density and also a more suitable arrangement of grains together have no other results than increasing post-cyclic strength and stiffness.
- Increasing excess pore water pressure during the cyclic loading for all tests leads to a reduction in pore water pressure during the post-cyclic loading and an increase in post-cyclic strength.
- The first stage of multistage cyclic loading has

the most important role in post-cyclic behavior of soil.

- Test results of medium relative density of specimens (about 50%) showed that the contact surface of grains increased with increase in the cyclic shear strain and strength of sands (especially angular sand such as Bushehr sand as observed on microscope). However, there was no noticeable increase in crushing values (grain surface erosion) with the escalation of grains movements. Although the post-cyclic shear strength was greater than pre-cyclic shear strength, similar results can be achieved at high shear strain rates for post-cyclic rather than pre-cyclic tests. Clear trends with respect to crushing parameters were not exhibited for post-cyclic sample tests at 200 kPa of confining pressure. Future research on this soil under other condition can help discover a better trend for crushing values.

Notation

The following symbols are used in this paper:
B = Skempton pore pressure parameter;
B_r = Hardin's relative breakage [17];
C_c = coefficient of curvature;
C_u = coefficient of uniformity;
D_r =relative density;
D_{50} = a mean grain size;
G_s =specific gravity;
K_0 = initial stress ratio;
N = number of cycles;
P' = mean effective stress, $P' = (\sigma'_1 + 2\sigma'_3)/3$;
P'_0 = initial mean effective pressure;
q = Deviatoric stress, $q = (\sigma'_1 - \sigma'_3)$;
q_{cyc} = cyclic deviator stress;
ε_{speak} = the maximum cyclic shear strain during a cycle;
ε_s^* = accumulative cyclic axial strain and
σ'_1, σ'_3 = effective principal stresses.

Abbreviation

CSR = cyclic stress ratio and
PTL = phase transfer line

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