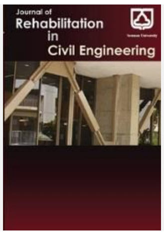

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Shear Strength Behavior of Oil-Contaminated Bushehr Carbonate Sand

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ABSTRACT

The crude oil leakage in soils could lead to an extreme reduction in resistance. It is significant for oil-rich countries, such as Iran, with several crude oil resources. The clean and oil-contaminated Bushehr carbonate coastal sand cyclic simple shear behavior is investigated. The clean and crude oil-contaminated sands were prepared with a relative density of 60%, and oil-contaminated samples were prepared using 2%, 4%, and 6% crude oil. Shear modulus (G) and damping ratio (D) rely on soil particle characteristics. Using 2% crude in Bushehr carbonate sand leads to an approximately 5% increase in shear modulus. Also, applying 4% oil in the specimens caused roughly 8% enhancement in the dynamic strength of Bushehr carbonate sand. Keeping the conditions constant, the effects of oil contamination on this carbonate sand were investigated using a cyclic simple shear apparatus. The results indicate that 6% crude oil contamination will lead to a decline in shear modulus (10.6%), a growth (27.6%) in the damping ratio, and a decrease (16.6%) in the friction angle of Bushehr sand in comparison to clean sands. However, 2% and 4% contamination led to static and dynamic resistance increase of Bushehr carbonate sand. The results indicated that using 2% and 4% crude oil caused a 12.5% and 20.8% increase in the static resilience of Bushehr carbonate sand, respectively.

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1. Introduction

Crude oil leakage is a high risk in areas near oil wells. It is significant for hydraulic or offshore structures adjacent to oil wells or refinery zones. Oil leakage and contamination of the mentioned areas are possible due to failure and damage to the buried pipelines, oil eruption from wells, and terrorist and sabotage operations. In the first Persian Gulf war, oil lakes surrounded lands over 110 km^2 [1]. In the case of this problem, in addition to geotechnical aspects, it will also bring environmental issues. Accordingly, knowledge of reducing the load-bearing capacity of these areas is considered a vital issue.

Various approaches have been introduced in soil stabilization, such as chemical [2-4] and physical methods [5-12]. Mohammadi et al. [4] used three types of pollutants (diesel, crude, and engine oil) to investigate the impact of oil contamination on the interaction between sandy soil and piles. The results of their research showed that the presence of oil between the sand particles would have significant adverse effects on reducing the pile's load-bearing capacity. Al-Adly et al. [5] research showed that sand pollution with crude oil changes the load-settlement curve and drastically reduces the load-bearing capacity. They also indicated that the failure mode changes from local to punching failure. Joekar and Hajiani-Bushehrian [6], numerically examining the bearing load tolerance of the strip footing on the sandy slope contaminated with crude oil, concluded that by improving the thickness of the contaminated layer and increasing the amount of pollutants, the bearing tolerance decreased. Sands with bigger grain sizes have higher friction angles than smaller particles [7]. Nasr [8] showed that the CBR value of contaminated sand using heavy engine oil dropped sharply. The aging process improves the strength of oil-contaminated silica sands [9]. Also, aging improved the oil and soil interaction in contaminated soils [10]. Using environmentally friendly stabilizers such as Nano clay [11], Bentonite Nanofluid [12], and zeolite [13] is another effective technique in enhancing the geotechnical properties of oil-contaminated soils.

Shin et al. [14] showed that the strip foundation load-bearing capacity located on the oil-contaminated sand bed is significantly reduced compared to the clean bed. As the amount of oil increases from zero to 1.3% by weight, the load-bearing decreases to 75%. The results of Nasiri et al. [15] experiments indicated that the sands contaminated with 6% crude oil-bearing capacity are reduced by at least 50% compared to clean sands, and the strain-stress diagrams of these soils will be severely reduced. Their study showed that there are affecting factors such as the shape of particles (sharpness), the percentage of coarse particles in the soil mass, and the grain size in the resistance of sand contaminated with crude oil. Decreased permeability and reduced resistance of soils contaminated with crude oil are the main effects of the presence of this chemical in soil mass [16]. Bio-remediation is an effective technique in oil-contaminated soil stabilizations [26-31]. Microwave remediation [18] and phytoremediation [19] are other methods in oil-contaminated soils. Biochar aerogel revved the biodegradation of crude oil contaminants in soil [20].

The damping ratio and shear modulus rely on the particle shape, grain size, grain voids, and stiffness [21]. Dynamic analysis is vital for geotechnical structures [22]. In the range of 0.05% to 1% shear strain for the cyclic shear apparatus used in laboratory tests, the sand exhibits nonlinear behavior and will experience a decrease in stiffness and hysteresis damping [23]. As investigated by various researchers, the cyclic simple shear test is most closely related to ground conditions during cyclic loading [38-42]. Using simple shear devices dates back to about 80 years ago. Kjellman [25] described the direct shear apparatus of the Royal Swedish Geotechnical Institute (SGI), built in 1936, having a mold 60 mm in diameter and 20 mm high. Roscoe [26] introduced the Cambridge

Type Simple Shear, in which square samples with a length of 60 mm and a height of 20 mm were tested. In 1961, the Norwegian Geotechnical Institute (NGI) developed a simple shear machine similar to the SGI apparatus. NGI device's larger models were also used in the 1980s. The SGI device uses a series of rings around the mold to confine the sample, while the NGI apparatus employs a wire-reinforced membrane.

Damping in sand is due to energy loss. The elastic energy stored in the soil element is consumed by destroying the soil structure, breaking down soil particles, and rotating the soil grains [27]. In this regard, Vucetic et al. [28] showed that nonlinearity and soil viscosity are the most important contributing factors in the area of the hysteresis cycle. The simple shear apparatus will provide a close and accurate simulation of the horizontal shear pressure employed in the specimens. The specimens are confined laterally in the cyclic shear machine (via Teflon rings or wire-reinforced membranes) and consolidated in the vertical direction by increasing the vertical stress (at K_0 condition). The specimen's end is then subjected to cyclic stress (shaking of the control stress or control strain type) while confining the top of the sample to sideways displacements. A simple shear machine manufactures dynamic pressure situations on-site more pleasingly than the cyclic triaxial machine. The simple shear examination in dynamic conditions is known as a proximate experimental simulation to understand the dynamic behavior of soils. Using shear modulus (G) and damping ratio (D) are two main factors of dynamic features to assess the ground reaction. Typically, the shear modulus computes by calculating the maximum points in the hysteresis loop. The area inside this loop leads to the damping ratio.

Liquefaction analysis is another dynamic behavior in sands. There are various research in this regard due to its significance. Mazaheri et al. [29] revealed that adding 3wt% clay to the Dorood liquefied sand would decrease the liquefaction potential to 39%. Bushehr carbonate sand behavior differs from silica sand, especially in the case of liquefaction. The outcomes revealed that in the same situations and low CSR values, by decreasing overburden pressure, Bushehr sand liquefaction resistance will be increased 35 times [30].

This paper provides the dynamic properties of Bushehr carbonate sand in clean and contaminated situations with 2%, 4%, and 6% crude oil using cyclic simple shear tests and in medium strain range for earthquake-related design. Will the dynamic parameters of carbonate sand due to crude oil undergo tangible changes? If yes, to what extent? This study employs 60% relative density with the same conditions to compare the clean and polluted sands' dynamic behavior (shear modulus and damping ratio). Despite research on crude oil-contaminated sands, there is a need to pay more attention to the overlooked dynamic conditions of carbonate sands. This study aims to address this issue.

2. Test equipment

A cyclic simple shear machine (Figure 1) has been used for cyclic tests on cylindrical specimens with a D=70 mm and H=20 mm. The machine could employ vertical and horizontal loads. This device has a base, column, beam, and loading frame, and also three electronic components of servo valve, load cell, and LVDTs are installed on it to control the jack and reading data. The load cell can tolerate 500 kg, and the span of LVDT is 50 mm. The shaft conveys load to the specimen, which is applied to the sample by commands from the software to the hardware and from the hardware to the control valve.

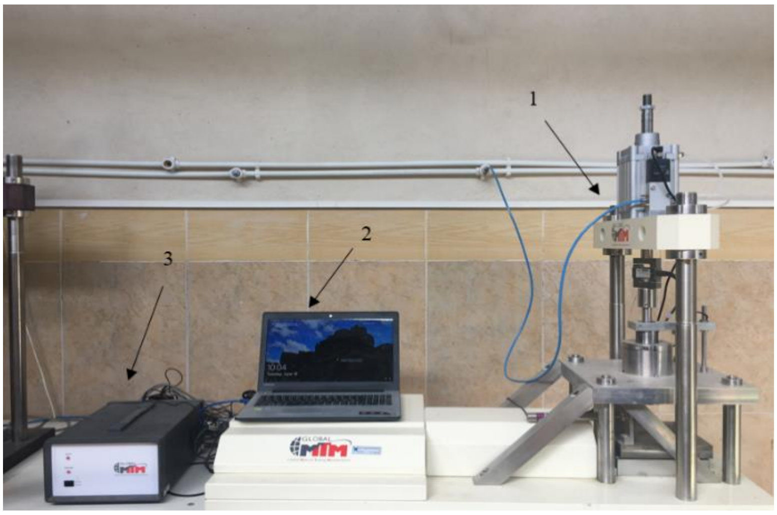

Fig. 1. Simple shear device: 1) Loading frame, 2) Laptop to control and enforce the commands, 3) hardware to convey the commands.

This investigation employs an NGI-cyclic simple shear machine, performing under stress control (i.e., constant vertical stress). This device provides lateral confinement for the samples utilizing metal rings coated with Teflon around a latex membrane.

2.1. Sample preparations

The crude oil pollution percentage for mixing with base soils was 2%, 4%, and 6% by weight of dry soil. According to previous research on oil contamination soils, 6% oil is the highest percentage of pollution for sandy soils [18,24]. Because in higher percentages, the soil lost its efficiency, and performing experiments is not possible. Also, in lower percentages, the pollution effect is not examinable.

A certain amount of dry soil is first weighed and spread on a flat surface to prepare samples contaminated with crude oil. Then, considering the equivalent of 2%, 4%, and 6% by weight of dry soil, weigh the crude oil, pour it on the soil surface, and mix the desired mass for 20 minutes to obtain a homogeneous and uniform composition. Afterward, the samples are placed in a laboratory for 48 hours to allow them to undergo chemical processes [8]. Then, the cyclic simple shear tests begin. All performed experiments were at a uniform relative density of 60% due to their proximity to natural surface conditions in polluted areas, expressed by other researchers who have used this relative density. These include investigations conducted by Al-Sanad et al. [31], Cook et al. [32], and Khosravi et al. [33]. The significant point is that this paper examines and evaluates the condition of contaminated surface layers. Therefore, this investigation considers the worst possible conditions for soil characteristics (including relative density) and pollution percentage (crude oil content). This paper employs the dry precipitation technique to prepare specimens. The reason for choosing this method is that it is an easy method to prepare dry sand samples in a certain void ratio [34]. After finishing this step and preparing the sample, it is positioned within a cyclic simple shear device and vertically loaded to achieve consolidation in K_0 conditions.

2.2. Experiments condition

Since the amount of damping ratio declines with growing vertical pressure employed to the sample because this parameter is strongly dependent on vertical stress [28], in the presented paper, a specific vertical pressure is used to achieve the damping situation under the same conditions for clean and contaminated samples. In this study, the diameters of the largest sand particles in the samples met the requirements of ASTM D6528. Sand samples in this study were all used in dry conditions. Numerous studies have examined the condition of dry sand in cyclic simple shear tests, including [18,35,53].

Behind specimen construction, put the mold in the machine and fix the base box. Subsequently, the examinations start. To achieve the first stage (i.e., the consolidation procedure under the K_0 state), specified vertical pressure was used on the sample under static requirements for one minute. There is no requirement to consume more periods of static pressure engagement because the sample is dry. The dynamic examination begins by setting the CSR, limited cycles, and frequency.

Based on the findings of previous studies, *D* and *G* rely on the shear strain amplitude, density, frequency, and vertical pressure. Therefore, in the presented paper, the behavior of oil-polluted sand under the same circumstances of test conditions is investigated to understand the effects of this pollutant on the resistance behavior of Bushehr carbonate sand. In this study, keeping all test conditions constant, this paper explores carbonate sand dynamic parameters' interaction with crude oil and compares these parameters in clean (non-contaminated) and polluted conditions.

In this study, the stress-control method has been used for studies. This method has been well-used by various researchers [35]. According to researchers [36], the dynamic features are significantly untouched by the frequency of 0.1 to 4 Hz. Based on the mentioned references and the research conducted by Madhusudhan et al. [37], the Freq.=1 Hz has been employed for cyclic simple shear tests.

2.3. Material characteristics

Table 1 presents the Bushehr carbonate sand's physical characteristics. Figures 2 and 3 show the sample under a microscope and grain size distribution, respectively. Figure 4 presents the maximum dry density of the studied sample. Table 2 displays the features of crude oil.

Table 1. Physical characteristics of Bushehr sand.

C_u	2.876
C_c	0.909
D_{50}	0.197
USCS	SP
G_s	2.696
e_{max}	0.595
e_{min}	0.359
Type	Fine

Fig. 2. sand grain under an optical microscope.

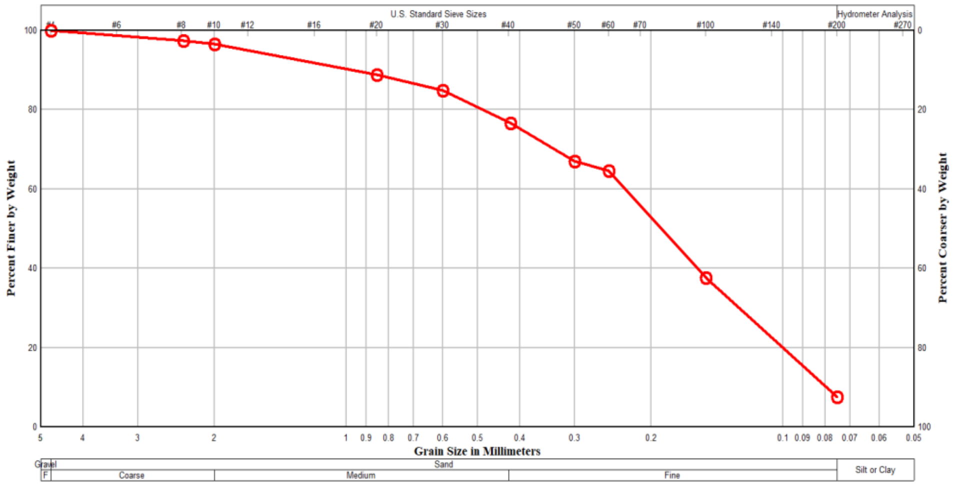

Fig. 3. Grain size distribution of sands.

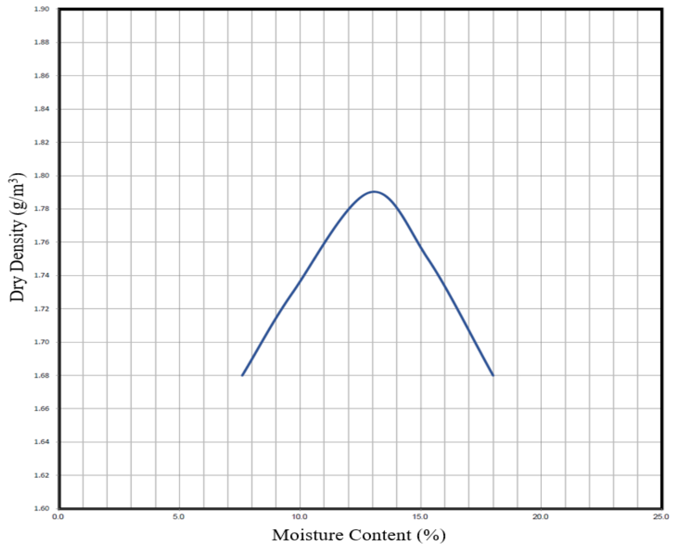

Fig. 4. Compaction test result of Bushehr sand.

Table 2. Characteristics of crude oil.

Density (N/m^3)	API gravity (-)	Viscosity ($10^{-6} \times m^2/s$)
8000	33.6	98.80

3. Experimental results

3.1. Dynamic tests

This paper conducts 12 cyclic tests. In the first stage, clean sand, and in the next step, carbonate sand contaminated with 2%, 4%, and 6% crude oil were subjected to cyclic tests under constant conditions to investigate and evaluate their dynamic behavior. Repeating each test twice ensures the outcomes. Generally, with decreasing the *G*, the *D* increases, and the shear modulus increases with increasing the number of applied cycles. The same was true in this study for clean sands.

In simple shear dynamic experiments, *G* and *D* depend on the cycle numbers during the simple shear experiment. As the cycle number boosts, the hysteresis loop's slope grows, and the area of the loop decreases. With an increase in cycles from 2 to 100, *G* increased from 5792 to 9001 kPa, and *D* from 15.08 reached 10.11%. Most examinations have shown that raising the cycles from 10 to 100 has a limited effect on *G*, and this research also proved the same. Since the behavior of the 50 and 100 cycles are closer to each other, this paper uses cycle 50 as the primary study criterion for determining *G*and *D*. Figure 5 shows the diagrams of the hysteresis loops of Bushehr carbonate sands in their fiftieth cycle in both clean and contaminated with 6% crude oil samples.

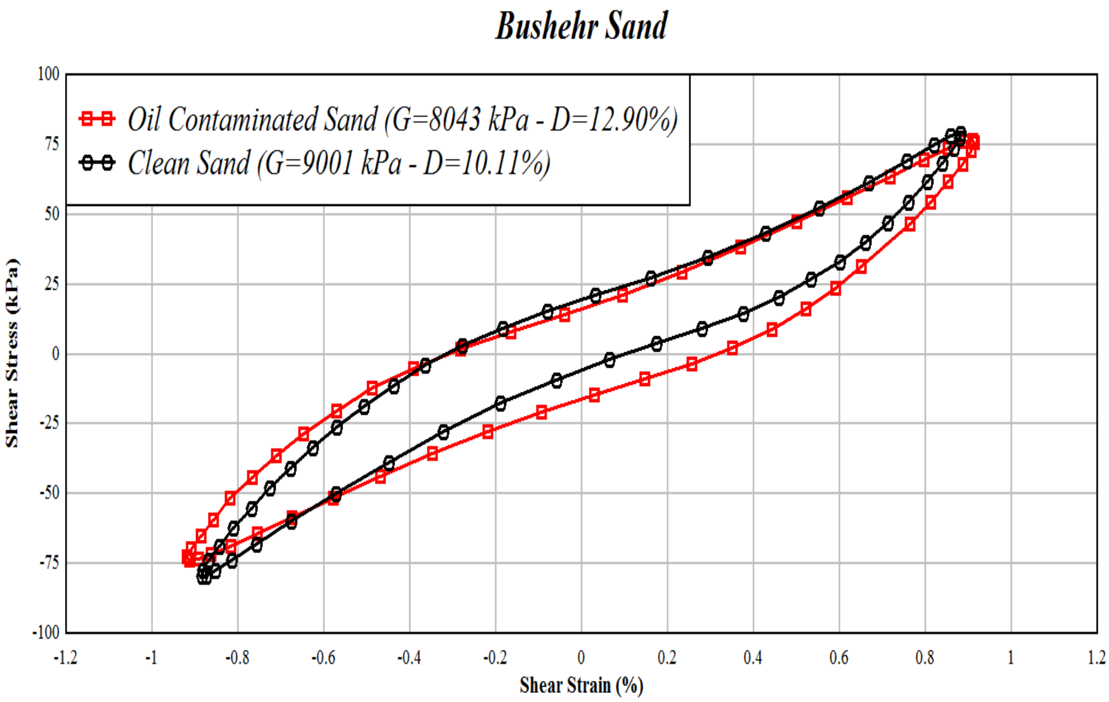

Fig. 5. Results of cyclic test for Bushehr carbonate sand in both clean and contaminated conditions.

Table 3 shows the dimensionless parameters of the *G* and the *D* for carbonate sand in crude oil-contaminated situations. To obtain these parameters, $GI=\frac{\Delta G}{G(Clean)}\times 100$ and $DI=\frac{\Delta D}{D(Clean)}\times 100$ used [18,35]. In these mentioned relations, $\Delta G = \mathrm{G(Contaminated)} - \mathrm{G(Clean)}$, $\Delta D = \mathrm{D(Contaminated)} - \mathrm{D(Clean)}$. G and D(Contaminated) are the shear modulus and damping ratio of contaminated sand. G(Clean), and D(Clean) are the clean sand's shear modulus and damping ratio, respectively.

The aim was to better comprehension of the effects of crude oil pollution on sand behavior. With the help of this method, it is possible to determine the increase or decrease in the value of *G* and *D* of crude oil-contaminated sands compared to clean sands. As shown in Table 2, crude oil contamination positively impacts the Bushehr carbonate sample in the case of 2% and 4% crude oil contamination. However, using 6% crude oil in the sand exhibits adverse effects on this sand, leading to a decline in the shear modulus and a growth in the damping ratio. This bizarre reaction to oil contamination in Bushehr sand relates to the carbonate nature of this sand, which contradicts silica sands. Previous studies [9] revealed that silica sand decreases steadily due to crude oil contamination.

Table 3. The amount of decrease or increase in *G* and *D* due to crude oil contamination.

Oil Percent (%)	$GI=\frac{\Delta G}{G(Clean)}\times 100$	$DI=\frac{\Delta D}{D(Clean)}\times 100$
6	-10.64	+27.60
4	+8.25	-9.85
2	+4.86	-4.91

3.2. Static tests

This paper performs static tests (i.e., direct shear experiment) to confirm the dynamic outcomes of 2% and 4% oil contamination, besides better and further comprehending crude oil's influence on carbonate sands. Direct shear test results were performed on clean and 2% and 4% oil-contaminated specimens, revealing that clean sand had an internal friction angle of 24°. Due to 2% oil contamination, the friction angle increased to 27° (i.e., the shear strength improved). Also, employing 4% oil in the sample leads to further enhancement of 29°. These enhancements reveal the outstanding findings of this paper and the interaction of oil with carbonate sand grains. As indicated, using 2% and 4% oil leads to static strength of Bushehr carbonate sand improvement by increasing the friction angle of samples. These outcomes verified the results of dynamic experiments described in the previous section. Therefore, carbonate sand shows different reactions to crude oil due to the distinct nature of carbonate sand from a chemical point of view.

Table 4 shows the friction dimensionless parameter for each type of sand in clean and contaminated situations. To obtain these parameters, $\varphi I = \frac{\Delta\varphi}{\varphi(Clean)} \times 100$. In this relation, $\Delta\varphi = \varphi(\text{Contaminated}) - \varphi(\text{Clean})$. $\varphi(\text{Contaminated})$ is the crude oil-polluted sand's friction angle. $\varphi(\text{Clean})$ is the clean sand friction angle. According to Table 4, 4% crude oil in the carbonate sand leads to an outstanding enhancement of friction angle (more than 20% increase in static strength).

Table 4. The amount of decrease or increase in *G* and *D* due to crude oil contamination.

Oil Percent (%)	$\varphi I = \frac{\Delta\varphi}{\varphi(Clean)} \times 100$
2	+12.5
4	+20.8

4. Chemical analysis

This section describes chemical assessments through Scanning Electron Microscope (SEM) images. SEM is a kind of electron microscope capable of delivering high-resolution images employing a concentrating beam of electrons, rather than light, to form an image. SEM is the most typical approach utilized to acquire the specimen's morphology. The SEM merely needs milligram portions of material to gain shape, size, and texture determination. The SEM examines a fine shaft of electrons across the designed specimen in parallel media. The electron interacts with the specimen and yields diverse signs, which can be noticed and depicted on the screen of a cathode ray tube. This device is used for particles even less than 1 nm. SEM demands more preparation time for specimens than optical microscopes and cannot differentiate between noncrystalline and crystalline. However, studying soil particles using SEM is a comprehension approach in the geoengineering field. Figure 6 displays SEM images of clean and oil-contaminated samples. These images verify the obtained physical experiments.

As can be seen from Figure 6, clean sand has a rough surface, while the surface of the 2% oil-contaminated specimen did not change considerably. It is a reason that 2% pollution with oil enhances the shear strength of Bushehr carbonate sand. However, according to Figure 6-C, it is evident that using 4% oil in Bushehr sand leads to a rougher surface, even more than the clean state.

In the case of 6% oil, the sand particles' surface evolves slippery, leading to friction decline between grains.

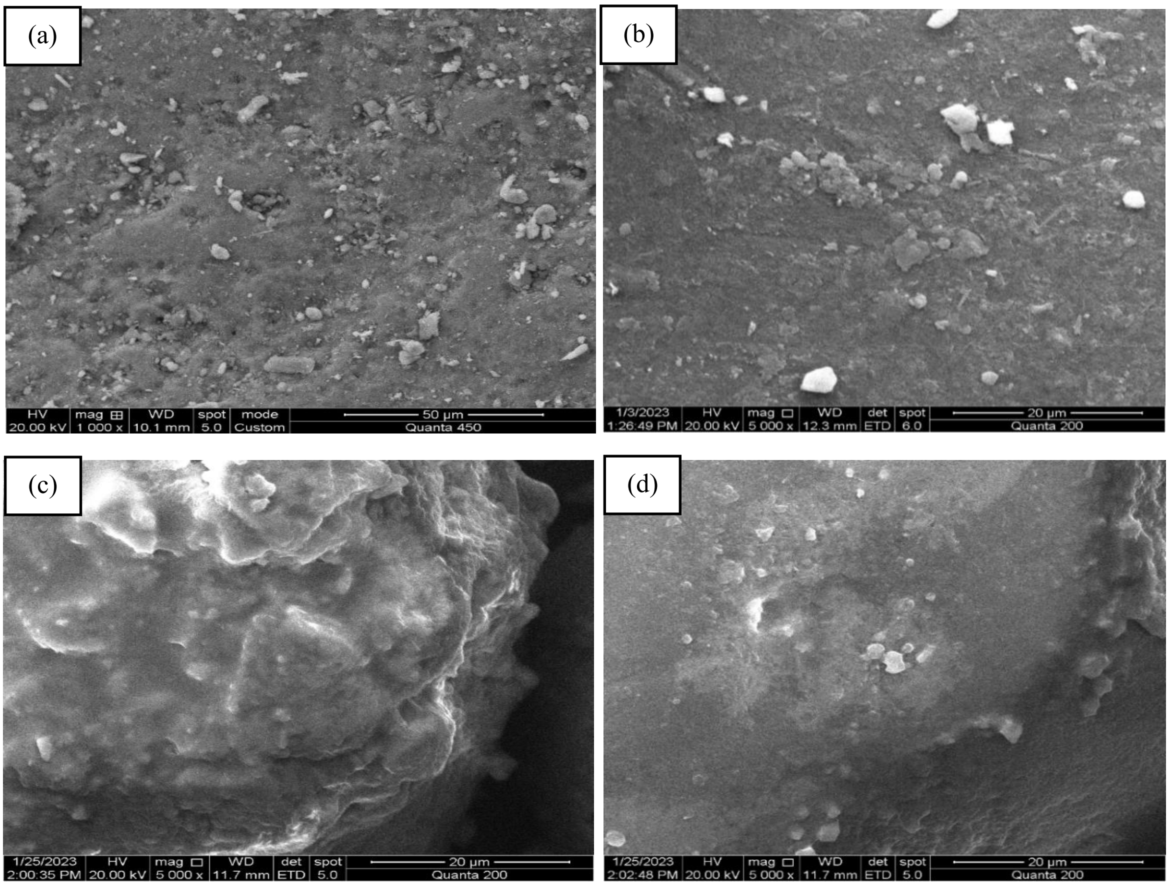

Fig. 6. SEM images of samples, (a) clean, (b) 2%, (c) 4%, and (d) 6% oil content.

Bushehr sand polluted with 6% oil has more slippery surfaces than samples polluted with 4% crude oil. Accordingly, the shear strength of the specimen contaminated with 4% crude oil is higher than the sample with 6% oil since its surface has a more friction angle. As a result of this issue, the friction between the particles will increase, increasing the shear strength of 2% and 4% oil. It is significant to note that by mixing Bushehr carbonate sand with different percentages of crude oil, the sand's configuration and grain size do not alter.

5. Discussion

This paper investigates dynamic parameters of uncontaminated and polluted Bushehr carbonate sand with 2%, 4%, and 6% crude oil. The results of cyclic simple shear experiments and direct shear tests on fine Bushehr carbonate sand contained significant information. Interestingly, the static test result verified the cyclic behavior of this studied sand. A specific pattern for both G and D proved for Bushehr carbonate sand. It indicates the need to pay more attention to the carbonate sands in such contamination circumstances. It means that sands, depending on their chemical compounds and particle size, exhibit a specific behavior in crude oil contamination. The results obtained from the experiments show an increase in friction angle and shear modulus with contamination of 2% and 4% oil content. The 6% oil is the milestone point since carbonate sand revealed a decrease in static and dynamic strength.

According to Figure 5, it is clear that 6% contaminated Bushehr carbonate sand, due to crude oil contamination, experiences more than a 10% decrease in shear modulus besides shifts in the slope of hysteresis loops and an increase in their area, leading to an increase in damping ratio. It will cause a significant shear modulus value reduction in crude oil-contaminated samples higher than 6% oil. The noteworthy point from Tables 3 and 4 is that the presence of 2% and 4% crude oil, Bushehr carbonate sand, experienced an improvement in shear modulus and friction angle. It means that the addition of crude oil of less than 6% crude oil leads to enhancement in static and dynamic strength. The SEM images verify the physical experimentation. These findings contradict the obtained results about silica sands. The main reason for this contradiction is the carbonate sand chemical compound, which is diverse from silica sands. The main composition of carbonate sand is $CaCO_3$ (Calcium carbonate, constituted by three major components: carbon, oxygen, and calcium. It is a typical material encountered notably as limestone. Silica sand is composed of quartz, which is SiO_2 (known as silicon dioxide) and is composed of silicon and oxygen. This difference in this regard caused the contradictory behavior of sands in the crude oil existence.

This study underscores the crude oil role in the strength parameter of carbonate sands. Contradicted to silica nature sands, Bushehr carbonate sand reveals a strength increase in both static and dynamic behavior. For instance, Nasiri and Amiri [12], Nasiri et al. [18,24], and Long et al. [13] indicated that silica sands, due to pollution with crude oil, experience a static and dynamic strength loss. However, this paper's outcome agrees with the finding of Mazaheri et al. [11] since the nature of both studied sands is the same.

6. Conclusion

In this study, the condition of G, D, φ of fine Bushehr carbonate sand in case of contamination with crude oil with different contamination levels (i.e., 2%, 4%, and 6%) and their comparison with clean state in the same experimental situation has been investigated. Static and dynamic tests on dry samples with 60% relative density have the following results:

1- Crude oil contamination reduces the slope of the hysteresis loop and grows the area.

2- Contamination in carbonate sand with crude oil (beyond critical level) will reduce the static (i.e., friction angle) and dynamic (i.e., shear modulus) strength of Bushehr carbonate sand.

3- The critical amount of contamination with crude oil in Bushehr carbonate sand is 6%. So, adding this amount of crude oil to carbonate sand will lead to a 10.6% and 16.6 decrease in shear modulus and friction angle, respectively.

4- Using 2% crude in Bushehr carbonate sand leads to approximately 5% and 13% increase in shear modulus and friction angle, respectively.

5- Applying 4% oil in the specimens caused roughly 8% and 21% enhancement in dynamic and static strength of Bushehr carbonate sand, respectively.

6- The main reason for the diverse behavior of silica and carbonate sands is their chemical composition, leading to bizarre features of carbonate sand in case of contamination less than the critical contamination level (i.e., 6%).

7- Both static and dynamic experimentations are consistent with each other, verifying the obtained results.

8- When mixing the sand with different percentages of crude oil, the sand grain size does not change.

9- According to the SEM images, it is significant to note that when mixing Bushehr carbonate sand with different percentages of crude oil, the sand's configuration and grain size do not alter.

10- SEM images revealed that Bushehr carbonate sand polluted with 6% oil has more slippery surfaces than samples polluted with 2% and 4% crude oil, which enhanced the shear strength of contaminated specimens less than 6%.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Masoud Fallah: Data curation; Writing an original draft.

Ahmad Reza Mazaheri: Supervision.

Hamid Lajevardi: Visualization.

Masoud Nasiri: Resources; Validation; Methodology.

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