Proc. of the 9th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Zhongqiang Liu, Jian Dai and Kate Robinson
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doi: 10.3850/GRF-25280825_isgsr-008-P366-cd

ISGSR2025

EFFECT OF NON-PLASTIC FINES AND CYCLIC STRESS RATIO ON POST-CYCLIC RESISTANCE OF BUSHEHR CALCAREOUS SAND

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Estimating the post-cyclic resistance of soils in practical geotechnical projects is essential for predicting settlements and bearing capacity, particularly in regions susceptible to earthquake loading. Understanding the effects of fines content on post-cyclic monotonic resistance contributes to safer geotechnical design and mitigates the risk of foundation failure due to strength loss after seismic events. While the post-cyclic behavior of siliceous sands has been widely studied, limited research exists on calcareous mixed soils, whichhave different physical and mechanical properties comparedto siliceous sands. This study investigates the role of non-plastic fine content and cyclic stress ratio (CSR) on the post-cyclic resistance of Bushehr calcareous sand, which is extracted from a coastal region with high-seismicity risk. Undrained monotonic triaxial tests were performed after termination of cyclic tests on calcareous sands combined with various silt contents (0%, 10%, 20%, 30%, and 40%) and subjected to different CSRs to induce liquefaction. Post-cyclic resistance of samples was compared with shear resistance in monotonic tests. The results indicate that CSR influences post-cyclic resistance in two different ways depending on silt content: at lower fines content (0–10%), CSR improves post-cyclic resistance, whereas at higher fines content (20–40%), it leads to a reduction in strength. These findings provide crucial insightsinto offshore geotechnical safety and risk management by highlighting the post-cyclic behavior of calcareous soils, which is essential for geotechnical design in regions susceptible to seismic events.

Keywords: Post-cyclic resistance, Calcareous silty sand,Effect of fine content, Cyclic stress ratio,Cyclic triaxial tests, Liquefaction, Offshore geotechnical safety

1. Introduction

Estimating the post-earthquake settlements occurin soil helps calculate the bearing capacity of the foundation located on the soil after termination of cyclic load. Post-cyclic resistance is a suitable index for estimating these settlements (Sitharam, Dash and Jakka, 2013). Although the post-cyclic resistance in siliceous sands and silty sands has been studied by many researchers before (Vaid and Thomas, 1995; Sitharam, Dash and Jakka, 2013; Dahl *et al.*, 2014; Varghese *et al.*, 2019; Xu *et al.*, 2019; Juneja and Mohammed-Aslam, 2020); it has only been evaluated in calcareous sands in recent years (Kargar, Salehzadeh and Shahnazari, 2016; Shahnazari, Rezvani and Tutunchian, 2019). Calcareous sands have different properties from siliceous sands in terms of void ratio, friction angle, crushing and soil formation (Semple, 1988). Hence, post-cyclic behavior of these sands should be examined by considering effective parameters such as presence of fine content and effect of cyclic stress ratio (CSR). Post-cyclic resistance of a calcareous sand from Bushehr Port in Iran was investigated with five silt ratios of 0, 10, 20, 30 and 40% and three different CSRs through undrained monotonic triaxial tests.

2. Materials and Methods

The calcareous silty sand was obtained from a depth of 0-2 meter in Bushehr Port located in the northern coastal regions of Persian Gulf in Iran. Calcareous sand and silt were separated and combined again with silt ratios of 0%, 10%, 20%, 30% and 40% to consider different silt contents found in the area. Bushehr calcareous silty sand used in this study, has been previously studied for its monotonic response in a paper by the authors (Ghanbari Alamouti, Ziaie Moayed and Naeini, 2023). Hence, the particle size distribution charts and SEM pictures are similar to those provided in the last paper. As it was seen, calcareous sand and silt contain sub-angular and very angular particles with skeletal remains of marine organisms.The physical properties of the silt-sand combinations, including specific gravity (G_s), maximum and minimum void ratio ($e_{max}$and e_{min}), plasticity index (*PI*), and grading characteristics (C_u, $C_c$and D_{50}) were measured based on ASTM D854-14 (2014); ASTM D4253-16e1(2016); ASTM D4254-16(2016); ASTM D4318-17e1(2017);and ASTM D6913-17 (2017)and provided in Table 1(Ghanbari Alamouti, Ziaie Moayed and Naeini, 2023).

All samples were prepared using under-compaction method which has been first introduced by Ladd(1978) and ensures the uniformity in terms of relative density in sample height. Trials and errors were conducted to reach a similar after consolidation void ratio of $e_{ac\approx}$≈0.66 for all samples.

Table 1. Physical properties of Bushehr calcareous sand-silt combinations

Soil combination	G_s	e_{max}	e_{min}	D_{50} (mm)	C_u	C_c	PI
Clean sand	2.73	0.70	0.43	0.20	1.85	0.97	NP
Sand+10% silt	2.74	0.72	0.39	0.18	2.69	1.24	NP
Sand+20% silt	2.76	0.79	0.40	0.16	15.96	6.04	NP
Sand+30% silt	2.79	0.83	0.42	0.14	37.11	7.48	NP
Sand+40% silt	2.82	0.90	0.45	0.10	51.15	2.96	NP
Silt	2.82	2.30	0.72	0.01	17.04	1.09	NP

Undrained cyclic tests were performed under stress-controlled conditions and effective confining pressure of $(\acute{\sigma_c})100\ kPa.$ Three different cyclic stress ratios (the ratio of cyclic deviator stress to the mean effective confining pressure; $CSR = q_{cyc}\ /(2\acute{P})$ were applied in cyclic tests, and cyclic loading continued until the "liquefaction state" was reached. In this study, liquefaction criterion is defined as the excess pore pressure (Δu)reachingthe effective confining stress $(r_u = \Delta u/(\acute{\sigma_c}) = 1)$. Afterward,post-cyclic monotonic shear tests were performed with a strain rate of 0.5 mm/min to reach the final strain rate of 20%, following by a full consolidation stage.

3. Results

Results of post-cyclic shear tests performed on clean sands are depicted in Figure 1. For comparison,the results of monotonic shear tests (with no cyclic loads) reported previously by the authors are also shown in Figure 1(Ghanbari Alamouti, Ziaie Moayed and Naeini, 2023). It is evident that with the occurrence of liquefaction, the clean sand exhibitsstrain-hardening behavior(an increasing in deviator stress (q) while axial strain (μ_z) increases as shown in Figure 1-a) and presents dilative behavior (Figure 1-c), as it is also observed in monotonic test.Adittionally, it is seen that in post-cyclic tests the maximum deviator stress(q_{cs}) (post-cyclic resistance)for clean sand increases comparedto that in monotonic tests (Figure 1-a). Furthermore, by increasing in cyclic stress ratio (CSR) post-cyclic resistanceimproves(Figure 1-a), ultimate excess pore water pressure ("u)becomesnegative(Figure 1-b), and consequently contractive behavior diminishes in stress-strain plane (q-p' in Figure 1-c) inclean sands. Strain-hardening and dilative behavior in post-cyclic tests for different sands have been reported in previous studies (Vaid and Thomas, 1995; Dahl *et al.*, 2014; Kargar, Salehzadeh and Shahnazari, 2016). Also, an increase in post-cyclic resistance when CSR rises was observed in previous studies by Kargar, Salehzadeh and Shahnazari(2016); and Juneja and Mohammed-Aslam (2020).

Figure 2 compares the results of post-cyclic tests with those of monotonic testsfor samples with sand and two silt ratios of 10% and 30%. As it can be seen, samples with a 10% silt ratiodisplayed dilative behavior in the post-cyclic condition while their behavior was completely contractive in the monotonic shear tests (Figure 2-b and 2-c). As a result, the post-cyclic resistance increases significantly after occurrence of liquefaction (Figure 2-a), which improves with an increase in CSR. Figure 2-c demonstrates that 30% silt-sand samples exhibit a similar strength in both the post-cyclic testat CSR=0.14 and the monotonic test, while it decreases with increasing CSR values (Figure 2-c).The dilative behavior of these samples transformsinto contractivebehaviorin higher CSR values (CSR=0.15 and 0.16). It was also observed that in samples with silt ratios of 20% and 40%, post-cyclic resistance improves comparedto the monotonicone, but the trend of variation in post-cyclic resistance with CSR is decreasing. Hence, it can be said that post-cyclic resistance improves in clean sand and sand with 10% silt ratio in all CSR values comparing with that in monotonic shear test. While this improvement would exhibit in lower CSR values (CSR=0.13-0.14) in other silt ratios. This opposite trend between these two groups can be explained by the measured residual cyclic strains. A decrease in post-cyclic resistance with CSR was also observed for a siliceous silty sand in the study bySitharam, Dash and Jakka(2013).

According to the findings of Shahnazari, Rezvani and Tutunchian(2019), the most important parameter that could predict the post-cyclic resistance of sandy samples is post-cyclic volumetric strain ($\mu_{v,r}$). Additionally, Shahnazari, Rezvani and Tutunchian (2019) stated that the most effective parameter influencing post-cyclic volumetric strain is maximum cyclic-induced shear strain (γ_{max}), which is defined as the maximum single-amplitude shear strain. When γ_{max} increases at the end of the cyclic test, the resulting post-cyclic volumetric strain ($\mu_{v,r}$) increases and more excess pore water pressure dissipates. Hence, cyclic stress ratio (CSR) does not directly influence the post-cyclic resistance of soils. In this study, the maximum cyclic-induced shear strain was measured when liquefaction occurs for all silty sand samples in different CSR values as provided in Table 2. It can be seen that, with increasing CSR values for clean sand and 10% silt and sand combinations, higher maximum shear strains(γ_{max})developed. Hence, the post-cyclic resistance improves with increasing in CSR. However, this trend reversed for sands with other silt ratios.

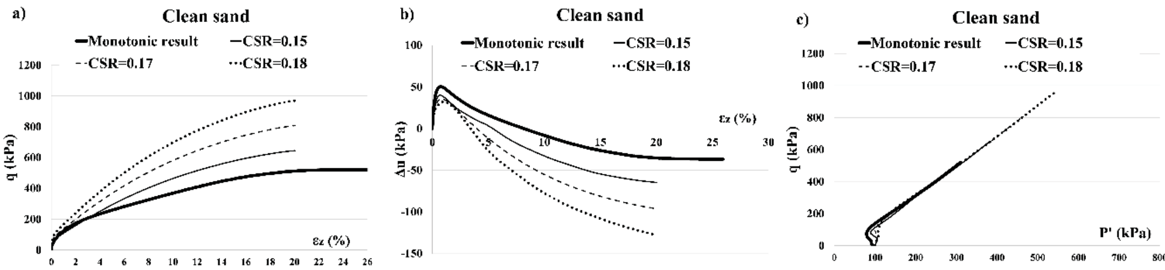

Fig. 1. Results of post-cyclic and monotonic shear tests under different CSRs on clean sand; a) deviator stress versus axial strain (q-μ_z), b) excess pore water pressure versus axial strain (" u-μ_z), c) stress paths (q-p')

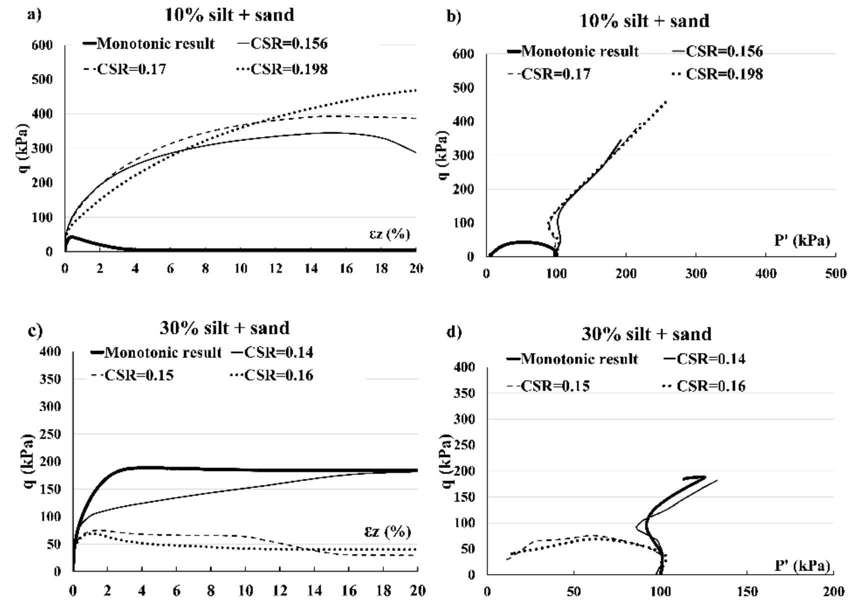

Fig. 2. Results of post-cyclic and monotonic shear tests under different CSRs on silty sand samples; a) variation of deviator stress versus axial strain (q-μ_z) in 10% silt-sand samples, b) stress path in 10% silt-sand samples (q-p'), c) variation of deviator stress versus axial strain (q-μ_z) in 30% silt-sand samples, d) stress path in 30% silt-sand samples (q-p')

Table 2. Maximum cyclic-induced shear strain (γ_{max}) measured in different silt-sand mixtures and CSRs

Sample	SP (%)	CSR	γ_{max} (%)	Sample	SP (%)	CSR	γ_{max} (%)
Clean sand	0	0.15	6.9	Sand + 20% silt	20	0.16	2.2
Clean sand	0	0.17	8	Sand + 30% silt	30	0.14	3.3
Clean sand	0	0.18	10	Sand + 30% silt	30	0.15	2.7
Sand + 10% silt	10	0.15	5	Sand + 30% silt	30	0.16	2
Sand + 10% silt	10	0.17	6.5	Sand + 40% silt	40	0.13	4
Sand + 10% silt	10	0.198	8	Sand + 40% silt	40	0.14	3.5
Sand + 20% silt	20	0.13	3.5	Sand + 40% silt	40	0.15	2.5
Sand + 20% silt	20	0.15	3	--	--	--	--

3. Conclusions and discussion

Understanding the post-cyclic behavior of calcareous sands is essential for predicting soil settlements and ensuring the stability of foundations, particularly in coastal and offshore environments subjected to cyclic loading. This study examined the effects of non-plastic fines content and cyclic stress ratio (CSR) on the post-cyclic resistance of Bushehr calcareous sand through undrained monotonic triaxial tests.

The main conclusions from this study are as follows:

1- Effect of fine content and cyclic stress ratio:

a) at low fine contents (0, 10%), higher CSR values enhance the post-cyclic resistance of soil, and dilative behavior becomes more pronounced. The soil's resistance also improves relative to that in monotonic tests. This behavior reduces the risk of ignoring post-cyclic resistance in design of foundations. Although post-cyclic settlements should be estimated through maximum cyclic-induced shear strains (γ_{max}) and considered in foundation design.

b) At higher fine contents (20, 30, and 40%), an increase in CSR leads to reduction in post-cyclic resistance of the soil. Post-cyclic resistance resembles the monotonic shear resistance in lower values of CSR. This implies that by ignoring the post-cyclic resistance in foundation design, the risk of failure and instability condition will arise after an earthquake event specially for earthquakes with higher intensity.

2- Maximum cyclic-induced Shear strain $(\boldsymbol{\gamma_{max}})$:

It was demonstrated that shear strains occurred after liquefaction, directly influences the post-cyclic behavior; when producedγ_{max} after the cyclic loads increases, the soil produces more volumetric strains which leads to improvement in post-cyclic resistance.

3- **Engineering Implications:** The results highlight thatestimating post-cyclic resistance provides a reasonable insight for designing important offshore foundations like wind turbines, oil platforms, and submarine pipelines. It can be directly inferred that considering factors like fines content, CSR, and shear strains will contributeto minimize risks associated with post-cyclic settlements and strength loss in geotechnical designs to.

In concluding, it is proposed that foundation designs should incorporate conservative safety factors to account for post-cyclic strength loss, especially in fine-rich calcareous sands. Ground improvement techniques such as preloading, injection, or cementationmay be necessary to enhance soil stability.

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