

Effect of Oil Contamination on the Behavior of Collapsible Soil

Saber Nokande¹, Mohammad Ali Khodabandeh^{2*}, Ali Besharatinezhad², Gábor Nagy²,
Ákos Török²

¹ Department of Geotechnical Engineering, Faculty of Civil Engineering, University of Semnan, 19111-35131 Semnan, Iran

² Department of Engineering Geology and Geotechnics, Faculty of Civil Engineering, Budapest University of Technology and Economics, H-1111 Budapest, Műegyetem rkp. 3., Hungary

* Corresponding author, e-mail: mohammad.khodabandeh@emk.bme.hu

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Abstract

Loessial soil is moisture-sensitive soil susceptible to settle when fully saturated. In this study, efforts were made to investigate the effect of oil pollutants on mechanical behavior of soil. The loess soil was contaminated by 2,4,6,8 and 10% dry weight of lamp oil and gasoline. Atterberg limits, direct shear, unconfined compressive strength (UCS) and scanning electron microscope (SEM) tests were performed to evaluate the behavior of oil-contaminated collapsible soils. The results of Atterberg tests showed that the plasticity of the soil decreased, due to the reduction in the thickness of the absorbed surface layer and double water layer. According to the direct shear test, with increasing contamination up to 10% of lamp oil and gasoline, the cohesion of the soil was decreased from 14.5 kPa to 7.3 kPa and 7 kPa, respectively, which was due to the reduction in soil plasticity and diffuse double-layer. Because of the lubrication of soil particles, the internal friction angle of soil was reduced from 18.5° to 13.6° and 13.9° for 10% lamp oil and gasoline. UCS of contaminated soil increased in low strains due to the apparent cohesion of hydrocarbons and it decreased 31% for gasoline and 53% for lamp oil at high strains due to the softening behavior of the contaminated soil. SEM test revealed that hydrocarbons covered the soil particles and changed the soil fabrication to dispersed skeleton. Generally, collapsible soil contaminated with different lamp oil and gasoline contents showed a decrease in shear strength and UCS with increasing oil content.

Keywords

cohesion, internal friction angle, loess, oil-contaminated soil

1 Introduction

Loess is a collapsible wind-deposited soil with low dry density, low moisture content, poor cohesion, high void index and high fine particle content (mostly silt and clay) [1–4]. Collapsible soils are among the problematic soils; hence, the effects of various contaminations on them have been investigated in previous research [5–6].

Oil is one of the most challenging pollutants with detrimental effects on the collapsible soil [5]. Nowadays, petroleum products can enter the environment in different ways such as oil extraction, oil transportation and leakage from the corroded storage tanks and pipelines. Changes in the mechanical properties of oil-contaminated soils have been mentioned in previous research [7–9]. Furthermore, several methods of stabilization and multiple remediation have been recommended to utilize oil-contaminated soils [10–12]. Various types of hydrocarbon contaminants have been used to evaluate the strength parameters of different soils [13–15].

Safedian et al. [16] investigated the effect of diesel oil on the geotechnical properties of illite. It was observed that soil compaction increased faced to organic fluids. Moreover, increasing diesel oil in soil caused a reduction in cohesion, internal friction angle and unconfined compressive strength (UCS).

A decrease in permeability, strength, maximum dry density, optimum water content, and Atterberg limits of oil-contaminated sandy and clayey soils was observed by Khamechian et al. [17]. The effects of oil-contaminated sandy soil on the uplift behavior of vertical piles were investigated by Nasr et al [18] and the results showed that the soil-piles cohesion and the uplift resistance of the piles decreased.

ur-Rehman et al. [19] compared the mechanical properties of uncontaminated and contaminated clays and they observed a reduction in the cation exchange capacity (CEC) of oil-contaminated clay. Karkush and Kareem [20]

observed an increase in the consolidation parameters and a decrease in cohesion and internal friction angle of fine-grained soils after contamination with petroleum hydrocarbons. Di Matteo et al. [21] investigated the compressibility of kaolinitic clay contaminated by ethanol–gasoline and a model was developed to predict the compression index of kaolinite.

Kermani and Ebadi [22] investigated a contaminated clayey soil and they concluded an increase in maximum dry density, compression index, friction angle and Atterberg limits and a decrease in cohesion and optimum water content of the soil. Khosravi et al. [23] evaluated the geotechnical properties of gasoline-contaminated kaolinite and observed an increase in cohesion and a decrease in friction angle and compressibility of the contaminated kaolinite.

Al-Aghbari et al. [24] examined the characteristics of oil-contaminated sandy soils. They observed that increasing the percentage of oil pollution caused a decrease in Atterberg limits, permeability and moisture content of the soil. Regarding the shear strength parameters of the soil, they concluded that with an increase in oil content, soil cohesion increased and the internal friction angle of the soil decreased. Similarly, Nasehi et al. [25] studied the properties of fine-grained and coarse-grained soils when contaminated with gasoline. They observed that with an increase in gasoline content, soil cohesion and Atterberg limits increased but the angle of internal friction, the maximum dry density and the moisture content of the soil decreased. Salimnezhad et al. [26] concluded that shear strength, cohesion, internal friction angle and UCS of the high plasticity clayey soil decreased with increasing the crude oil contamination.

In addition, soil contamination by organic fluids changed the geotechnical properties of the soil. By testing contaminated kaolinite and bentonite with organic fluids, Kaya and Fang [27] showed that stress-strain behavior and hydraulic conductivity of contaminated soil were altered. They reported that the contaminated clay samples had behaviors similar to those of fine-grained silty sand soils. Moavenian and Yasrobi [28] examined the behavior of clay soils when exposed to organic fluids. They found that pure organic chemicals caused less heaving in comparison to distilled water. Moreover, organic fluid caused osmotic consolidation in the soil and reduced the plasticity and settlement.

The unconfined compressive strength of fine-grained soils contaminated with Glycerol, propanol and acetone was studied by Ratnaweera and Meegoda [29]. They

found that the mechanical interactions induced by the high viscosity of the fluids and the physico-chemical characteristics of soils and chemicals, were responsible for a reduction in shear strength of contaminated soils. In another study, a reduction in UCS for pure clay was observed with increasing gasoline contamination up to 8%. Following that, the UCS decreased until 16% gasoline contamination [30].

Overall, researchers have examined the oil contamination on different types of soil and previous studies show that the physical and mechanical properties of soils could be changed by hydrocarbon products. However, limited studies on oil-contaminated collapsible soil have been published [5, 17] to the best of our knowledge. For this reason, it is important to investigate the mechanical properties of collapsible soil due to the specific behavior of this kind of soil when saturated with various hydrocarbons. In the present study, in order to investigate the properties of oil-contaminated loessial soil, Atterberg limit, direct shear, UCS, and SEM tests were performed. Up to 10% lamp oil and gasoline were added to the samples by mixing method.

2 Materials and methods

2.1 Materials

2.1.1 Properties of the soil

The loessial soil used in this research was taken from Kalaleh in Golestan Province, northern Iran with 37°30'12.6"N 55°30'42.9"E coordinates. To prevent any upper grass roots and organic soil layer, the soil samples were taken with 30 × 30 × 30 cm³ boxes in undisturbed condition from 1 m below the ground surface. In order to preserve the soil moisture, the boxes were immediately insulated with paraffin after sampling.

Hydrometer and grain size analysis tests were conducted according to ASTM D422 [31]. Grain size distribution curve of the soil is presented in Fig. 1. Table 1 presents the properties of the soil. From the presented soil properties and according to the Unified Soil Classification System (USCS) [32], the soil type was clay with low plasticity (CL) and based on EN ISO 14688-2, the soil type was medium silt (MSi). The studied soil is categorized as severely collapsible soil, which was proved in previous research on the same soil [6].

The XRD test was carried out on the soil sample to assess the soil phase and ratio of minerals. The quartz, albite and calcite were the main soil minerals. The ratio of soil minerals are presented in Table 2.

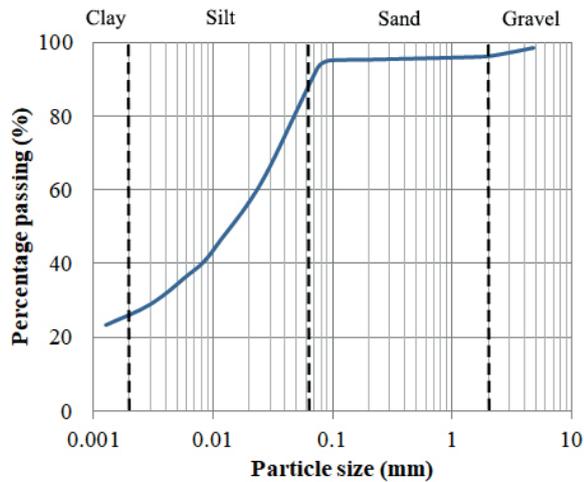


Fig. 1 Grain size distribution curve of the soil (modified after [6])

Table 1 Studied soil properties

Parameter	Value	Method Used
LL, PL, PI (%)	29, 21, 8	ASTM D4318 [33]
Natural water content (%)	5.57	ASTM D2216 [34]
G_s	2.67	ASTM D854 [35]
Void ratio (e)	0.9	ASTM D7263 [36]
γ_{dry} (kN/m ³)	14.2	ASTM D7263 [36]
D_{30} (mm)	0.003	-
D_{50} (mm)	0.015	-
D_{60} (mm)	0.030	-
Sand (%)	7	-
Silt and clay(%)	93	-

Table 2 The results of XRD test

Soil minerals	Mineral phases ¹
Quartz	+++
Calcite	++
Albite	++
Muscovite	+
Clinochlore	+
Doloite	*

¹ main: +++ ; common: ++ ; present: + ; traces: *

2.1.2 Properties of the pollutants

The type of hydrocarbon pollutant has a significant effect on the mechanical behavior of the soil. For this reason, two different types of hydrocarbons including lamp oil and gasoline were used in this research. The hydrocarbons were provided from national iranian oil refining and distribution company (NIORDC). The Table 3 shows the properties of studied hydrocarbons including the density, ignition temperature, self-ignition temperature, and boiling point.

2.2 Sample preparation

Due to the fact that the undisturbed samples had different initial moisture, density and void index, just like the previous study [6], the remolded samples were used in this research to create a homogeneous mixture of soil and contaminants. At first, the average values of initial moisture, density and void index for undisturbed soils were determined. It should be noted that all remolded samples had the same void ratio, moisture, and unit weight as the average values for undisturbed samples. Table 4 presents the characteristics of undisturbed and remolded soils.

Fig. 2 shows the flowchart of the tests. The procedure of sample preparation was the same as the previous research [5].

In the present study, initially prepared remolded samples were contaminated with lamp oil (group A) and gasoline (group B) at 2, 4, 6, 8, and 10% by weight of the dry soil specimens. Then, in order to achieve the equilibrium

Table 3 Properties of the gasoline and lamp oil (from the supplier, NIORDC, Iran)

Oil type	Density (g/cm ³)	Ignition temperature (°C)	Self-ignition temperature (°C)	Boiling point (°C)
Gasoline	0.80–0.84	56	257	150–390
Lamp oil	0.78–0.81	51	220	150-300

Table 4 The properties of undisturbed and remolded samples

Sample conditions	Sample	Void index	Moisture content (%)	γ_d (kN/m ³)
Undisturbed	1	1.05	3.72	13
	2	0.89	3.79	14.1
	3	0.74	3.14	15.3
Remolded	4	0.9	3.5	14.2

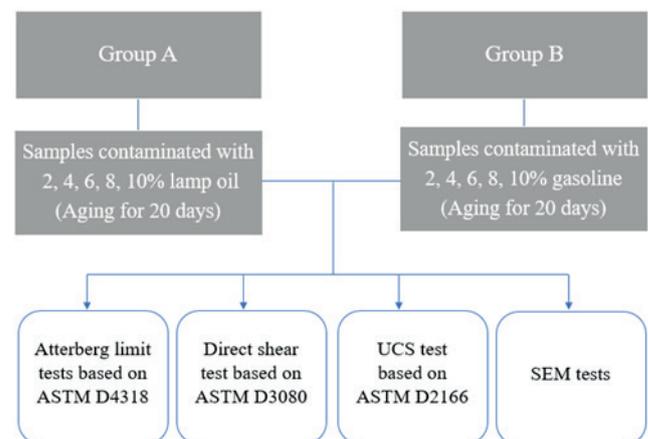


Fig. 2 Flowchart of the tests

state, aging and possible reactions between soil and contaminants, the samples were placed in insulated plastic containers for 20 days (after [5]). After curing, Atterberg limits, direct shear, UCS and SEM tests were conducted.

2.3 Methods

2.3.1 Direct shear tests

In this study, in order to investigate the shear strength parameters of oil-contaminated loessial soil, the direct shear tests were performed on soil samples contaminated with different percentages of lamp oil and gasoline under drained conditions according to ASTM D3080 [37]. The contaminated samples were prepared by mixing the soil specimens with lamp oil and gasoline in the amount of 2%, 4%, 6%, 8%, and 10% by dry weight. According to the examined fine-grained soil, the shear box with a dimension of $60 \times 60 \times 60$ mm was used to perform the direct shear test. Each test was repeated at least three times and totally 33 direct shear tests were conducted in this study. Note that for all direct shear tests, the speed of force was set at 0.048 mm/min.

2.3.2 Unconfined Compressive Strength (UCS) tests

In order to evaluate the effect of contamination on the undrained shear strength and stress-strain characteristics, the unconfined compressive test was performed according to the ASTM D2166 standard [38] on the clean and contaminated soils when exposed to different mass percentages of lamp oil and gasoline. The soil samples were contaminated by lamp oil and gasoline solutions at the 2%, 4%, 6%, 8% and 10% (by weight%). After the treatment, unconfined compressive tests were then conducted on the clean and contaminated soil samples.

2.3.3 Scanning electron microscope (SEM) tests

Scanning electron micrographs (SEM) photographs are among the greatest techniques for evaluating a soil element's morphology because soil properties are affected by its structure. SEM images were enlarged to $20 \mu\text{m}$ to show the changes in the microstructure of the soils when 10 percentages of hydrocarbons were introduced to the specimens. Instead of very thin discs, 10 mm width sections of contaminated soil were utilized in the SEM analysis because SEM visualizes the surface of three-dimensional objects. The samples were also covered with a thin gold layer. The metal coating rendered the samples conductive, like an electrical wire, and drew away the electrons bombarding the sample.

3 Results

3.1 Effect of oil contamination on Atterberg limits

Atterberg limits tests are recognized as one of the basic tests to identify the behavior of cohesive soils. According to Fig. 3, the liquid limit decreased from 29 to 18 or 17, and the plastic limit reduced from 21 to 14 or 13, as the content of lamp oil and gasoline increased up to 10%, respectively. With a decrease in both parameters of the liquid and plastic limits, the plasticity index also decreased from 8 to 4 and 3 for lamp oil and gasoline, respectively, and the cohesive soil properties became like granular soil. Fig. 4 schematically shows the effect of soil contamination on the double layer water. Apart from that, with the increase in the percentage of pollutants, the decrease in the Atterberg limits which was due to the concentration of pollutants around soil particles, became more significant.

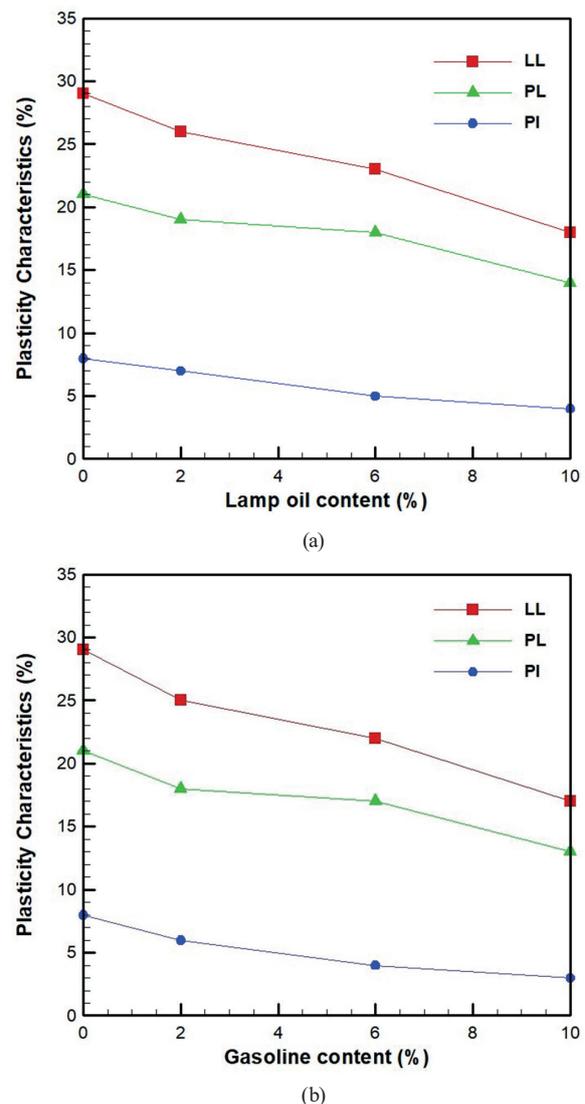


Fig. 3 Atterberg limits parameters of contaminated soil (a) lamp oil, (b) gasoline

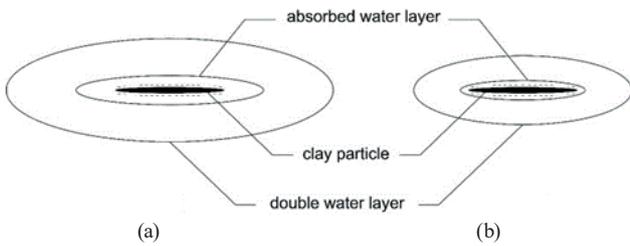


Fig. 4 Effect of soil contamination on the double layer water a) before contamination b) after contamination (modified after [16])

3.2 Effect of oil contamination on the shear strength parameters

The cohesion and internal friction angle parameters of soil were calculated with direct shear test and failure envelope graph was shown in Fig. 5. To evaluate the strength of oil-contaminated loessial soil, a direct shear test was initially performed on clean soil sample in water-saturated condition. Similarly, contaminated soil samples were examined in water-saturated conditions compared to the clean soil sample.

Fig. 6 indicate the stress-strain graph for all samples.

According to Fig. 7(a), soil cohesion has been decreased from 14.5 kPa to 7.3 kPa and 7 kPa with increasing contamination up to 10% of lamp oil and gasoline, respectively. Fig. 7(b) indicates a reduction in internal friction angle of the soil from 18.5° to 13.6° and 13.9° for 10% of lamp oil and gasoline due to the lubrication of soil particles. As a result of the bipolar molecules of water, it created a covalent bond with clay particles. However, hydrocarbon products changed the behavior of loessial soil from fine-grained soil to granular soil. Granular behavior of soil and high viscosity of hydrocarbons caused lubrication between soil particles, which led to easy slippage of clay sheets over each other.

3.3 Effect of oil contamination on the unconfined compressive strength

Fig. 8(a) and Fig. 8(b) present the strength behaviors of lamp oil and gasoline contaminated soils in the UCS test, respectively. A quick glance at these figures reveals that an increase in the percentage of hydrocarbons showed a softening behavior in the stress-strain curve and a lower unconfined compressive strength of the soil. From Fig. 8(a), increasing the lamp oil up to 6 percent enhanced the soil strength in small strains and showed even higher strength compared to soil without contamination. In addition, gasoline had a behavior similar to lamp oil (Fig. 8(b)). Fig. 8(c) shows 167 kPa and 97 kPa reduction in unconfined compressive strength of soil contaminated with 10% of lamp oil and gasoline.

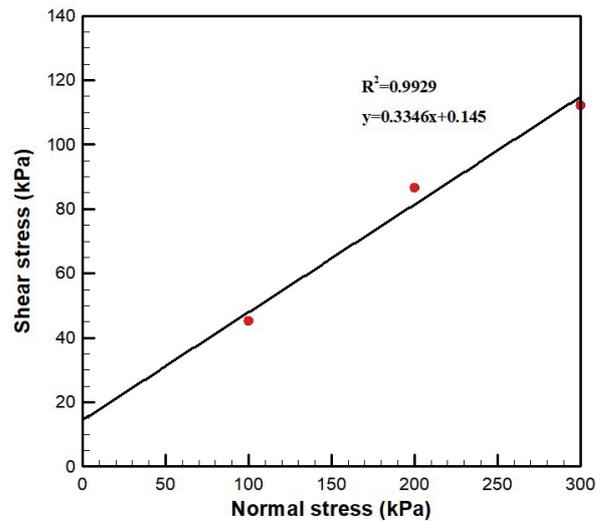


Fig. 5 Failure envelope graph of clean soil (modified after [6])

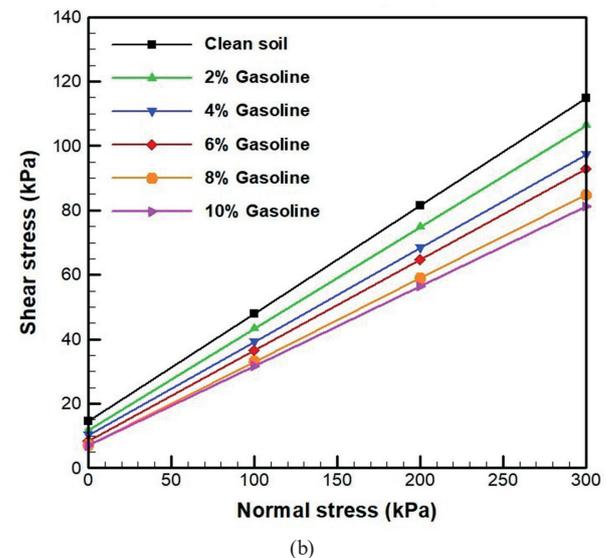
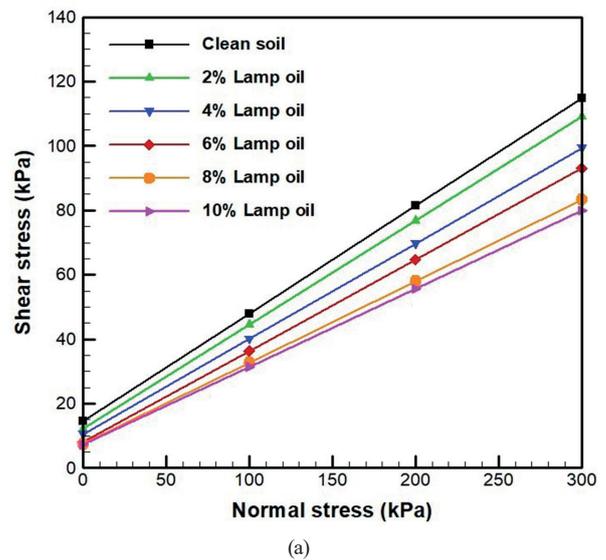
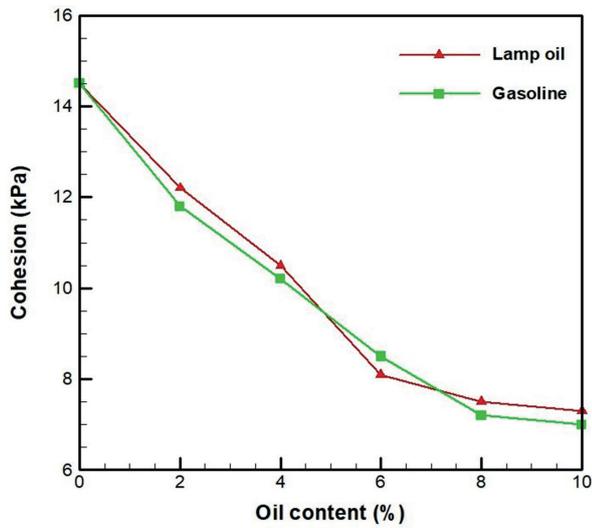
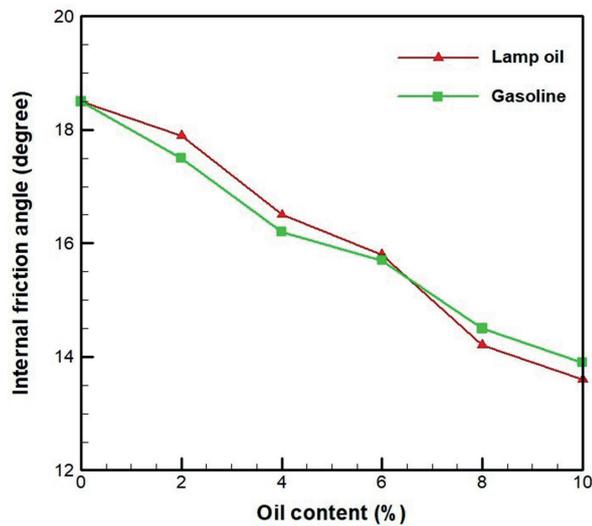


Fig. 6 Failure envelope graphs for soils contaminated with different percentages of (a) lamp oil and (b) gasoline



(a)

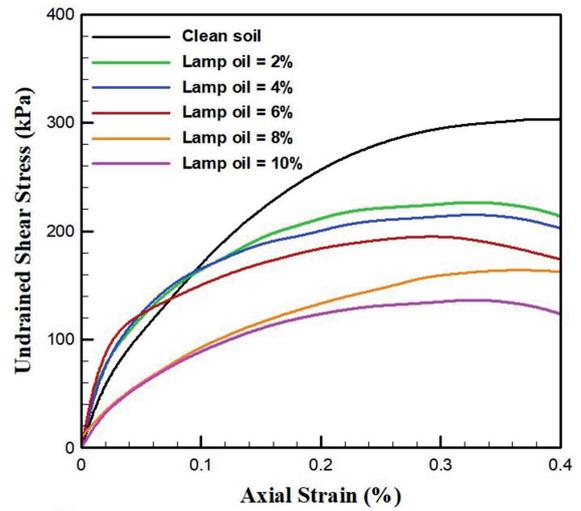


(b)

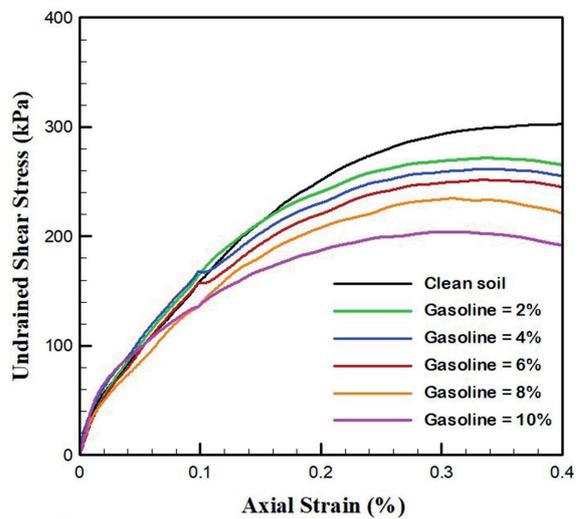
Fig. 7 (a) Cohesion of soils contaminated with different percentages of lamp oil and gasoline (b) Internal friction angle of soils contaminated with different percentages of lamp oil and gasoline

3.4 Effect of oil contamination on the soil morphology

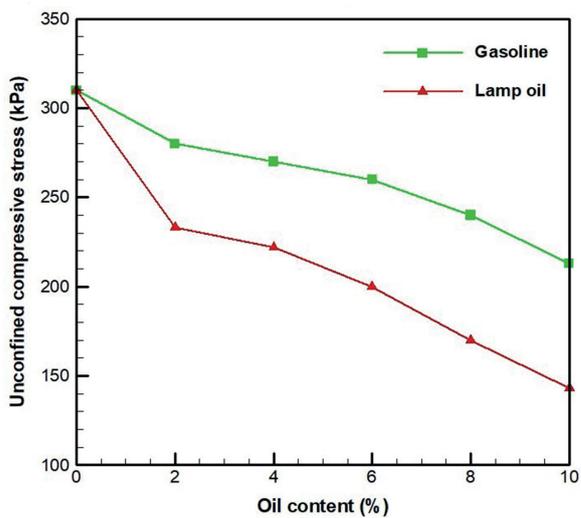
Fig. 9 shows SEM images of clean soil and soil contaminated with 10% lamp oil and gasoline. As shown in Fig. 9(a), the clean soil was flocculated and the particles were interconnected. However, in Fig. 9(b) and Fig 9(c) the hydrocarbon contaminants surrounded the soil particles and did not allow them to interact with each other, consequently, the particles were more granular. Due to the granulation of the soil and the presence of hydrocarbons, a lubrication mechanism occurred between the particles. Hence, the soil particles slid more easily on each other.



(a)



(b)



(c)

Fig. 8 (a) Influence of lamp oil on the undrained shear strength of collapsible soil (b) Influence of gasoline on the undrained shear strength of collapsible soil (c) Comparison of unconfined compressive strength of soil contaminated with lamp oil and gasoline

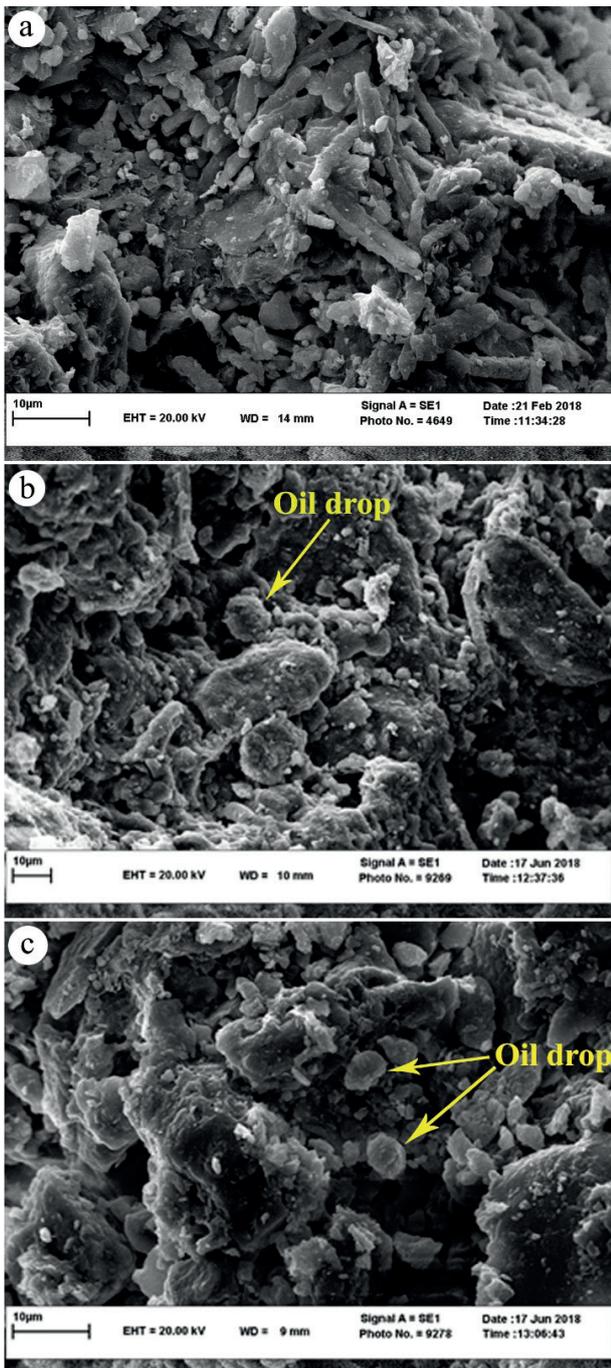


Fig. 9 SEM images of (a) clean soil (b) contaminated soil with 10% lamp oil (c) contaminated soil with 10% gasoline

4 Discussion

The findings of several tests were compared for a comprehensive review, and it was observed that the results were consistent and comparable to the previous findings [5, 6, 16, 17]. The results of the SEM test showed that; the hydrocarbons surrounded the clay particles and the soil behaved like granular soil. A reduction in liquid and plastic limits of oil-contaminated soil was achieved due

to the thinner absorbed surface layer and double water layer of contaminated soil particles compared to the clean soil. As a result of lower soil plasticity, granular behavior of soil was also observed in Atterberg limit test. It was also observed in previous research that soil plasticity was reduced by decreasing the double water layer around clay particles [39]. Regarding the diffuse double-layer theory, the relation between the pore fluids with the negative ions of the soil surface affects the absorbed surface water layer [40]. Moreover, the reduction of the liquid limit depends on the double water layer around the soil particles. Due to the non-polarity of the hydrocarbon molecules, the covalent bond between the contaminated soil particles and water is reduced and the double layer becomes thinner compared to clean soil and water [23].

In the present study, according to the results of direct shear test, soil cohesion was decreased, which was consistent with the reduction of plasticity in the Atterberg limits test. The decrease in cohesion of soil was attributed to the decrease in diffuse double-layer. Mitchel and Soga [41] stated that the double-layer thickness of clay soil can change due to the different dielectric of pore fluid. The reason for the reduction in the double water layer around the clay particles was the decrease in the dielectric constant of the porous fluid. In a similar research, the double layer of negatively charged clays is being reduced because of the contaminated soil with lower dielectric constant [42]. Safehian et al. [16] and Khamechian et al. [17] also showed that the cohesion of fine-grained soil has been reduced in the presence of diesel and crude oil, respectively.

Granular behavior of soil, as observed in SEM test, can be proved by reducing plasticity and soil cohesion, which was due to the covering of particles by hydrocarbons and the slippage between grains. Lubrication between clay sheets reduced soil internal friction angle. As a result of a decrease in cohesion and internal friction angle of soil, a reduction in the shear strength of soil has been occurred. In a similar research, Nokande et al. [5] investigated the collapse potential of the same oil-contaminated loessial soil, stating that with an increase in the percentage of contamination, the lubrication between soil particles occurred and consequently the rate of collapse increased. Furthermore, Ghadyani et al. [43] emphasized that higher viscosity of organic fluid enhanced lubrication between soil particles.

In the present study, it was also found that an increase in the percentage of pollutants up to 10% contamination led to a decrease in the unconfined compressive strength of the soil. In small strains (up to almost 0.1% axial strain), with

increasing the oil pollutants by up to 6% contamination, the UCS was slightly higher than that of uncontaminated soil. However, in higher strain (up to 0.4% axial strain) the UCS of oil-contaminated soil decreased significantly compared to soil without contamination. Because hydrocarbons were non-polar, their effects on grains bonding were less severe than water at low percentage of contamination. On the other hand, the effect of grain lubrication increased in high percentages of contamination. This was evident in other experiments, such as the soil collapse test done by Nokande et al. [5] on the same loess soil. In the UCS test, low strains caused slight slippage between the grains, and the soil grains were less surrounded by hydrocarbons at low contamination rates. Therefore, grain lubrication had less effect on the soil behavior at low strains. In previous research [16], the hydrocarbon-contaminated fine-grained soil behaved similarly at low strains of the UCS test. By investigating the UCS and direct shear tests, it was found that soil strength has been decreased in both tests. Although the reduction in the shear strength parameters of contaminated soils was the same for both contaminants, the decrease in unconfined compressive strength of soil contaminated with lamp oil was higher than gasoline, which can be due to the difference in the condition of direct shear (saturating with water) and UCS tests (without saturating with water). In a similar study on loessial soil, Khodabandeh et al. [6] investigated the effect of pH on the same soil and concluded that alkaline contaminants decreased cohesion and unconfined compressive strength of loessial soil. Due to the alkalinity of hydrocarbons, the results of this study were consistent with those of Khodabandeh et al. [6].

The results of the present study were consistent with those of [16, 17, 20] resulted in a reduction in Atterberg limits, cohesion, internal friction angle, and strength of contaminated soil. But, there was no similarity between the results of the present study compared to those of [43, 44, 45] that were related to the type of soil and contaminants, how to prepare and contaminate the samples. Procedure of sample

preparation influenced the behavior of contaminated soil in the UCS test [6, 16]. So that sample preparation by permeating method done by Moore and Mitchell [46] and Sridharan and Rao [47] showed an increase in unconfined compressive strength (UCS). However, Khamchayan et al. [17] and Ratnaweera and Meegoda [29] concluded a decrease in the strength of contaminated soil by preparing the sample by mixing method. In this study, the mixing method was used to prepare the samples and a reduction in UCS was concluded which was in agreement with other researches including the same preparation method.

5 Conclusions

In this study, the effect of lamp oil and gasoline on the mechanical properties of loessial soil was investigated. Atterberg limits, shear strength parameters and UCS of oil-contaminated soils was evaluated. The results of the Atterberg limit test showed that the liquid and plastic limits and plasticity index of soil decreased, due to the reduction in the water absorbed layer and the double water layer around the clay sheets. According to the results of direct shear test, soil cohesion was decreased from 14.5 kPa in clean soil to 7.3 kPa and 7 kPa in soil contaminated with 10% lamp oil and gasoline, respectively.

The internal friction angle of the soil was reduced by 4.9° and 4.5° with 10 % lamp oil and gasoline contamination, respectively, which referred to the lubrication between soil particles. Similarly, this granular behavior and lubrication between soil particles were seen in SEM test. The results of UCS test showed that with up to 0.1% strain, contaminated soil obtained higher strength than clean soil, but at strains more than 0.1%, uniaxial compression strength of soil contaminated with oil and gasoline decreased. Generally, increasing the percentage of contaminants led to a decrease in the unconfined compressive strength of contaminated loess soils. The results can be applied when soil contamination occurs after oil leakage from storages, pipelines, and petrochemical industries.

References

- [1] Smalley, I. J. "The properties of glacial loess and the formation of loess deposits", *Journal of Sedimentary Research*, 36(3), pp. 669–676, 1966.
<https://doi.org/10.1306/74D7153C-2B21-11D7-8648000102C1865D>
- [2] Smalley, I. J. "In-situ theories of loess formation and the significance of the calcium-carbonate content of loess", *Earth-Science Reviews*, 7(2), pp. 67–85, 1971.
[https://doi.org/10.1016/0012-8252\(71\)90082-1](https://doi.org/10.1016/0012-8252(71)90082-1)
- [3] Garakani, A. A., Haeri, S. M., Khosravi, A., Habibagahi, G. "Hydro-mechanical behavior of undisturbed collapsible loessial soils under different stress state conditions", *Engineering Geology*, 195, pp. 28–41, 2015.
<https://doi.org/10.1016/j.enggeo.2015.05.026>
- [4] Sabbaqzade, F., Keramati, M., Moradi Moghaddam, H., Hamidian, P. "Evaluation of the mechanical behaviour of cement-stabilised collapsible soils treated with natural fibres", *Geomechanics and Geoengineering*, 2021.
<https://doi.org/10.1080/17486025.2021.1974579>

- [5] Nokande, S., Khodabandeh, M. A., Hosseini, S. S., Hosseini, S. M. "Collapse potential of oil-contaminated loessial soil (Case study: Golestan, Iran)", *Geotechnical and Geological Engineering*, 38, pp. 255–264, 2020.
<https://doi.org/10.1007/s10706-019-01014-9>
- [6] Khodabandeh, M. A., Nokande, S., Besharatinezhad, A., Sadeghi, B., Hosseini, S. M. "The effect of acidic and alkaline chemical solutions on the behavior of collapsible soils", *Periodica Polytechnica Civil Engineering*, 64(3), pp. 939–950, 2020.
<https://doi.org/10.3311/PPci.15643>
- [7] Estabragh, A. R., Beytollahpour, I., Moradi, M., Javadi, A. A. "Consolidation behavior of two fine-grained soils contaminated by glycerol and ethanol", *Engineering Geology*, 178, pp. 102–108, 2014.
<https://doi.org/10.1016/j.enggeo.2014.05.017>
- [8] Spagnoli, G., Sridharan, A., Oreste, P., Di Matteo, L. "A probabilistic approach for the assessment of the influence of the dielectric constant of pore fluids on the liquid limit of smectite and kaolinite", *Applied Clay Science*, 145, pp. 37–43, 2017.
<https://doi.org/10.1016/j.clay.2017.05.009>
- [9] Trzeźński, J., Williams, D. J., Żbik, M. S. "Can hydrocarbon contamination influence clay soil grain size composition?", *Applied Clay Science*, 109–110, pp. 49–54, 2015.
<https://doi.org/10.1016/j.clay.2015.03.014>
- [10] Ma, F., Wu, B., Zhang, Q., Cui, D., Liu, Q., Peng, C., Li, F., Gu, Q. "An innovative method for the solidification/stabilization of PAHs-contaminated soil using sulfonated oil", *Journal of Hazardous Materials*, 344, pp. 742–748, 2018.
<https://doi.org/10.1016/j.jhazmat.2017.11.015>
- [11] Mneina, A., Soliman, A. M., Ahmed, A., El Naggar, M. H. "Engineering properties of controlled low-strength materials containing treated oil sand waste", *Construction and Building Materials*, 159, pp. 277–285, 2018.
<https://doi.org/10.1016/j.conbuildmat.2017.10.093>
- [12] Polyak, Y. M., Bakina, L. G., Chugunova, M. V., Mayachkina, N. V., Gerasimov, A. O., Bure, V. M. "Effect of remediation strategies on biological activity of oil-contaminated soil - A field study", *International Biodeterioration & Biodegradation*, 126, pp. 57–68, 2018.
<https://doi.org/10.1016/j.ibiod.2017.10.004>
- [13] Rasheed, Z. N., Ahmed, F. R., Jassim, H. M. "Effect of crude oil products on the geotechnical properties of soil", *WIT Transactions on Ecology and the Environment*, 186, pp. 353–361, 2015.
<https://doi.org/10.2495/ESUS140301>
- [14] Ahmadi, M., Ebadi, T., Maknoon, R. "Effects of crude oil contamination on geotechnical properties of sand-kaolinite mixtures", *Engineering Geology*, 283, 106021, 2021.
<https://doi.org/10.1016/j.enggeo.2021.106021>
- [15] Karkush, M. O., Al-Taher, T. A. A. "Geotechnical evaluation of clayey soil contaminated with industrial wastewater", *Archives of Civil Engineering*, 63(1), pp. 47–60, 2017.
<https://doi.org/10.1515/ace-2017-0004>
- [16] Safehian, H., Rajabi, A. M., Ghasemzadeh, H. "Effect of diesel-contamination on geotechnical properties of illite soil", *Engineering Geology*, 241, pp. 55–63, 2018.
<https://doi.org/10.1016/j.enggeo.2018.04.020>
- [17] Khamchichyan M., Hossein Charkhabi A., Tajik M. "Effects of crude oil contamination on geotechnical properties of clayey and sandy soils", *Engineering Geology*, 89, pp. 220–229, 2007.
<https://doi.org/10.1016/j.enggeo.2006.10.009>
- [18] Nasr, A. M. A. "Uplift behavior of vertical piles embedded in oil-contaminated sand", *Journal of Geotechnical and Geoenvironmental Engineering*, 139(1), pp. 162–174, 2013.
[https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000739](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000739)
- [19] ur-Rehman, H., Abduljawwad, S. N., Akram, T., 2007. "Geotechnical behavior of oil contaminated fine-grained soils", *Electronic Journal of Geotechnical Engineering*, 12 A, Paper ID 2007-0720, 2007.
- [20] Karkush, M. O., Kareem, Z. A. "Investigation of the impacts of fuel oil on the geotechnical properties of cohesive soil", *Engineering Journal*, 21(4), pp. 127–137, 2017.
<https://doi.org/10.4186/ej.2017.21.4.127>
- [21] Di Matteo, L., Bigotti, F., Ricco, R. "Compressibility of kaolinitic clay contaminated by ethanol–gasoline blends", *Journal of Geotechnical and Geoenvironmental Engineering*, 137(9), pp. 846–849, 2011.
[https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000494](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000494)
- [22] Kermani M., Ebadi T. "The effect of oil contamination on the geotechnical properties of fine-grained soils", *Soil and Sediment Contamination: An International Journal*, 21(5), pp. 655–671, 2012.
<https://doi.org/10.1080/15320383.2012.672486>
- [23] Khosravi, E., Ghasemzadeh, H., Sabour, M., Yazdani, H. "Geotechnical properties of gas oil-contaminated kaolinite", *Engineering Geology*, 166, pp. 11–16, 2013.
<https://doi.org/10.1016/j.enggeo.2013.08.004>
- [24] Al-Aghbari, M., Dutta, R., Mohamedzeini, Y. "Effect of diesel and gasoline on the properties of sands – a comparative study", *International Journal of Geotechnical Engineering*, 5(1), pp. 61–68, 2011.
<https://doi.org/10.3328/IJGE.2011.05.01.61-68>
- [25] Nasehi, S. A., Uromeihy, A., Nikudel, M. R., Morsali, A. "Influence of gas oil contamination on geotechnical properties of fine and coarse-grained soils", *Geotechnical and Geological Engineering*, 34, pp. 333–345, 2016.
<https://doi.org/10.1007/s10706-015-9948-7>
- [26] Salimnezhad, A., Soltani-Jigheh, H., Soorki, A. A. "Effects of oil contamination and bioremediation on geotechnical properties of highly plastic clayey soil", *Journal of Rock Mechanics and Geotechnical Engineering*, 13(3), pp. 653–670, 2021.
<https://doi.org/10.1016/j.jrmge.2020.11.011>
- [27] Kaya, A., Fang, H.-Y. "Experimental evidence of reduction in attractive and repulsive forces between clay particles permeated with organic liquids", *Canadian Geotechnical Journal*, 42(2), pp. 632–640, 2005.
<https://doi.org/10.1139/t04-099>
- [28] Moavenian, M. H., Yasrobi, S. S. "Volume change behavior of compacted clay due to organic liquids as permeant", *Applied Clay Science*, 39, pp. 60–71, 2008.
<https://doi.org/10.1016/j.clay.2007.04.009>
- [29] Ratnaweera, P., Meegoda, J. N. "Shear strength and stress-strain behavior of contaminated soils", *Geotechnical Testing Journal*, 29, pp. 133–140, 2006.
<https://doi.org/10.1520/GTJ12686>

- [30] Hosseini, F. M. M., Ebadi, T., Eslami, A. "Properties of fine soils contaminated with gas oil", *Materials Testing*, 59(9), pp. 803–810, 2017.
<https://doi.org/10.3139/120.111075>
- [31] ASTM "ASTM D422 Standard test methods for particle-size analysis of soils", ASTM International, West Conshohocken, PA, USA, 2007.
- [32] ASTM "ASTM D2487-11 Standard practice for classification of soils for engineering purposes (Unified soil classification system)", ASTM International, West Conshohocken, PA, USA, 2011.
<https://doi.org/10.1520/D2487-11>
- [33] ASTM "ASTM D4318-00 Standard test methods for liquid limit, plastic limit, and plasticity index of soils", ASTM International, West Conshohocken, PA, USA, 2000.
<https://doi.org/10.1520/D4318-00>
- [34] ASTM "ASTM D2216-10 Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass", ASTM International, West Conshohocken, PA, USA, 2010.
<https://doi.org/10.1520/D2216-10>
- [35] ASTM "ASTM D854-14 Standard test methods for specific gravity of soil solids by water pycnometer", ASTM International, West Conshohocken, PA, USA, 2014.
<https://doi.org/10.1520/D0854-14>
- [36] ASTM "ASTM D7263-09 Standard test methods for laboratory determination of density (unit weight) of soil specimens", ASTM International, West Conshohocken, PA, USA, 2009.
<https://doi.org/10.1520/D7263-09>
- [37] ASTM "ASTM D3080-11 Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions", ASTM International, West Conshohocken, PA, USA, 2011.
- [38] ASTM "ASTM-D2166-06 Standard test method for unconfined compressive strength of cohesive soil", ASTM International, West Conshohocken, PA, USA, 2006.
<https://doi.org/10.1520/D2166-06>
- [39] Das, B. M. "Advanced Soil Mechanics", 4th ed., CRC press, London, UK, 2014.
- [40] Khodary, S. M., Negm, A. M., Tawfik, A. "Geotechnical properties of the soils contaminated with oils, landfill leachate, and fertilizers", *Arabian Journal of Geosciences*, 11(2), Article number: 13, 2018.
<https://doi.org/10.1007/s12517-017-3372-7>
- [41] Mitchell, J. K., Soga, K. "Fundamentals of Soil Behavior", 3rd ed., Wiley, New York, NY, USA, 2005.
<https://doi.org/10.2136/sssaj1976.03615995004000040003x>
- [42] Murray, B. M. "Environmental Chemistry of Soils", Oxford University Press, Oxford, UK, 1994.
- [43] Ghadyani, M., Hamidi, A., Hatambeigi, M. "Triaxial shear behaviour of oil contaminated clays", *European Journal of Environmental and Civil Engineering*, 23(1), pp. 112–135, 2019.
<https://doi.org/10.1080/19648189.2016.1271359>
- [44] Ostovar, M., Ghiassi, R., Mehdizadeh, M. J., Shariatmadari, N. "Effects of crude oil on geotechnical specification of sandy soils", *Soil and Sediment Contamination: An International Journal*, 30(1), pp. 58–73, 2020.
<https://doi.org/10.1080/15320383.2020.1792410>
- [45] Nazari Heris, M., Aghajani, S., Hajjalilue-Bonab, M., Vafaei Molamahmood, H. "Effects of lead and gasoline contamination on geotechnical properties of clayey soils", *Soil and Sediment Contamination: An International Journal*, 29(3), pp. 340–354, 2020.
<https://doi.org/10.1080/15320383.2020.1719973>
- [46] Moore, C. A., Mitchell, J. K. "Electromagnetic forces and soil strength", *Géotechnique*, 24(4), pp. 627–640, 1974.
<https://doi.org/10.1680/geot.1974.24.4.627>
- [47] Sridharan, A., Venkatappa Rao, G. "Shear strength behaviour of saturated clays and the role of the effective stress concept", *Géotechnique*, 29(2), pp. 177–193, 1979.
<https://doi.org/10.1680/geot.1979.29.2.177>