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Influence of Nano-Silica Stabilization on the Shear Strength Behavior of Crude Oil–Contaminated Silty Sand

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Abstract: The degradation of mechanical performance in soils contaminated with crude oil has increasingly necessitated the development of effective stabilization strategies, particularly for supporting infrastructure constructed on compromised geomaterials. In this study, the influence of nano-silica on the shear strength parameters of crude oil–contaminated silty sand was systematically examined through monotonic triaxial testing. Silty sand specimens were prepared by incorporating 0%, 15%, 30%, and 40% silt into clean sand, after which each mixture was uniformly contaminated with crude oil at 8% of the dry soil weight. All contaminated specimens were stabilized using a 15% colloidal silica solution, applied at 15% of the dry soil mass, and subsequently cured for seven days to enable the formation of silica-based bonding networks within the soil matrix. The untreated oil-contaminated mixtures exhibited a marked reduction in shear strength with increasing silt content. In contrast, significant increases in shear strength were observed following stabilization with colloidal silica. The extent of improvement was found to depend strongly on the silt fraction. These findings provide new insight into nanoscale stabilization mechanisms in oil-contaminated geomaterials and highlight the potential of colloidal silica as a sustainable and effective agent for improving shear resistance in soils adversely affected by petroleum pollutants.

Keywords: Crude oil–contaminated soils; Silty sand; Soil stabilization; Colloidal silica; Nano-silica; Shear strength

1 Introduction

Oil contamination is an unavoidable consequence of rapid population growth based on oil technology and an increase in the large-scale use of oil resources. A considerable number of studies have focused on the response of soils affected by different types of hydrocarbon pollution, including artificial sand. Rodriguez Ochoa [1] found that with increasing contamination levels, the resistance parameters (adhesion and internal friction angle) of silty sand increased. Khamehchiyan et al. [2] conducted a laboratory experiment to investigate the effect of crude oil contamination on the geotechnical properties of clay and sandy soils. It was found that with increasing crude oil content, the strength, maximum dry density (MDD), permeability, optimum moisture content (OMC), and Atterberg limits decreased. Kermani and Ebadi [3] indicated that along with the increased oil content, the internal friction angle, MDD, compression index, and Atterberg limits increased, and the water content decreased. Naeini and Shojaedin [4] studied the influence of oil contamination on the liquefaction potential of sandy soils. The results illustrated that oil contamination up to 8% led to an increase in the soil liquefaction resistance, and by increasing the contamination content greater than 8%, the liquefaction resistance decreased. Kererat [5] investigated the effect of 95 octane gasoline and water saturation on the strength properties of silty sand soil. Test results showed that the ultimate bearing capacity of soil contaminated with 2 wt% and 4 wt% gasoline was reduced by an average of 30% and 52%, respectively, compared to clean soil.

Improving the resistance parameters of oil–contaminated soils makes it economically feasible to reuse these soils. In the past, traditional materials such as cement and lime were used to stabilize soils. Tuncan et al. [6] studied the improvement of oil–contaminated soils using cement, fly ash and lime as road base materials. The results show that a subgrade material can be used in road projects as chemically and mechanically modified materials. After examining the treatment of glycerol–contaminated clay soils with cement, Estabragh et al. [7] found that the presence of glycerol interrupted the interplay between soil and cement. However, adding cement to clean and contaminated samples increased the soil strength, depending on the percentage of cement, working time, and the degree of contamination. An experimental assessment carried out by Akinwumi et al. [8] investigated the effectiveness of Portland cement in modifying the plasticity, strength, and permeability of crude oil–polluted soil for potential use in earthwork applications. The study reported that oil contamination significantly degraded the soil's engineering properties; however, stabilization with cement enhanced its performance due to chemical bonding, agglomeration, and cation exchange processes. Oluwatuyi et al. [9] studied the effect of adhesive cementitious materials on the geo-environmental parameters of kaolin clay contaminated with crude oil. The results indicate that the maximum unconfined compressive strength (UCS) values were achieved for kaolin clay stabilized with 15% cement–lime at different curing times (0, 7, 14, and 28 days). By changing the amount of cement–lime mixture from 5% to 15%, the strength values of the samples increased from 785 kPa to 1160 kPa. Ahmad et al. [10] investigated the use of a stabilizing and solidification (S/S) technique to improve sand soils contaminated by diesel and crude oil using three cement stabilizers, including ordinary Portland cement (OCP), cement kiln dust (CKD), and limestone powder (LSP). Based on the results, changing the particle size distribution and reducing the specific gravity of the soil caused the formation of large lumps due to the effect of hydrocarbons on the repulsive forces between soil particles.

Due to the environmental threats posed by these materials, the use of environmentally friendly nanomaterials has attracted the attention of researchers in recent years. Persoff et al. [11] and Gallagher and Mitchell [12] reported that the UCS of Monterey sands grouted with colloidal silica increased linearly with an increasing percentage of colloidal silica, while the permeability coefficient decreased. Experiment results of Gallagher and Lin [13] represent increased adhesion and cohesion between soil particles and reduced viscosity due to the use of silica–cellulose. Delavar and Noorzad [14] examined the behavior of silty sand treated with varying dosages of colloidal silica. The study revealed that the addition of colloidal silica led to an increase in drained cohesion for all soil samples, while a reduction in the drained internal friction angle was observed for the silty sand. Seddighi and Roshan Zamir [15] investigated the effects of crude oil contamination on the soil resistance parameters of the Isfahan Oil Refinery site using direct shear tests. In this study, the effect of nanoclay stabilizer in the remediation of contaminated soil was evaluated with respect to the amount of nanoclay and setting time. The results showed a significant increase in the strength of samples stabilized with 2.25% nanoclay additive (as the optimal amount).

Nezhad et al. [16] presented the effect of using nano-silica and hydrated lime in improving the properties of contaminated clay. During the preparation of the contaminated samples, oil contaminants were mixed with 0%, 3%, 6%, and 9% clay by weight. The results indicated a decrease in the MDD and OMC in contaminated samples. In samples containing 3% of the pollutant, the UCS increased and then decreased with increasing pollutant content. Pirmohammadi [17] investigated the influence of nano-silica on the compressive strength of coarse-grained soil. The study concluded that nano-silica filled the pore spaces between sand particles, leading to the formation of a denser soil matrix and, consequently, an improvement in the compressive strength of the stabilized soil. Kulanthaivel et al. [18] experimentally evaluated the behavior of pond clay in both untreated and P-silica–treated conditions using a comprehensive testing program, including pH, electrical conductivity, UCS, California bearing ratio (CBR), free swell index (FSI), compaction, and Atterberg limit tests. The addition of 6% P-silica produced the highest strength value of 275.12 kPa. At this optimal content, both the FSI and the MDD decreased, suggesting the occurrence of a flocculation process induced by P-silica.

Considering the potential use of contaminated materials in road construction and the findings reported in previous studies, it is evident that, despite the importance of contaminated soils, research on their stabilization remains limited. Colloidal silica, however, has emerged as a promising nanomaterial with a wide range of potential applications in civil engineering. Beyond its applications in ground improvement and liquefaction control, colloidal silica has also been explored for regulating fluid flow and limiting water production in the petroleum industry, decreasing permeability and immobilizing contaminants in environmental engineering, as well as preventing water infiltration in underground and tunneling projects. With the development of nanotechnology, it is widely used in civil engineering due to its obvious advantages such as cost-effectiveness, low disturbance and environmental sustainability. Despite the recognized importance of colloidal silica in soil remediation, especially for contaminated soils, few studies have been conducted on silty sand soils contaminated by crude oil with different silt contents. Therefore, this study examined the effect of nano-silica as a stabilizer in improving the shear strength parameters of contaminated silty sand using triaxial tests. To achieve this purpose, this study first investigated the effect of 8% crude oil on the mechanical behavior and strength of soil containing different percentages of silt content and the results were compared with natural soil. Then this study investigated the effect of colloidal silica addition and curing period on the strength parameters of oil–contaminated silty sand.

2 Materials and Test Methods

2.1 Materials Used

The main materials in this study include soil, crude oil, and colloidal silica, which are described below.

2.1.1 Soil

In this study, Firoozkooh Sand No. 161, with a specified mean grain size, was used in combination with different silt contents. Based on the Unified Soil Classification System, this soil is classified as poorly graded sand (SP). The silt required for the experiments was prepared from the portion of the sand passing the No. 200 sieve. Figure 1 shows the grain size distribution curves for sand–silt mixtures according to ASTM D422-63 [19], and Table 1 presents the physical properties of sand used for this study according to ASTM D854-10 [20] (for specific gravity GS) and ASTM D4253-16 [21] and ASTM D4254-16 [22] (for maximum and minimum dry densities, respectively).

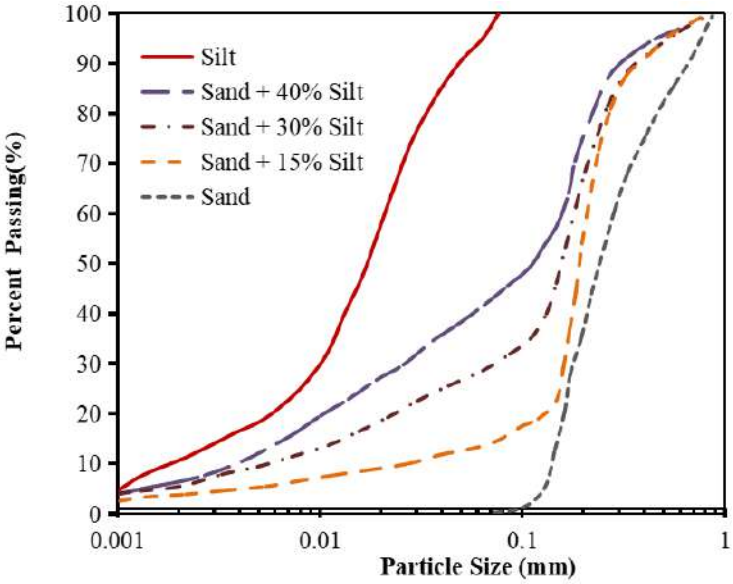

Figure 1. Particle size distribution curves of sand–silt mixtures

Table 1. Physical properties of sand

Properties	Value
Classification (unified method)	SP
Specific gravity G_S	2.65
Coefficient of curvature C_C	0.93
Coefficient of uniformity C_U	1.87
Minimum void ratio emin	0.61
Maximum void ratio emax	0.86
Optimum water content $\omega_{\text{apt}\,(\%)}$	9.96
Maximum dry unit weigh $\gamma_{d\,\max}$ (g / cm^3)	1.63

2.1.2 Crude oil

Khuzestan light crude oil, obtained from the Tehran Refinery, was used as the pollutant in this study, and its properties are shown in Table 2.

2.1.3 Colloidal silica

Colloidal silica consists of a water-based suspension of fine silica particles formed from saturated silicic acid solutions. At low concentrations, its density and flow behavior are comparable to those of water. Table 3 presents the characteristics of colloidal silica used in this study.

2.2 Sample Preparation and Testing Procedure

To evaluate the shear strength parameters of unstabilized and colloidal silica-stabilized crude oil–contaminated soil, uniform triaxial tests were performed on clean, crude oil–contaminated, and colloidal silica-stabilized soils under confining pressures of 50 kPa, 100 kPa, and 150 kPa. In addition, the effect of crude oil contamination on soil compaction properties was investigated through compaction tests.

Table 2. Properties of crude oil

Properties	Value
Specific gravity at 15.6	0.8592
American Petroleum Institute (API) gravity at 15.6	32.67
Dynamic viscosity (cP)	41.3
Kinematic viscosity at 37.8° (cSt)	7
Reid Vapor Pressure (R.V.P.) (kPa)	51
Salt content (lb/1000 bbl)	6
Sulphur content (%)	0.12
Pour point	-17
Flash point	43.3
Total acid content (mg KOH/g)	0.29
Moisture content	0.06

Table 3. Properties of colloidal silica

Properties	Value
SiO_2 content (%)	30 ± 5
pH value	9.5–10
Titrable alkali (w/w, %)	0.32-0.38
Silica-to-soda ratio (w/w, %)	77–88
Mean particle diameter (nm)	9.30–10.50
Surface area (m^2/g)	250–280
Viscosity at 27°C	12.55–13.00
Specific gravity at 25°C	1.200–1.218

2.2.1 Sample preparation

All samples were prepared using the Moist Tamping (MT) method at a relative density (Rd) of 95%, following the procedure described by Terzaghi [23]. For this purpose, a standard Proctor density test was performed on clean and contaminated samples according to ASTM D698-07 [24] to determine the moisture–dry density relationship.

A series of sand–silt mixtures containing 0%, 15%, 30%, and 40% silt contents were mixed with 8% crude oil by dry weight of soil. This amount of crude oil was selected based on previous studies conducted by Khamehchiyan et al. [2], Rahman et al. [25], Zomorodian et al. [26], Kermani and Ebadi [3], and Naeini and Shojaedin [4]. According to Figure 2, the oil–contaminated samples were put into closed plastic bags for at least one week to allow possible reactions between soil and crude oil.

Figure 2. Oil–contaminated samples

To understand the effect of stabilization on the shear strength parameters of crude oil–contaminated samples, a colloidal silica solution with a 30% concentration was mixed with the required water content to obtain Rd = 95%, resulting in final concentrations of 10%, 15%, and 20% by weight. To achieve the desired pH (6–6.5) and to obtain the optimum gelation time and solution strength, hydrochloric acid and sodium chloride (NaCl) were added based on the study conducted by Noll et al. [27]. The prepared solution was sprayed onto the mixture and blended by hand to form homogeneous samples. After molding the specimens for triaxial testing, each specimen was removed from the mold and placed in a plastic bag for curing periods of 7, 14, and 28 days.

2.2.2 Testing procedure

Consolidated undrained monotonic triaxial tests were performed using a strain-controlled method on specimens with a diameter of 50 mm and a height of 100 mm in accordance with ASTM D4767-11 [28]. To evaluate the shear strength parameters, all saturated specimens achieved a minimum B-value of 0.95 and were isotropically consolidated under three effective confining pressures (σ_3) of 50 kPa, 100 kPa, and 150 kPa. In this research, the strain rate was set to 0.5 mm/min and the loading operation continued until the axial strain reached 20% for all specimens. Scanning Electron Microscopy (SEM) was employed to examine the microstructure of the samples under different conditions.

3 Results and Discussion

3.1 Effect of Crude Oil on Compaction Parameters

The compaction test results on clean and contaminated sand and sand–silt mixture according to the ASTM D698-07 [25] standard are presented in Table 4 in terms of MDD and OMC values. By increasing the silt content of the samples, MDD and OMC increased. It should also be mentioned that, for all evaluated samples, 8% oil reduced OMC and increased MDD. However, according to Figure 3 and Figure 4, these variations are more obvious for sand samples. It is probably due to the absorption of crude oil by finer particles, which consequently reduced the lubricating property of crude oil in sand–silt mixtures. Contamination with crude oil caused the particles to slip better and easier on each other and increased the density of soils. In addition, covering the soil particles with crude oil led to a decrease in the amount of moisture absorbed by particles during compaction due to the hydrophobicity of the oil. The obtained results are in line with those reported by Rahman et al. [25] and Zomorodian et al. [26].

Table 4. Values of MDD and OMC for clean and contaminated samples

Sample No.	Silt Content (%)	Crude Oil Content (%)	w_{opt} (%)	$\gamma_{d\ max}\left(\frac{gr}{cm^3}\right)$
1	0	0	9.96	1.63
2	0	8	6.87	1.72
3	15	0	10.11	1.81
4	15	8	6.84	1.83
5	30	0	10.17	1.88
6	30	8	6.68	1.92
7	40	0	10.58	1.94
8	40	8	6.58	1.95

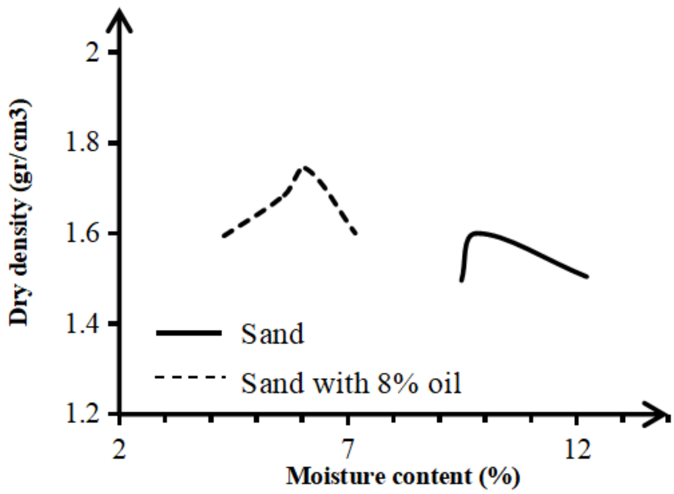

Figure 3. Standard compaction curves for sand

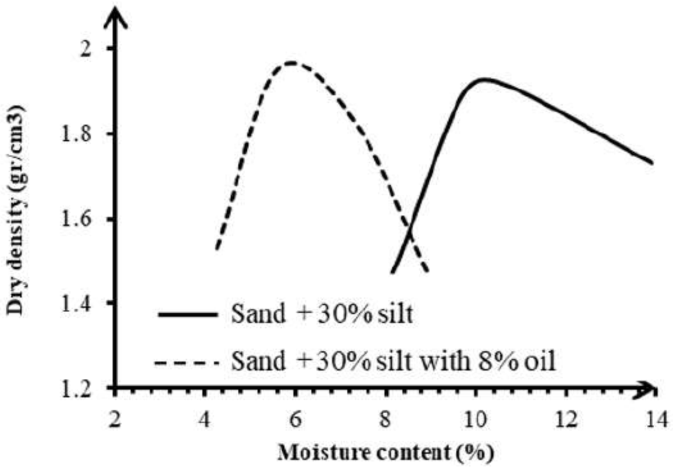

Figure 4. Standard compaction curves for silty sand

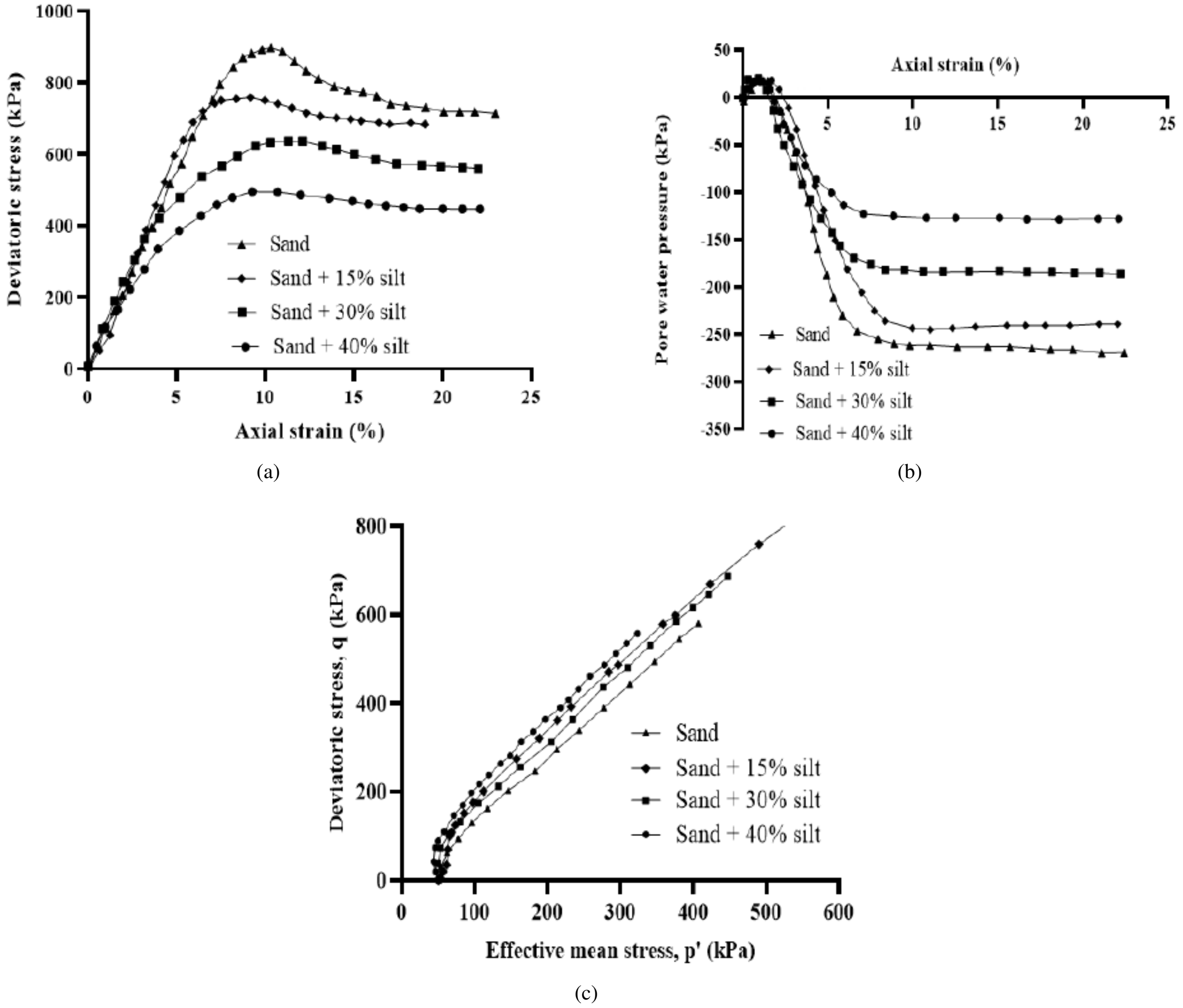

Figure 5. (a) Stress–strain curves, (b) pore water pressure responses, and (c) q–p' stress paths for clean sand and sand–silt mixtures at a confining pressure of 50 kPa

3.2 Effect of Crude Oil on Shear Strength Parameters

As described, consolidated undrained triaxial tests were conducted to evaluate the effects of oil contamination on the strength parameters of soils. The stress–strain, pore water pressure behavior, and q-p' stress paths of clean soils and soils contaminated with 8% crude oil obtained under a confining pressure of 50 kPa are presented in Figure 5.

At a confining pressure of 50 kPa, the saturated clean sand exhibits strain-hardening behavior; in other words, the sand shows a dilatational response under compressive loading (Figure 5a). At the initial strains, positive pore water pressure increases, and then at higher strains, negative pore water pressure increases due to dilation and the rearrangement of sand grains (Figure 5b). As shown in Figure 5a and Figure 6a, adding silt reduces shear strength, similar to the trend of shear strength in contaminated samples. The reason for the strength reduction in sand mixtures with different percentages of silt (15%, 30%, and 40%) can be explained by the way silt particles are placed between sand grains, which act like small rollers and cause sand grains to slide over each other, reducing the angle of friction and, consequently, shear strength.

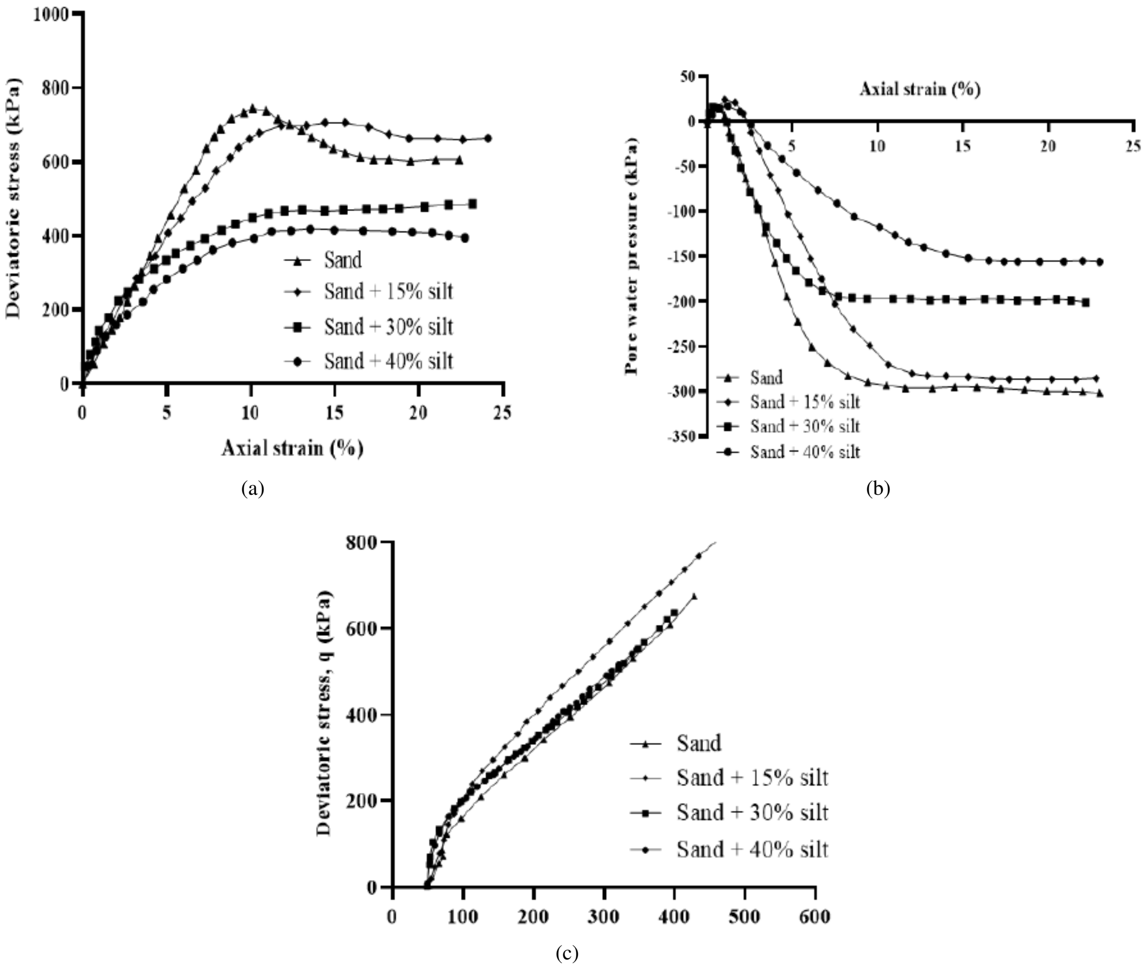

Figure 6. (a) Stress–strain curves, (b) pore water pressure responses, and (c) q–p' stress paths for sand–silt mixtures contaminated with 8% crude oil at a confining pressure of 50 kPa

Figure 6 shows the variations in deviatoric stress, pore water pressure, and q–p' stress paths for different sand–silt mixtures contaminated with 8% crude oil under a confining pressure of 50 kPa. As can be seen in Figure 6a, in general, contamination of clean sand soil with crude oil reduces the undrained shear strength and changes its shear behavior. The obtained result is consistent with the findings of studies by Khamehchiyan et al. [2], Abusnina et al. [29], Mehdizadeh et al. [30] and Sadighi and Roshan Zamir [15] on clean sand in the wet state using direct shear tests. The reason for the change in soil shear behavior can be attributed to the reduction in soil strength, which is caused by the reduction in friction between sand grains due to the lubricating property of crude oil, as well as changes in excess pore water pressure. As can be seen in Figure 6, the changes in pore water pressure in the clean sand under study are dilatational and the soil sample has a negative pore water excess pressure at the moment of reaching a steady state, which somehow causes suction inside the soil. While in the sample contaminated with 8% crude oil, the pore water pressure, due to the dominant behavior of crude oil in creating excess pore pressure instead of water and the high surface tension between soil grains and crude oil, decreases the positive pore water excess pressure at initial strains compared to clean sand, and at higher strains, the negative pore water pressure increases, causing a decrease in soil intergranular contacts and subsequently a decrease in effective stress and shear strength of the soil. Moreover, adding oil causes a reduction in shear strength and increases ductility of the sand–silt mixtures.

The oil in both sandy and silty sand soil samples has a smaller effect on the trend of water pressure change in the samples, and Figure 5b and Figure 6b show the expansion behavior of the contaminated soil.

Figure 7 presents how deviatoric stress changes as silt content increases under confining stresses of 50 kPa, 100 kPa, and 150 kPa for both clean and contaminated samples. Obviously, at all confining pressures, an increase of silt content decreases the specimens' peak shear strength, while contamination in samples with a higher percentage of silt leads to a further reduction in the peak shear strength. For example, the peak shear strength of silty sand with 15% silt decreases up to 10% by adding crude oil under a confining pressure of 50 kPa. In contrast, a sample with 30% silt content under a confining pressure of 50 kPa shows a 25% reduction.

By comparing the clean and contaminated samples in Figure 8, it can be seen that contamination of sandy soil with 8% crude oil reduces the internal friction angle and increases adhesion. The internal friction angle of the soil decreases due to the lubricating properties of oil between soil grains. The adhesion of the soil increases due to the high viscosity of crude oil, the presence of polymeric derivatives, and the subsequent increase in surface tension between soil grains and oil. In fact, coating soil particles with crude oil with a viscosity higher than water caused an increase of slipping between particles. Similar results were obtained by Khamehchiyan et al. [2]. Figure 8 illustrates the variations in internal friction angle (Φ) and cohesion (c) for different percentages of clean and contaminated silty sand. As shown in Figure 8, the reduction of the internal friction angle in samples with a higher percentage of silt is greater compared to sand samples. The maximum reduction of the internal friction angle occurred in samples containing 30% silt with a decrease of 9%. In contrast, the minimum reduction of the internal friction angle occurred in the sand, with a decrease of around 1%. In addition, the adhesion of sand and silty sand contaminated with crude oil increases by about 1 kPa to 2 kPa.

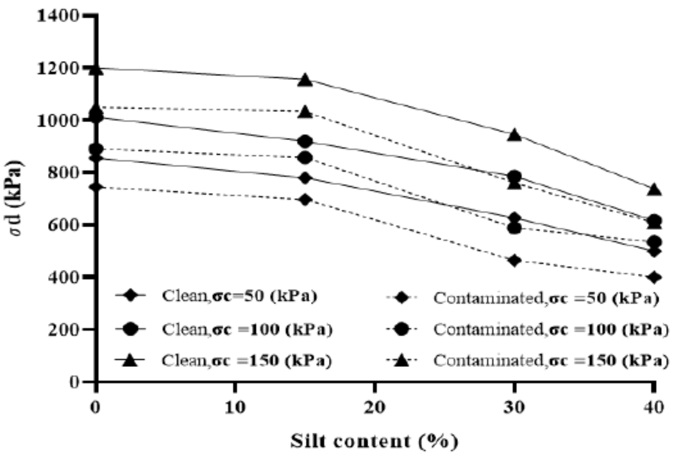

Figure 7. Variations in peak stress for clean and contaminated sand–silt mixtures at different confining pressures

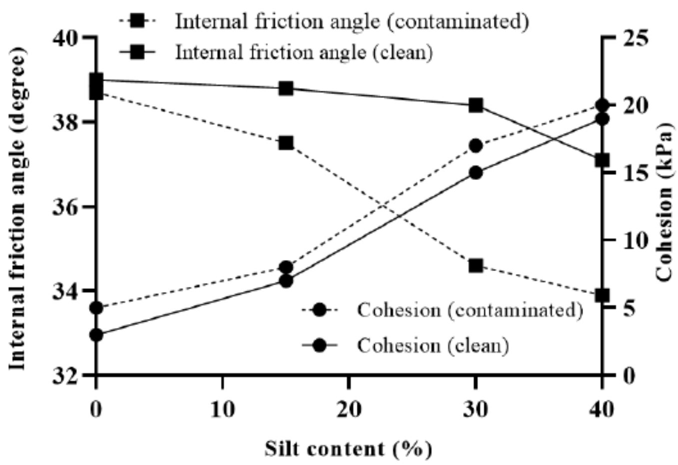

Figure 8. Variations in internal friction angle and cohesion of clean and contaminated silty sands

3.3 Optimum Curing Time and Solution Concentration for Colloidal Silica

To investigate the effect of curing period and solution concentration on shear strength of stabilized soils, the colloidal silica solution was prepared at a concentration of 10%, 15%, and 20% by weight and mixed with crude oil–contaminated sand soil. Then a triaxial test under a 100 kPa confining pressure was applied to the mixture after curing times of 7, 14, and 28 days. Figure 9 shows the maximum deviation stress achieved during triaxial loading for described mixtures. The figure reveals that an increase of curing time causes negligible variation in shear strength. In other words, the rate of increase in resistance after the first seven days is negligible. This result aligns with the observations of Persoff et al. [11]; that is, as a sample was cured for a period of time, which was at least four times the initial gel time, a significant part of the acquisition of resistance occurred.

The evaluation of this figure also concludes that the peak strength of stabilized soil increases with an increase in the concentration of colloidal silica up to 15% by weight. However, no significant additional improvement is observed when the concentration is increased from 15% to 20% by weight. A noteworthy point in this context is the reduction of the gel time and the time it takes for the stabilization process in construction projects by increasing the density of the solution. According to the observations made during this study, gel time (the time interval between initial mixing of grout components) is 5 hours for a 10% solution, which decreases to 2 hours for a 20% solution. Considering the above description and economic aspect, the 15% colloidal silica solution was used to continue the experiments. The aforementioned trend for maximum shear stress was seen for silty sand samples.

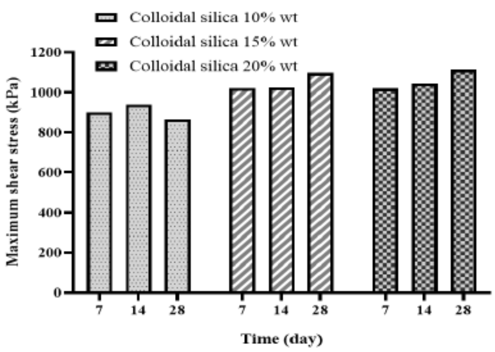

Figure 9. Effect of colloidal silica on shear strength of sand contaminated with 8% crude oil under a 100 kPa confining pressure at different curing times

3.4 Effects of Stabilization of Crude Oil–Contaminated Soil with Colloidal Silica

Figure 10 presents the stress–strain curves for different sand–silt mixtures stabilized with colloidal silica under different confining pressures. The figure indicates that adding colloidal silica to contaminated samples leads to an increase of shear stress. The shear strength of stabilized specimens is higher than that of original clean specimens.

An improvement in soil stress–strain behavior was observed in stabilized soil. It can be seen from Figure 10 that the elastic modulus of soils increases by adding colloidal silica solution. The shear stress diagrams in clean, polluted, and stabilized samples do not show peak stress points by increasing the silt percentage. During the consolidated undrained test, the ductility of the soil decreased by adding the colloidal silica, and the soil became denser than the clean soil. The formation of tension cracks triggered the failure mechanism.

Figure 11 shows the variations in shear strength for clean, contaminated, and stabilized samples by colloidal silica after a curing time of seven days under varying confining pressures. As mentioned before, it is concluded from the figure that treated soils have higher shear stress compared to the contaminated specimens. The addition of colloidal silica to silty sand resulted in a greater strength improvement in the contaminated soil compared to the other samples. For instance, treating contaminated silty sand containing 30% silt with a 15% colloidal silica solution and curing it for seven days under a confining pressure of 100 kPa resulted in an increase in shear strength of approximately 36%.

Figure 12 shows the rate of increase in maximum shear strength of contaminated soil due to the stabilization by colloidal silica in three confining stresses. The obtained results showed that mixtures containing greater silt content were more significantly affected than other samples. According to this diagram, the maximum rate of increase in shear strength of contaminated silty sand occurred in samples containing 40% silt under all confining pressures by around 50%. The specific mechanism of action of colloidal silica solution in soil contaminated with crude oil is that it helps to create a bond between colloidal silica and soil particles, which results in higher compressive strength. The hydraulic conductivity of mixtures is reduced by colloidal silica solution. Ghasabkolai et al. [31] stated the relationship between compressive strength, colloidal silica and hydraulic conductivity. Noll et al. [27] also reported a decrease in the hydraulic conductivity of loose sand when mixed with a 5% colloidal silica solution by weight.

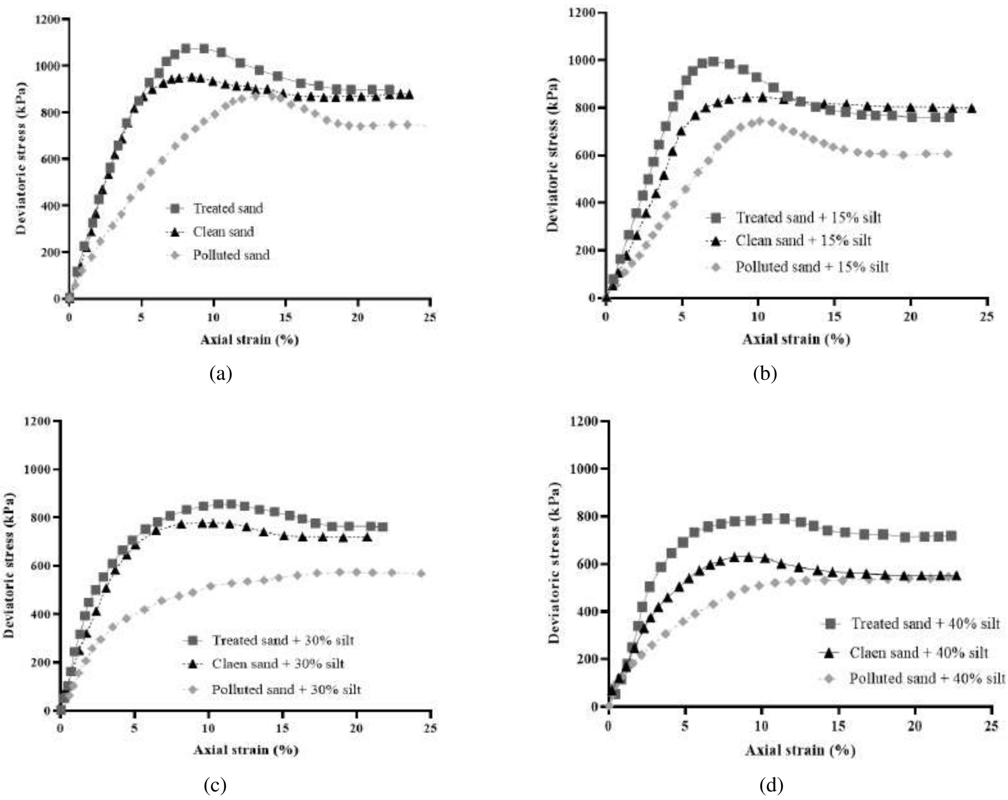

Figure 10. Stress–strain curves for clean, contaminated, and treated soils: (a) sand, (b) sand with 15% silt, (c) sand with 30% silt, and (d) sand with 40% silt, treated with 15% colloidal silica under a confining pressure of 100 kPa

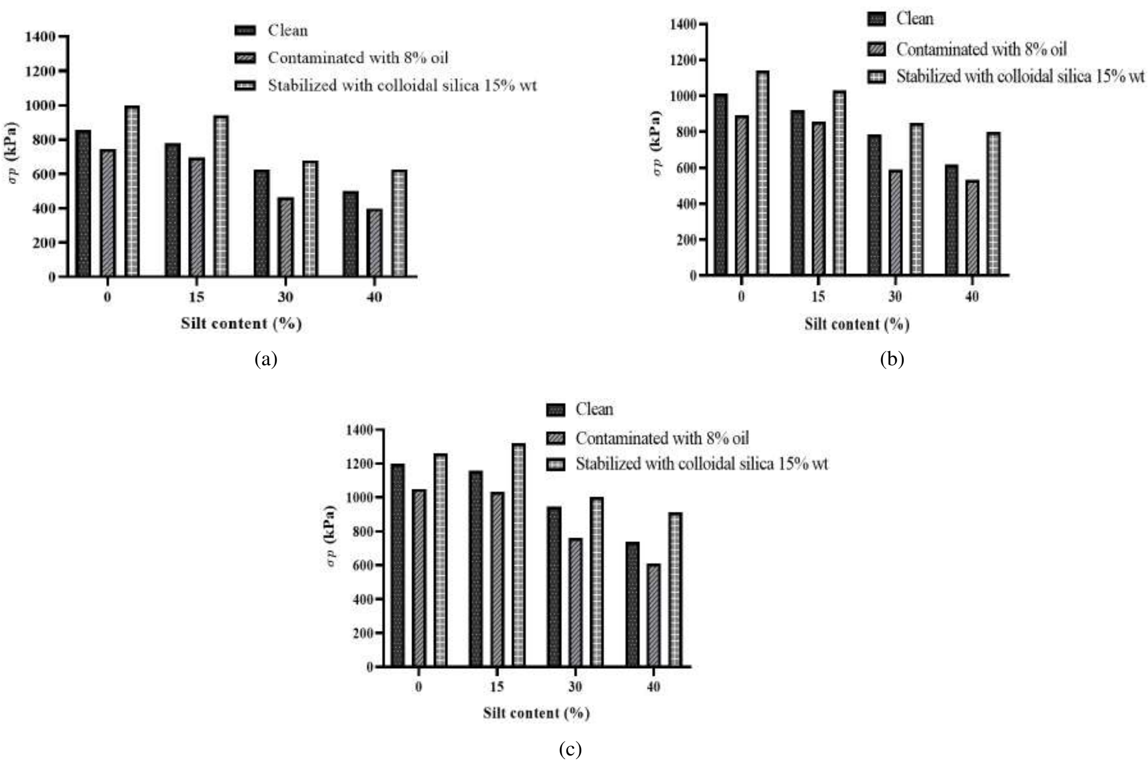

Figure 11. Effect of colloidal silica on shear stress of clean sand and contaminated silty sand after seven-day curing time at confining pressures of (a) 50 kPa, (b) 100 kPa, and (c) 150 kPa

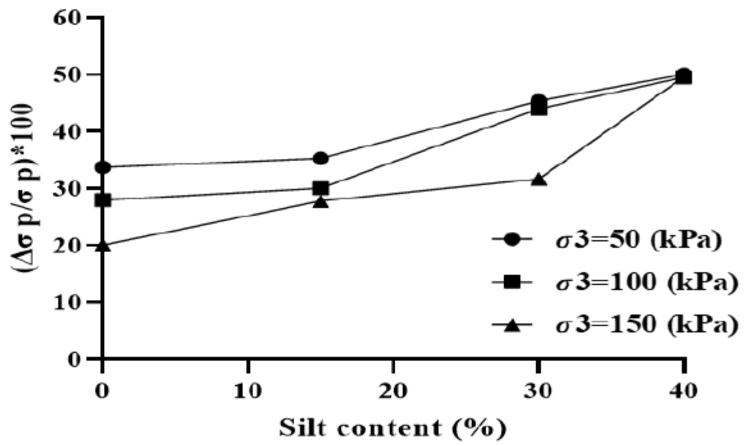

Figure 12. Percentage of increase in maximum shear strength of stabilized samples

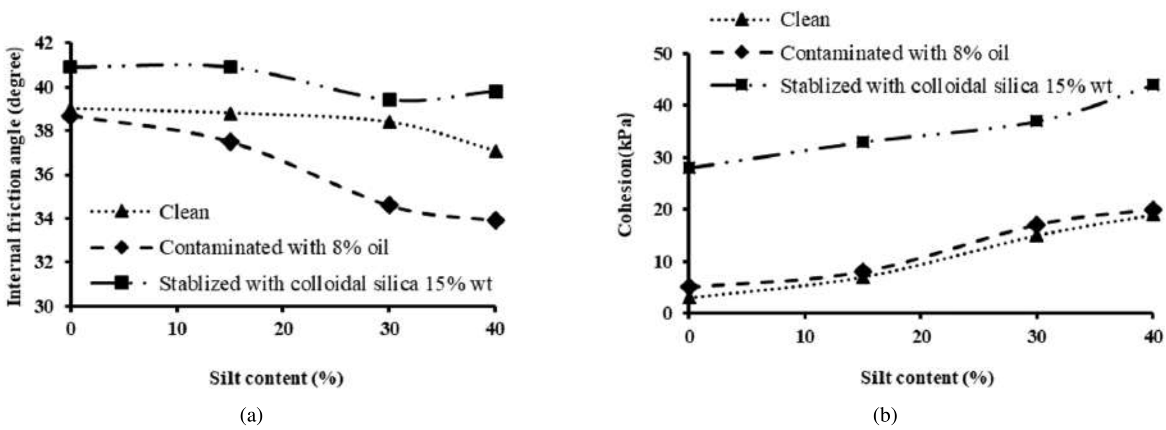

Figure 13. Variations in (a) internal friction angle and (b) cohesion for clean, contaminated and stabilized sand–silt mixtures

Colloidal silica solution, which is an inorganic substance, has various applications in various branches of civil engineering. In addition to ground improvement and liquefaction reduction, colloidal silica solution has been investigated by some researchers for controlling water production and fluid flow in the petroleum industry, reducing permeability and contaminant stabilization in environmental engineering and preventing water ingress in underground construction and tunneling. With the astonishing development of nanotechnology, nanomaterials have been extensively adopted in civil engineering due to their apparent advantages of cost-effectiveness, low disturbance, and environmental sustainability. It was concluded that nano-silica filled pore space between sand particles and a dense matrix was formed.

Figure 13 shows the variations in internal friction angle and cohesion by silt content for clean, contaminated, and stabilized silty sand. It was found that both the internal friction angle and cohesion of the contaminated soils increased after stabilization; however, the rate of increase in cohesion was greater than that of the internal friction angle. As shown in Figure 13a, the internal friction angle of soils decreases by polluting the soils with 8% oil, which is due to the lubrication of soil particles. Due to the gel properties of colloidal silica, the particles of soil moved toward each other and increased interlocking between particles. As a result, the contact surface between the soil particles was raised by increasing nano-silica, which improved the frictional forces and increased the friction angle of soils. Landman et al. [32] and Changizi and Haddad [33] presented similar results. Generally, as particles got close, the free space between particles was filled, and soil density increased. These results align with the findings of Hou et al. [34].

It is evident in Figure 13b that the stabilization of contaminated samples significantly increases cohesion. An average of 11% increase in cohesion was observed in stabilized specimens compared to contaminated ones. Colloidal silica produced viscous gel between the particles of the soil. The bond formed between the soil particles caused by the nano-silica viscous gel is probably stronger than the covalent bond and loose bond due to surface water absorption between soil particles, causing increased cohesion of contaminated samples.

The observed results are similar to the results of Taha and Taha [35] on the effects of nanoparticles on soil cohesion and other results reported by Changizi and Haddad [33], Delavar and Noorzad [14], and Vranna and Tika [36]. It can be seen that the increase in strength of the treated soils is due to increased friction angle and cohesion, with the latter contributing more significantly.

3.5 Steady-State Lines (SSLs)

Figure 14 shows the SSLs for clean, polluted, and stabilized soils. It should be mentioned that the SSL drops as the silt content increases up to 40%.

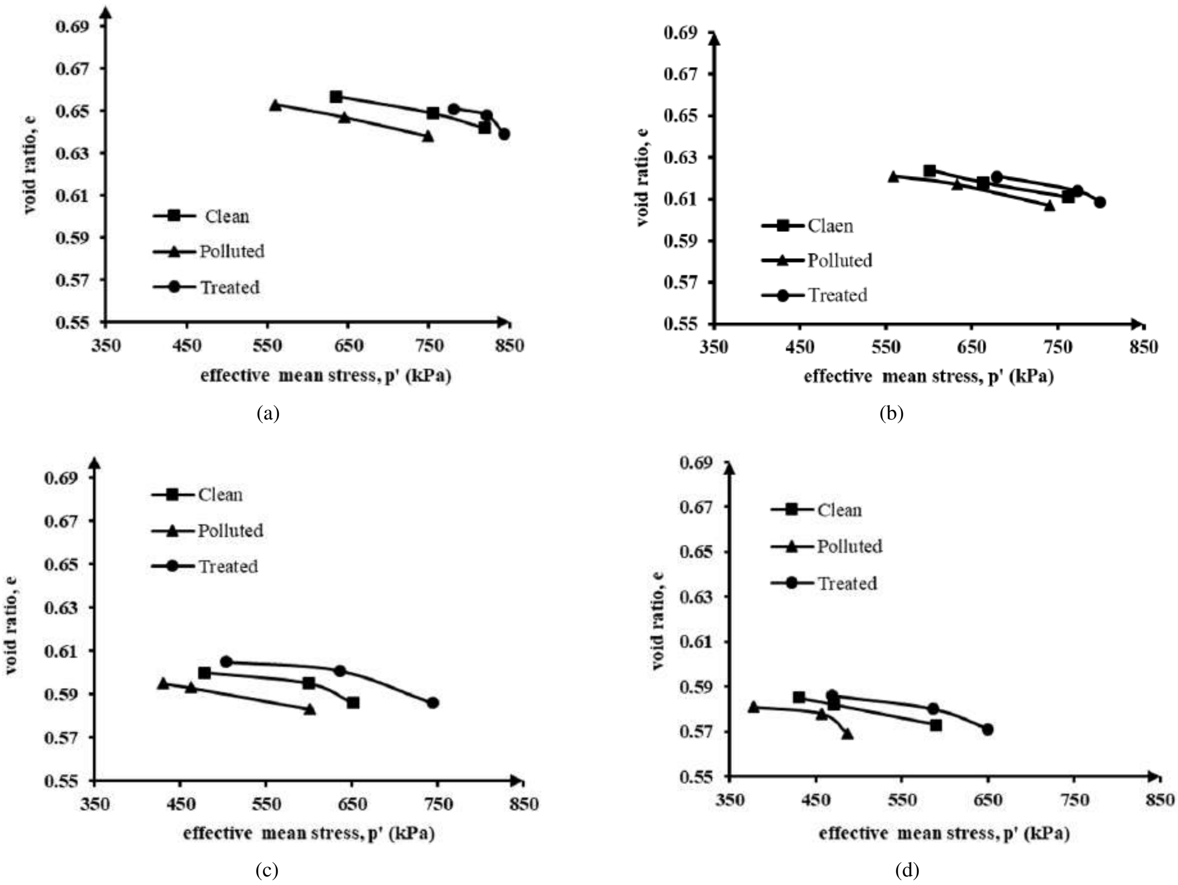

Figure 14. SSLs of triaxial tests for clean, contaminated, and stabilized sand–silt mixtures with (a) 0%, (b) 15%, (c) 30%, and (d) 40% silt contents

Naeini and Baziar [37] reported that silt, among the sand grains, acted as fillers and lubricants, causing the SSLs to shift downward. In all mixtures, the SSLs of the polluted samples were located at a lower position than those of the clean soils. The slope of the SSL increased with increasing fines content. This is consistent with a trend toward greater compressibility with increasing fines content. Therefore, the silt content can influence the SSL [38]. In addition, the grain size distribution and grain angularity are the primary factors. It has been shown that relatively small changes in grain size distribution (grain angularity being constant) can result in significant changes in the position of the SSL without substantially affecting its slope. Sample size has also been reported to affect SSLs. However, the effect of sample size is still unclear because some of the smaller samples tend to yield conservative results, while others indicate the opposite. Therefore, when sand is mixed with different percentages of silt, its grain size changes and, as a result, the SSL location shifts. In this study, the SSLs moved downwards. However, the slopes did not change. This indicates that oil contamination reduced the steady-state resistance and increased the liquefaction potential of the soils. By adding colloidal silica to contaminated samples, the SSL of sand containing various contents of the silt moved upward and was placed above the SSL of the clean sample, which indicated an increase in the final strength of the samples due to stabilization. In fact, when colloidal silica solution was mixed or injected into the contaminated samples, gel formation produced a denser matrix, increasing resistance and shifting the SSL upward. As a result of this behavior, the slopes of the SSLs of contaminated samples were slightly lower compared to those of pure sand and oil–contaminated sand.

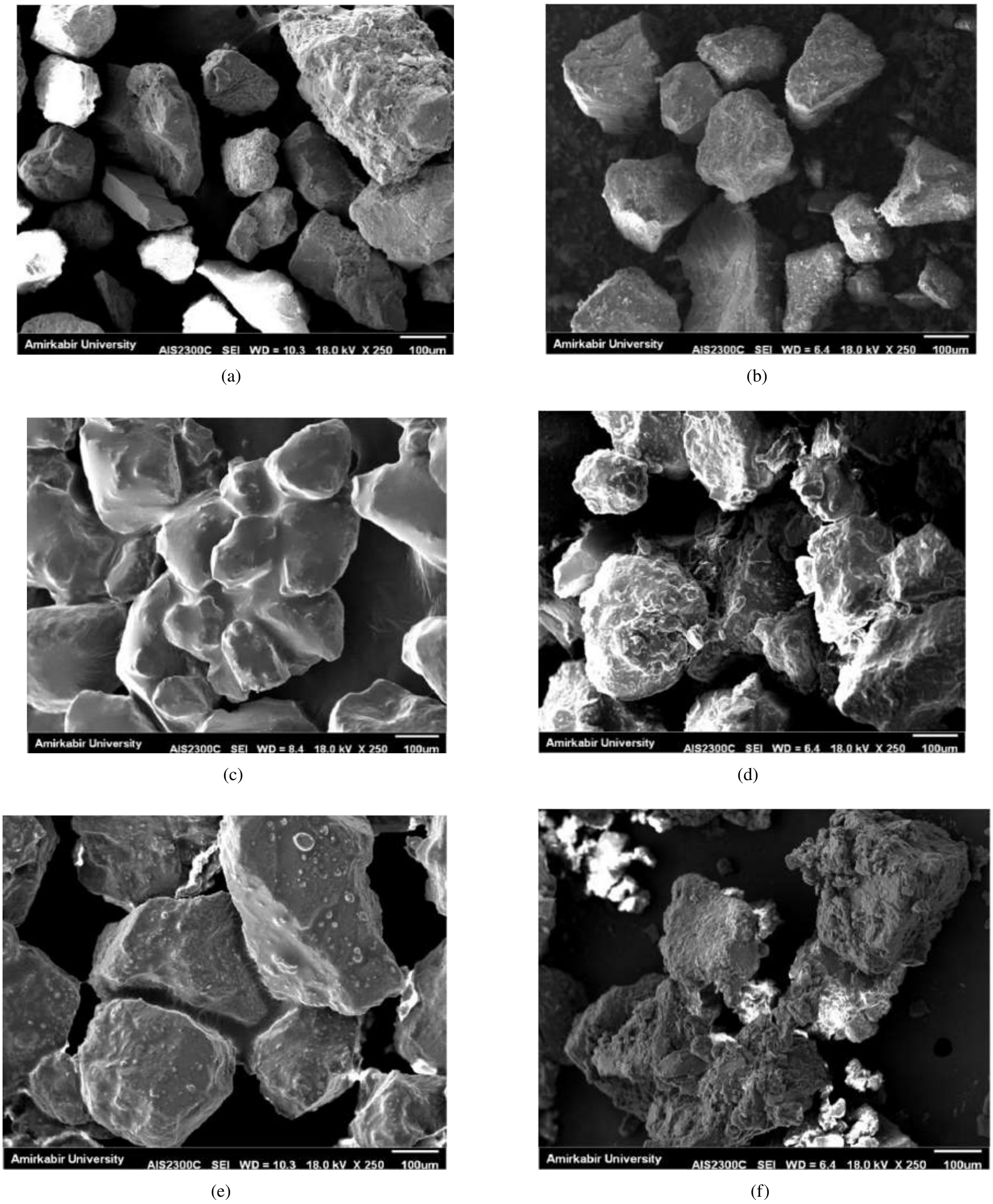

Figure 15. SEM images for (a) clean sand, (b) clean sand with 15% silt content, (c) contaminated sand, (d) contaminated sand with 15% silt content, (e) stabilized sand, and (f) stabilized sand with 15% silt content

3.6 SEM Image Analysis

The microstructure of the specimens containing 8% oil and 15% colloidal silica by weight after seven days of curing was investigated through SEM. To conduct the micromechanical analysis, the middle parts of the specimens were collected. The SEM micrographs of the clean, contaminated, and stabilized sand and sand with 15% silt are shown in Figure 15. As shown in Figure 15a and Figure 15b, the space between sand grains is filled with silt. The differences observed among the images in Figure 15a, Figure 15b, Figure 15d, and Figure 15e illustrate the distribution of hydrocarbon fluid in the specified soil. The oil appears to form coatings around the sand grains, promoting particle aggregation. As shown in Figure 15e and Figure 15f, sand and silty sand particles are connected together due to some links and bonding between sand particles. The viscous gel considerably modifies the interfacial bond properties and increases the frictional strength between soil particles.

3.7 Economic Viability and Practical Applicability

Huang and Wang [39] and Bao et al. [40] conducted detailed analyses comparing the cost-effectiveness of colloidal silica with that of other chemical solutions. Despite its relatively high price, only a limited dosage of colloidal silica is required to effectively mitigate liquefaction. According to Huang and Wang [39], treating one cubic meter of soil with a colloidal silica concentration of 5% requires an amount costing approximately 59 USD. However, the corresponding treatment costs per cubic meter of grouted soil are approximately 180 USD, 325 USD, and 500 USD for sodium silicate, acrylamide, and epoxy, respectively. Therefore, colloidal silica represents a cost-effective option, with treatment expenses amounting to less than one-third of those for conventional chemical solutions. Meanwhile, with the rapid global development of nanotechnology, the cost of nanomaterials is anticipated to decrease significantly. As an illustration, carbon nanotubes experienced a significant price reduction, dropping from 150 USD per gram in 2000 to 50 USD per gram in 2010. Therefore, it can be inferred that colloidal silica, as a type of nanomaterial, is expected to become considerably more affordable in the future. As highlighted by Huang and Wang [39], although the use of colloidal silica for ground improvement and liquefaction mitigation is currently at the experimental stage, it is expected to succeed commercially due to its environmental and economic advantages. The global population continues to rise rapidly in the 21st century, resulting in increased demand for infrastructure and construction projects. With the expansion of human construction projects, it is inevitable for engineers and architects to encounter certain "problematic soils" which cannot fulfill engineering requirements. The unimproved "problematic soils" may lead to a series of safety and reliability problems, including ground collapse, ground settlement, and foundation instability. All of these potential problems can threaten the safety of human life and property. With the development of nanotechnology, due to its great characteristics such as low price and environmentally friendly production process, nanomaterials are widely used in the area of civil engineering. Today, they have practical applications in various projects such as road construction, earth dams, foundation construction, and so on, reducing the energy consumption of buildings and improving the stability of soil.

4 Conclusion

The results of the laboratory investigations, conducted using triaxial monotonic tests on crude oil–contaminated sand and on contaminated samples stabilized with colloidal silica, are summarized as follows:

- By performing standard compaction tests on oil–contaminated samples and comparing them with clean samples, an increase in sand compressibility was observed in contaminated conditions. This increase was not significant for a higher percentage of silt. Oil in the samples decreased the OMC.
- Adding silt to the sand–silt mixtures led to decreased maximum shear strength in all three confining stresses. However, 8% oil contamination decreased the strength and increased the ductility of all soil specimens; the influence of the oil contamination on shear strength parameters was not uniform, and it depended on the silt content.
- Due to the soil contamination with crude oil, the internal friction angle of all studied samples was reduced, especially by increasing percentages of silt; the variation was considerable and reached 9%. At the same time, oil contamination led to a 1–2 kPa increase in the cohesion of the specimens.
- It was found that the treatment of the contaminated soil with colloidal silica was a practical approach to increase the strength of contaminated soil and make it a more workable material for earthworks. In other words, nano-silica led to stable contaminated soil with higher strength than the original clean specimens.
- Colloidal silica was more effective in improving soils containing more silt. According to the obtained results, the shear strength of contaminated soil containing 40% silt in all three stresses was raised by 50%.
- Compared with the contaminated samples, the internal friction angle increased in stabilized samples up to 17% following the addition of colloidal silica. Across the different fine-content percentages, cohesion increased by an average of 11% due to the gelation of colloidal silica. An increase in cohesion and friction angle led to an increase in the maximum shear strength.
- Under steady-state conditions, increasing the percentage of silt and contamination with 8% crude oil in all samples reduced the soil resistance and increased liquefaction. However, adding a stabilizer to contaminated specimens increased the final strength of the samples.

In conclusion, stabilized crude oil–contaminated soils could become efficient construction materials for road works or daily covering of landfills. The stabilization approach examined in this study demonstrates that colloidal silica can reduce project costs by enabling the reuse of contaminated soil materials. Finally, a colloidal silica solution is recommended to improve the geotechnical properties of crude oil–contaminated soils to make them suitable for reuse because it improves the mechanical properties of the studied soils.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare no conflict of interest.

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