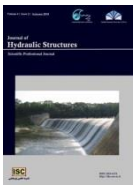
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Liquefaction Behavior of Bushehr Coastal Carbonate Sand

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Abstract

Over the past few years, liquefaction phenomena have always been one of the challenging issues in geotechnical engineering. The occurrence of liquefaction is due to cyclic tensions resulting from zero effective stress in the soil mass. Carbonate sands are significantly different in static and dynamic resistance than silicate sands. In this research, this phenomenon has been studied by studying the liquefaction behavior of Bushehr carbonate sand. In this paper, the liquefaction of Bushehr carbonate sand in multiple relative densities, different cyclic stress ratios (CSR), and different overburden stresses are studied and investigated. The liquefaction status of this sand is investigated in the simple shear apparatus. In order to evaluate the liquefaction behavior of dry samples, the tests were performed in volume constant situations. The samples were prepared in remolded conditions using a conventional latex membrane. The results indicated that in the same conditions and a low cyclic stress ratio, by reducing overhead stress from 300 to 50 kPa, resistance to liquefaction in Bushehr carbonate sand will be 35 times more. This is not true in the higher cyclic stress ratio, in which liquefaction occurs in very low cycles (up to three cycles). The results also indicated that carbonate sand shows lower liquefaction resistance compared to silica sand.

Keywords: Carbonate Sand, Liquefaction Phenomena, Simple Shear Apparatus.

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1. Introduction

The liquefaction phenomenon is recognized as one of the fundamental and challenging issues in geotechnical engineering science. When saturated soil is two directionally sheared rapidly due to seismic movements, the water pressure increases in the soil voids. In saturated loose non-cohesive soils, pore pressure increases rapidly and may reach the situation in which particles are suspended from each other separately and eliminate the strength and stiffness of the soil. In general, the tendency to volume change is the predisposing factor in liquefaction occurrence that

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the type of soil, its shape, and size of particles play important roles in this phenomenon [1]. The resistance of coarse soils is due to friction angle and soil particles interlock. In any depth of the ground, before the earthquake, part of the weight of the soil and overburden pressures is tolerated by the forces between particles and other parts carried out by the water. When the loose soil is excited by the earthquake, the tendency is to compress. The existence of water among the pores, due to slow drainage, leads to gradual volume reduction. Consequently, with the continuation of seismic depletion, upper weight is more and more transferred to pore water, and the force between soil particles decreases. In the end, pore pressure may reach the degree that causes water by splitting the upper layers, and all the weight of the upper aggregates is transmitted to the pore water. In these conditions, the soil is liquefied and behaves like a viscous fluid, and may cause considerable movements in the ground. The destructive effects caused by liquefaction in 1964 in the *Good Friday* earthquake in *Alaska* and *Niigata* earthquake in Japan attracted the attention of geotechnical engineers. Both earthquakes indicate destructive and surprising effects of liquefaction, including foundation and building rupture, slopes failure, and flotation of buried structures. Since ever, the phenomenon of soil liquefaction is one of the major considerations in designing structures inside or on loose saturated sandy soils. Experiences have shown that relatively clean sands with a few percent of fines are vulnerable to liquefaction. However, there are significant complexities about the potential of liquefaction of silty soils, silty-clay, and gravels.

The Rough theory can properly reduce the cost of project studies to evaluate the potential of liquefaction of soils [2]. The cyclic resistance increases by reducing the initial confining pressure and this resistance decrease with increasing the amount of silt in the sample. Another point is that coarse grains are less likely to be liquefied [1]. The results of Mazaheri and Nasiri's studies showed that the addition of 3% clay to liquefied Dorood sand leads to reducing its liquefaction potential up to 39%. Another method of reducing liquefaction potential is the use of stone columns [4-6]. Carbonate sands are created from the remains of animals (e.g. shells) and the erosion of limestone formations. Non-carbonate sands are generally created from inland ancient rocks that have been eroded. Compared to silica sand, carbonate sands generally have less particle stiffness, more porosity, various particle shape, and more complex structure. These sands account for about 40% of the ocean levels [7]. Brandes [8] showed that the dynamic strength and mobilized friction resistance of carbonate sands are higher than that of silica sand. While in the strain level of 0.05 to 1%, the shear modulus and damping ratio of carbonate sand are lower than the silica sand. The results of this study showed that the difference in carbonate and silica sand is due to particle geometry, particle stiffness, grain size distribution, and voids between particles in the soil mass. Some previous studies have shown that in the same relative density and similar stress conditions, the cyclic resistance of the loose carbonate sand is more than the silica sand [9 11]. Carbonate deposits create significant challenges in the construction of coastal structures, especially the dynamic response of driven piles in these areas [12]. So far, many studies have been carried out on the dynamic behavior of carbonate sands around the world, which is often carried out with the triaxial cyclic device, and the focus was on the shear modulus and the damping ratio of such sands [13-15]. Liquefaction behavior is an important topic in recent years which attract researchers' attention all across the world [16-18].

Shahnazari et al. [19] proposed a simple method based on shear wave velocity to assess the occurrence of liquefaction in carbonate materials in the port of Kawaihae, which was liquefied in the 2006 Hawaii earthquake. Salem et al. [20] indicated that the Egyptian carbonate sand shows high resistance to liquefaction. Rollins et al. [21] stated that liquefaction occurrence in carbonate sand will occur in different cycles than silica sand. On the other hand, Mejia and Yeung [22]

based on field observations about liquefaction, reported that both types of silica and carbonate sands have had the same type of liquefaction behavior.

Despite the research performed on the dynamic behavior of carbonate sands, the liquefaction aspects of these types of sands are not well assessed. An interesting point in this regard is that the potential of liquefaction in these types of sand until the 1993 earthquake in Guam was not known correctly [23]. This paper examines the behavior of the Bushehr carbonate sand liquefaction, trying to take a new step in obtaining more information on the liquefaction behavior of this sand located in the southern region of Iran.

2. Experiment Equipment

2.1. Cyclic Simple Shear Apparatus

Dynamic analysis is a valuable technique in recognizing the seismic behavior of geotechnical structures [24]. The cyclic simple shear device provides a precise simulation of horizontal shear stress distribution in the samples [25]. The soil sample in the cyclic simple shear machine is constrained on the side and consolidates in the vertical direction due to normal stress increase. Then, the end of the sample is exposed to cyclic load (vibration of stress control, strain control, or volume control), while the top of the sample is bound against lateral movements.

The cyclic simple shear device simulates seismic stress conditions better than the cyclic triaxial apparatus. In this paper, the simple shear device (Fig. 1) was used for cyclic tests to investigate the Bushehr carbonate sand liquefaction behavior on cylindrical samples with a diameter of 70 *mm* and a height of 20 *mm*. This device can apply horizontal and vertical loads and includes the base, column, beam, and loading jack. The load cell has a capacity of 500 *kg* and the *LVDT* motion range is also 50 *mm*. The loading frame is responsible for applying the load to the sample, with the command of the software to hardware, the force is applied to the sample. In this research, the simple shear device of the *NGI* type has been used and experiments were carried out in constant-volume conditions. The lateral confinement for samples is provided using Teflon coating rings around a conventional latex membrane.

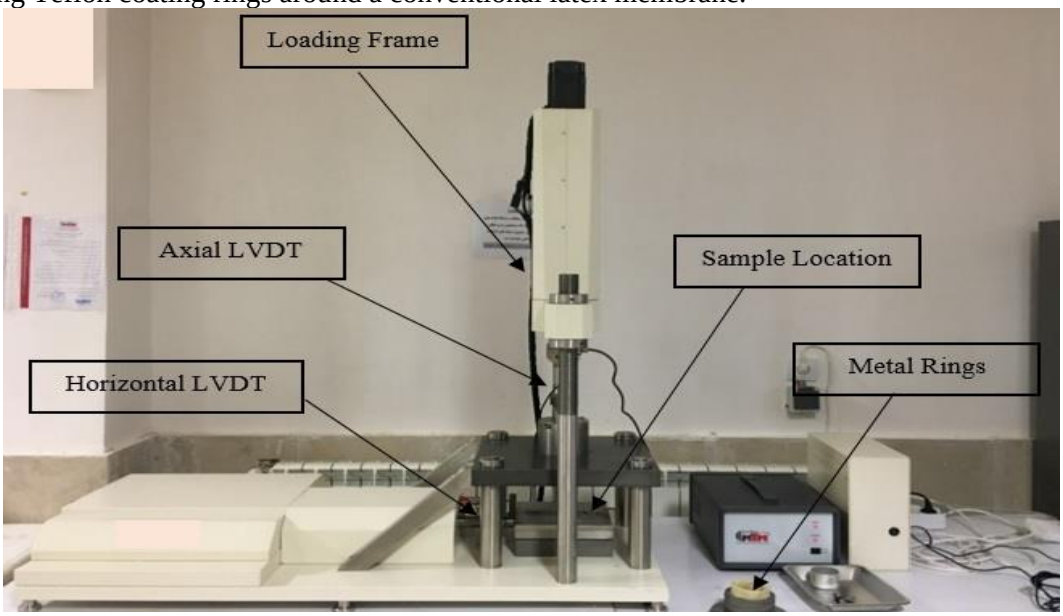


Figure 1. The simple shear device used in this study

2.2. Static Characteristics of Bushehr Carbonate Sand

The studied soil is Bushehr carbonate sand, whose static behavior of such soil was investigated by various researchers [26, 27] previously. The location of carbonate sand is shown in Figure 2. The design base acceleration of the area due to Iranian code 2800 is 0.3g. The soil particles under the optical microscope are shown in Figure 3 and the specifications of this sand are presented in table 1. The friction angle was obtained using a direct shear test. Figure 4 illustrates the grain size distribution diagram.

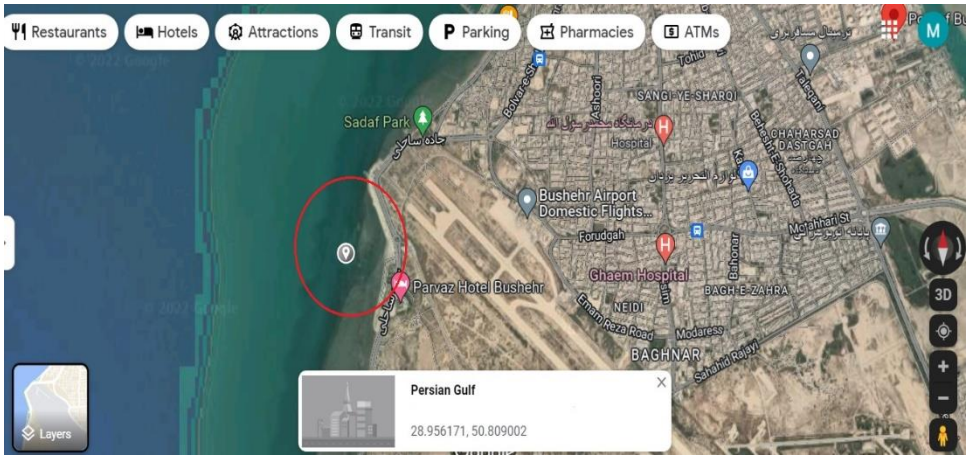


Figure 2. The location of Bushehr carbonate sand

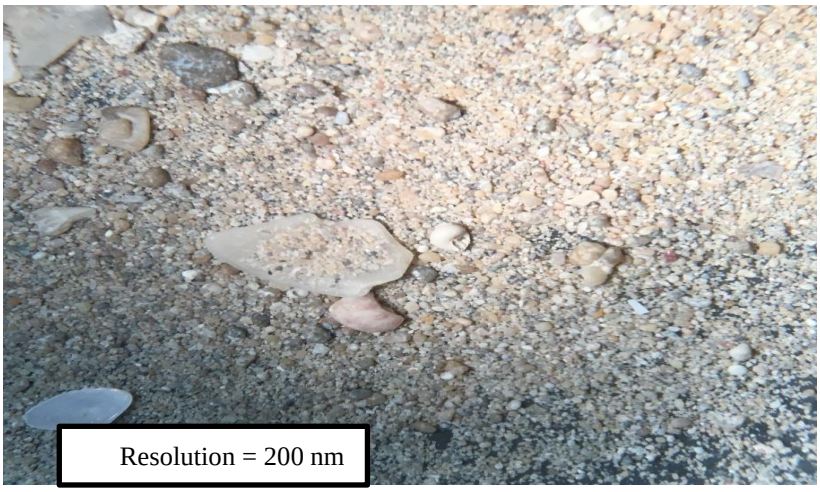


Figure 3. Bushehr carbonate sand grains under the optical microscope

Table 1. Physical characteristics of Bushehr carbonate sand

Coefficient of Uniformity (C_u)	Coefficient of Curvature (C_c)	Soil Classification (*USCS*)	Specific Gravity	Maximum Void Ratio	Minimum Void Ratio	Optimal Moisture Content (%)	Maximum Dry Unit Weight (gr/cm^3)	Internal Friction Angle (°)
2.786	0.909	SP	2.696	0.595	0.359	12.9	1.79	24

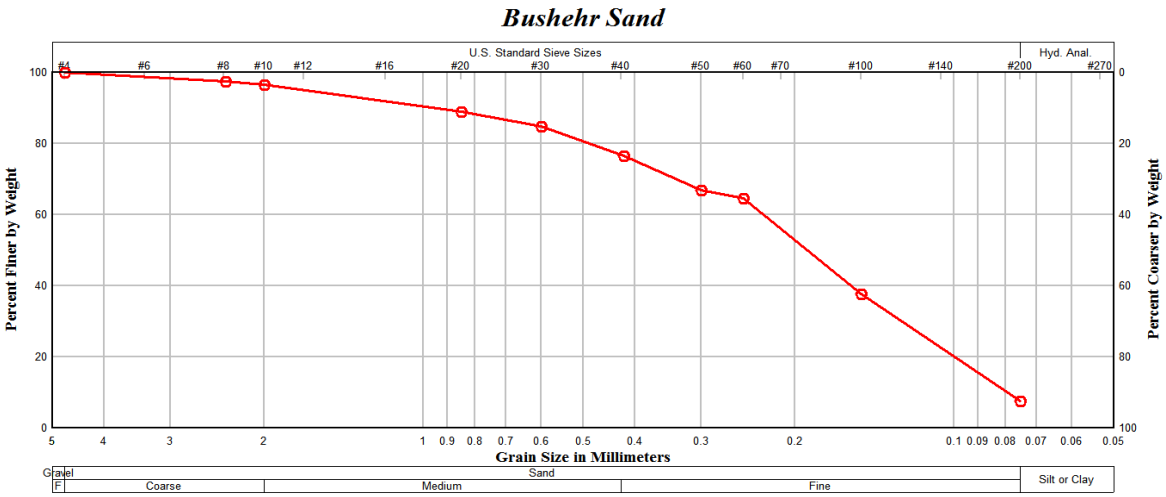


Figure 4. Grain size distribution of Bushehr sand

2.3. Sample Preparation Method

In this research, the dry pluviation method has been used to construct samples, since it is a convenient method for preparing dry soil samples in the known void ratio [25, 28]. The rate of pouring the sand and the fall height affects the amount of void ratio. Dry pluviation has been carried out by a funnel with a known fall height [29]. Vacuum pressure of about 20 *kPa* is applied to mold and rings to ensure the complete bonding of the membrane into the inner wall of the mold and round the Teflon coated rings so that the samples can be made in the specified volume in the mold. The sand is poured through a funnel in a circular pattern inside the mold so that the fall height is the same to make homogeneous samples. Since the samples studied in this paper were made with relative densities of 30% to 60%, there is no need for vibration or compaction to achieve higher densities. After completing the sample manufacturing in the mold, the sample is placed inside the simple shear device and vertical stress is applied to the sample.

2.4. Test Conditions

Since the purpose of this study is to investigate the behavior of Bushehr sand liquefaction, various relative densities (30%, 40%, 50%, and 60%) were used. The reason is that the occurrence of liquefaction is possible in the loose soil mass. Accordingly, the maximum relative density which has been studied was 60%. In this research, the standard conditions of *ASTM D6528* are considered and Bushehr carbonate sand was tested in dry conditions under constant volume situations. Several studies examined the status of dynamic and liquefaction parameters of dry sand in a cyclic simple shear device under constant volume conditions [30-33]. Since some researchers consider the dynamic properties of sands, unaffected from the frequencies in the range of 0.1 to 4 *Hz*, the frequency of 0.5 *Hz* has been used for all experiments in this paper to investigate the liquefaction behavior of Bushehr carbonate sand. In this research, the carbonate Bushehr sand liquefaction potential was investigated and the aim was to answer the question of how the effects of overburden stress, relative density, and cyclic stress ratio on the number of cycles of liquefaction occurrence in Bushehr carbonate sand. In most of the previous studies, the focus was on the silica sand liquefaction behavior. While in this research, the liquefaction behavior of Bushehr carbonate sand has been studied.

2.5. Dynamic Characteristics of Bushehr Carbonate Sand

To obtain basic information from the Bushehr sand shear modulus, initially, a series of cyclic tests under constant stress conditions with different cyclic stress ratios and relative density status were conducted which are shown in Fig. 5. As shown in this figure, the amount of sand shear modulus increases with increasing relative density. Also, the loose sand experienced more shear strain compared with samples of higher relative density. Since many studies in the past have proposed the 10th cycle as a suitable basis for determining the dynamic characteristics of soils [34], this cycle has been used for the above-mentioned comparison.

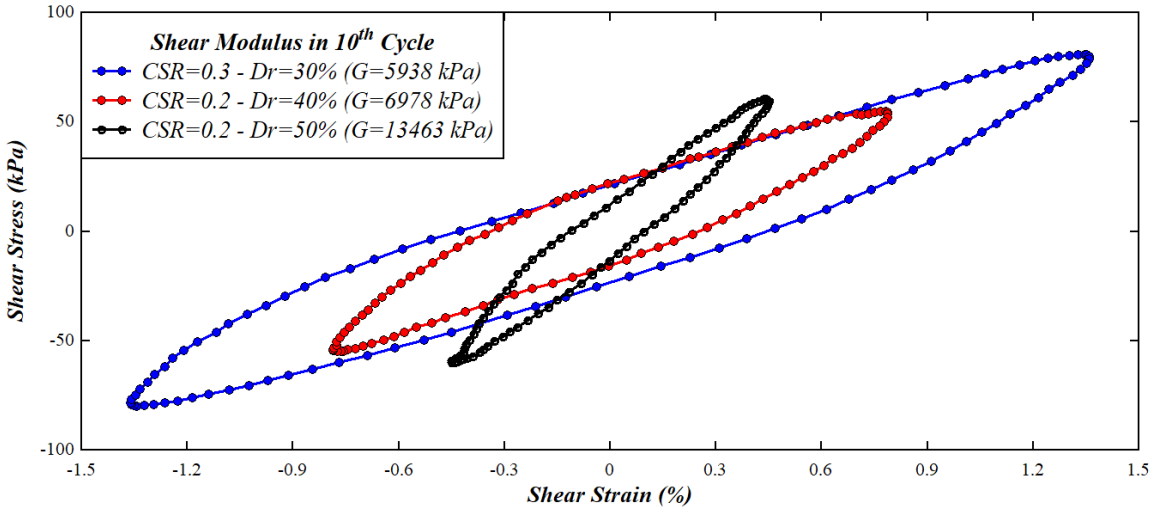


Figure 5. Bushehr sand hysteresis loops for relative densities of 30%, 40%, and 50%

3. Simple Shear Tests under Volume-Control Condition

The process of liquefaction experiments in dry conditions and the state of the constant volume is that by keeping the sample volume constant while applying the shear stress cycles to the sample. In this situation, the normal stress conditions applied to the sample are measured. The condition of liquefaction occurrence in soils is that the effective stress becomes zero. Accordingly, in cyclic simple shear experiments, when primary normal stress applied to the sample becomes zero, the soil has been liquefied. In other words, when hysteresis loops in the experiments are almost asleep, liquefaction occurs in the sample, and that cycle is known as a cycle of liquefaction occurrence.

In this study, four different relative densities, i.e. 30%, 40%, 50% and 60% are used. Cyclic stress ratio defined as $CSR = \frac{\tau_{cyc}}{\sigma_v}$, in which σ_v is normal stress applied to sample, and τ_{cyc} is one-directional shear stress amplitude in cyclic simple shear apparatus. In this research, *CSR* of 0.08, 0.1, 0.12, 0.2, and 0.3 used in experiments. In Table 2, the number of cycles required for the occurrence of liquefaction in the Bushehr carbonate sand due to the various relative density of the samples and the different cyclic stress ratios applied to samples is shown.

Table 2. Liquefaction test results conducted on Bushehr carbonate sand

CSR	**Normal Stress** *(kPa)*	**Relative Density** *(%)*	**Liquefaction Cycle**
0.12	50	30	6
0.12	50	40	37
0.12	50	50	60
0.12	50	60	512
0.08	50	50	772
0.10	50	50	600
0.20	50	50	100
0.30	50	50	3
0.08	300	50	37
0.10	300	50	17
0.12	300	50	11
0.20	300	50	8
0.30	300	50	2

In figures 6 to 8, examples of liquefaction graphs are shown according to the conditions of each test. As seen in these graphs, with the flattening of the hysteresis loops of each sample, liquefaction has occurred. In figures 9 and 10, the gradual reduction of applied overburden force with cycles is illustrated.

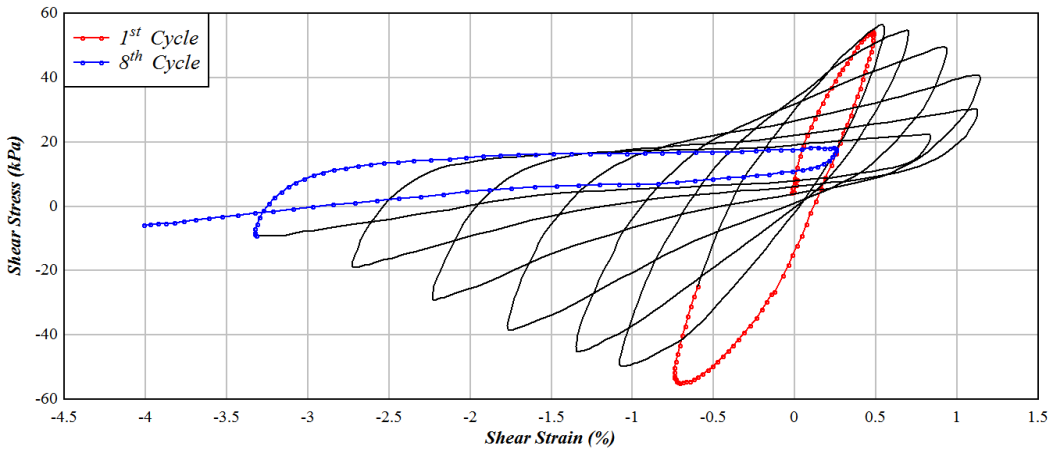


Figure 6. Simple shear test with CSR=0.2 and σ_v=300 *kPa* (soil liquefied in 8th cycle)

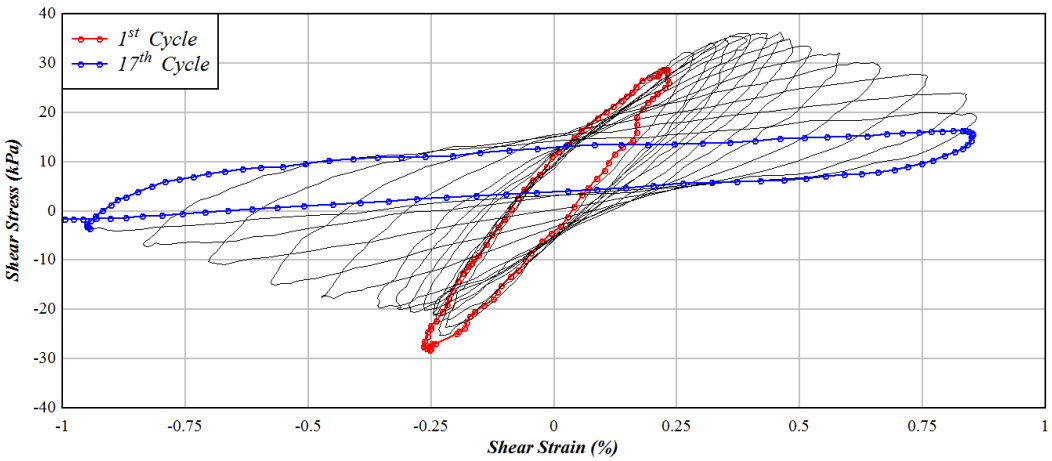


Figure 7. Simple shear test with CSR=0.1 and σ_v=300 *kPa* (soil liquefied in 17th cycle)

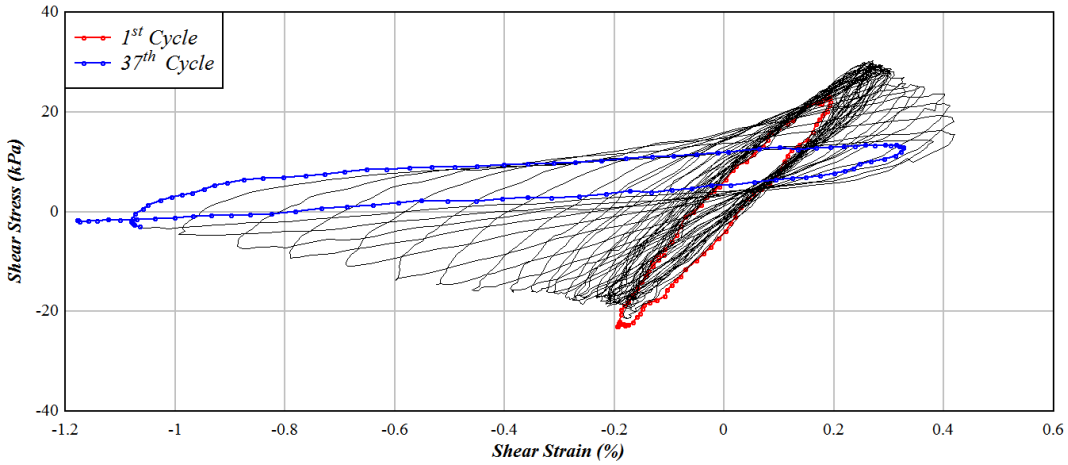


Figure 8. Simple shear test with CSR=0.08 and σ_v=300 *kPa* (soil liquefied in 37th cycle)

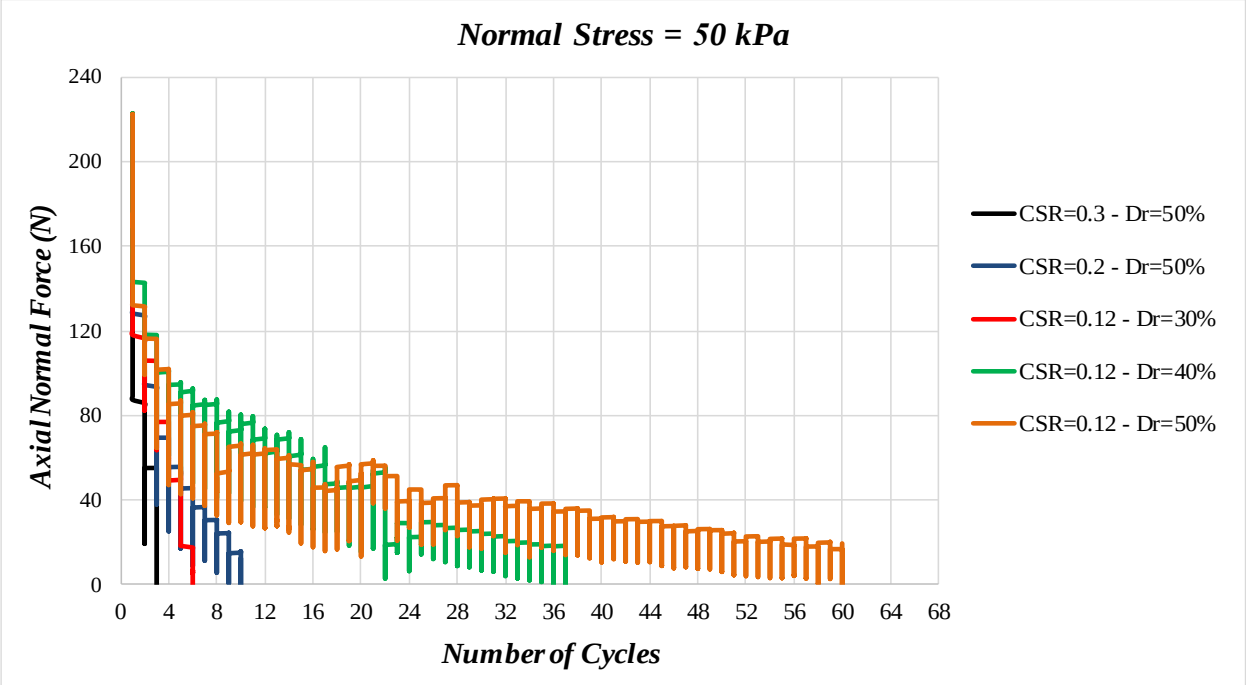


Figure 9. The trend of axial force fluctuation for determining the liquefaction cycle (σ_v=50 *kPa*)

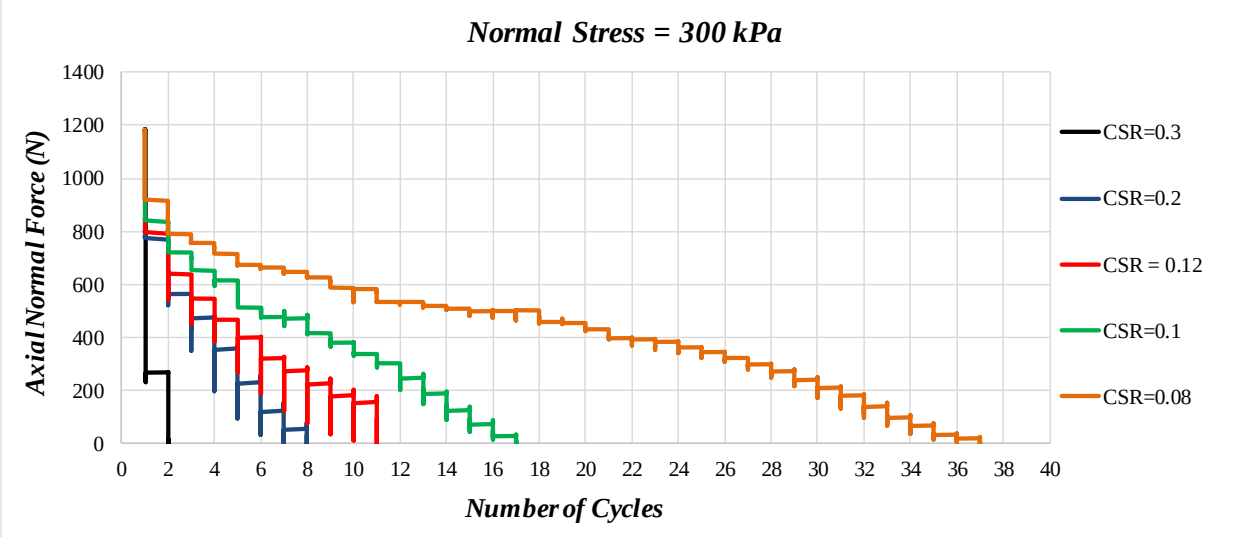


Figure 10. The trend of axial force fluctuation for determining the liquefaction cycle (σ_v=300 *kPa*)

4. Discussion

In this research, the behavior of Bushehr carbonate sand liquefaction has been studied using a cyclic simple shear apparatus in the dry state and constant-volume condition. The use of this method will determine the condition of the sand when effective stress (normal stress in dry conditions) becomes zero. The liquefaction of the samples is shown in figures 5 to 7. Based on these figures, the flattened hysteresis loops of samples can be seen when the soil liquefied. This

occurs when normal stress reaches zero in constant-volume conditions.

Based on figures 8 and 9, zero overburden stress has been shown by increasing the number of cycles. As it is clear, by increasing the relative density of the samples or reducing the cyclic stress ratio, the number of cycles needed for soil liquefaction will increase, and vice versa, with increasing the cyclic stress ratio, Bushehr sand liquefied in lower cycles.

The findings of the experiments showed that with increasing overburden stress on the samples in low cyclic stress ratios, resistance to liquefaction decreases strongly. For example, the liquefaction of a sample with the relative density of 50%, CSR=0.1, and normal stress of 50 *kPa* occurs in the 600 cycles, while if overburden stress increases to 300 *kPa*, liquefaction occurs in the 17^{th} cycle. This means that the resistance to liquefaction in such a sample will be 35 times lower, which is a considerable difference. This phenomenon is a concerning topic about the behavior of carbonate sand liquefaction. If the cyclic stress ratio increases to 0.3, the cycles that triggered liquefaction in overburden stresses of 50 and 300 *kPa* are 3 and 2 cycles, respectively, which is virtually negligible. This suggests that the effect of overburden stress in the occurrence of liquefaction phenomenon in carbonate sands is very important. Another point is that if the cyclic stress ratio is 0.12, the resistance to liquefaction from the 64 cycle reaches the 11 cycle, which decreases about six times. The results showed that in the same conditions, the increase of 0.02 in the cyclic stress ratio caused a six-time reduction in the liquefaction resistance. Another important point is that, in the condition of the highest cyclic stress ratio (i.e. 0.3), there is no difference between the liquefaction behavior of the samples. As an example for this situation, the maximum resistance to liquefaction was three cycles, which means that in such conditions the Bushehr carbonate sand will immediately liquefy. This information shows that with increasing the cyclic stress ratio in the Bushehr carbonate sand, the quantity of overburden pressure will not affect liquefaction occurrence.

4.1. Comparison Between Liquefaction Cycles of Carbonate and Silica Sand

To conduct a comparison between the liquefaction behavior of carbonate and silica sands, in this section, Kermanshah regional silica sand with fine particles (Fig. 11) with characteristics presented in Table 3 was used. The reason for choosing this type of sand is that it has relatively similar physical characteristics to Bushehr sand. It should be noted that according to the BS ISO146888 1: 2002 standard classification, both silica, and carbonate sands are considered to be fine sands. It is noteworthy that the particles of silica sand are smaller than the carbonate type (Fig. 12).

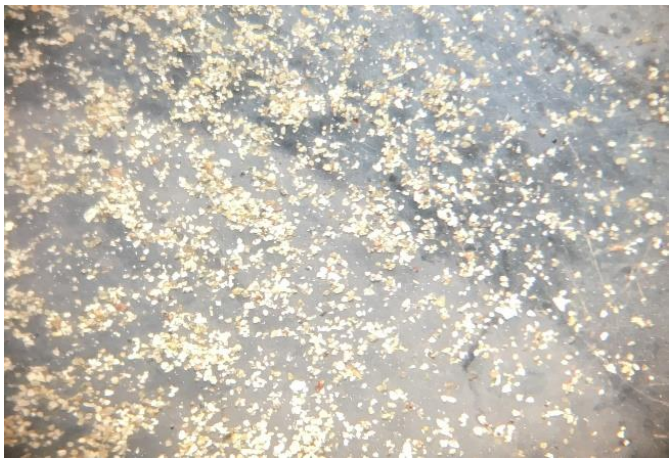


Fig. 11. The silica sand under the optical microscope

Table 3. Physical characteristics of silica sand

Coefficient of Uniformity (C_u)	Coefficient of Curvature (C_c)	Soil Classification (*USCS*)	Specific Gravity	Maximum Void Ratio	Minimum Void Ratio	Internal Friction Angle (°)
1.933	0.883	SP	2.712	0.997	0.652	24

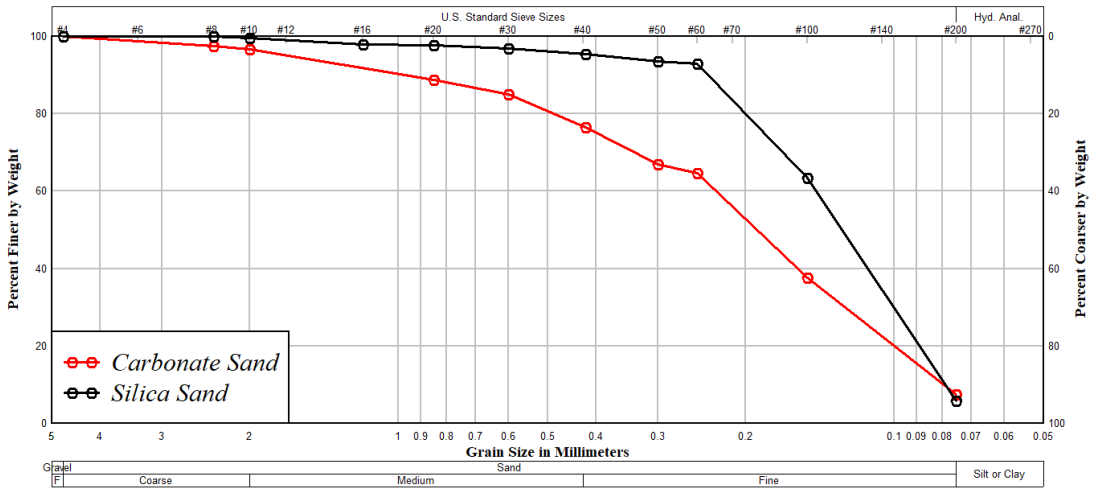


Figure 12. The comparison between grain size distribution of carbonate and silica sands

The experiment was conducted for CSR=0.3 and relative density of 50% in 300 *kPa* overburden pressure. As shown in Figure 13, in the same conditions, the silica sand liquefied in the fifth cycle; While the liquefaction of Bushehr carbonate sand occurred in the second cycle. The results also indicated that carbonate sand has experienced larger shear strains during the experiment. These data imply a different nature of carbonate sands compared to silica sands. Results show the importance of considering the type of sand in the liquefaction behavior.

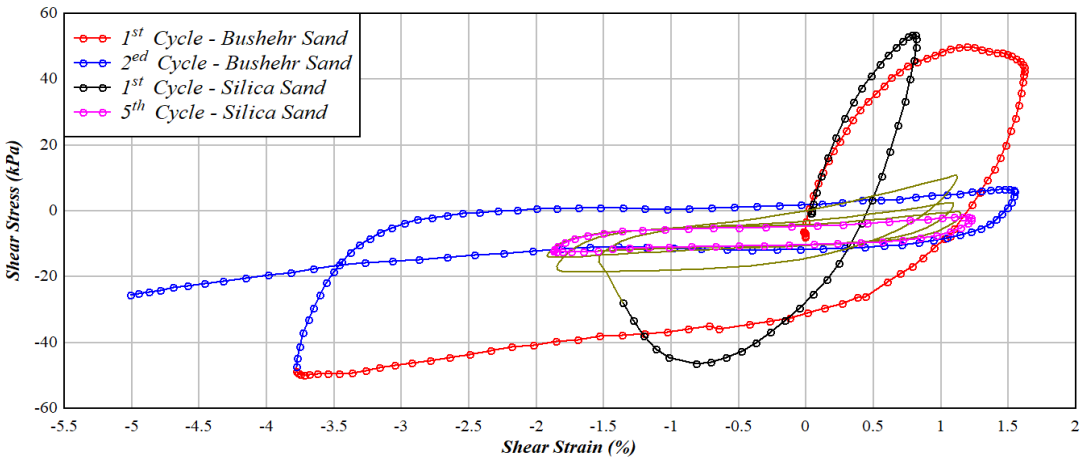


Figure 13. The comparison between liquefaction cycles of carbonate and silica sands in the same condition

5. Conclusion

The results of this study, which examined the behavior of Bushehr carbonate sand liquefaction in constant volume situations and dry conditions, showed that liquefaction resistance is dependent on the cyclic stress ratio more than that of overburden stress, or relative density of samples. The results obtained in this study are summarized as follows:

- With increasing normal stress in the low cyclic stress ratio, liquefaction resistance will be dramatically reduced (up to 35 times reduction in the liquefaction resistance).
- By increasing the normal stress in the higher cyclic stress ratio, liquefaction resistance will be changed negligibly (changing the liquefaction cycles from three cycles to two cycles).
- In the condition that the applied cyclic stress ratio to the samples is high, regardless of the overburden pressure, the liquefaction resistance in the carbonate sand, dramatically decreased. This means that where the *CSR* is the highest, regardless of its overburden stress, the sample will be liquefied immediately.
- In terms of moderate *CSR*, increasing the relative density of the samples leads to an increase in resistance to liquefaction (up to 85 times increase in the number of cycles necessary for the occurrence of liquefaction in the Bushehr carbonate sand).
- In a similar experimental condition, the Bushehr carbonate sand compared to the silica sand will be liquefied in a lower number of cycles and will experience larger shear strains.

Acknowledgments

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