Comparison of Mechanical Behaviors of Loess Based on Two Different Modes of Oil Contamination

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Title Page

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Abstract

In loess oil-production areas, oil leakage not only contaminates the loess, but also changes its mechanical properties. This study aimed to evaluate the effect of diesel oil contamination on mechanical behaviors of loess through extensive laboratory tests conducted on loess with different oil contents (0% to 16%) and dry densities (1.35, 1.45, and 1.55 g/cm³). Two different modes of oil contamination were proposed and applied in compression tests, direct shear tests and unconfined compressive strength tests to study the compressibility and strength characteristics of diesel-contaminated loess. Results show that oil-contamination modes have certain effects on the mechanical behaviors of loess. Under the first mode of oil contamination, compared with clean loess, the compressibility of contaminated loess increases and its unconfined compressive strength and shear strength all decrease. The compression modulus, friction angle, unconfined compressive strength of diesel-contaminated loess using the second mode of oil contamination are larger than those in the first mode of oil contamination at the same oil content and dry density. Understanding these effects of oil pollution can significantly guide soil and environment-remediation activities in oil-production areas.

Key words: Oil-contamination modes; Loess; Mechanical properties; Laboratory tests; Oil contents

1. Introduction

In the process of oil exploitation, transportation, and use, incidences such as pipeline damage, oil-tank accident, coastal-facility discharge, and oil-product leakage occur. Indeed, the problems of soil pollution caused by oil spillage are increasingly becoming serious (Umoren et al. 2019; Wu et al. 2017). Oil leakage causes serious contamination to soil and water, significantly affecting impact the surrounding environment (Wang et al. 2009). Oil spillages cause frequent pollution events to the soil and environment, which is a serious problem of oil-production areas. Oil leakage will not only contaminate the soil, but also change its physical and mechanical behaviors (Abousnina et al. 2019).

The Gulf War in Kuwait has caused the largest oil leakage in history, seriously contaminating water and land at a large scale (Randolph et al. 2018). Concern on the problem of soil contaminated by oil spillage is increasing at home and abroad. AlSanad et al. (1995) conducted a series of laboratory tests to study the influence of crude oil on the mechanical properties of

sand soil in Kuwait during the Gulf War. Subsequently, they considered the aging problem of crude oil contaminated Kuwaiti sand and found that the strength and rigidity of oil-contaminated Kuwaiti sand can be improved by the aging of oil and the decrease of oil content (AlSanad et al. 1997). In the study of Kuwaiti crude oil contamination on the mechanical properties of sand, Shin et al. (1999) studied the shear strength and bearing capacity of sand polluted by crude oil through the direct shear test and the bearing capacity test of strip shallow foundation, and the results showed that crude oil had a significant influence on the shear strength characteristics of sand, and the bearing capacity of foundation was significantly reduced. The above studies on the mechanical properties of Kuwaiti sand contaminated by oil spillage have started an upsurge of domestic and foreign scholastic research on the mechanical properties of oil-contaminated soil.

To evaluate the mechanical properties of oil-contaminated sand, Aiban (1998) conducted a series of laboratory tests and determined the influence of water content and temperature on the mechanical properties of oil-contaminated sand. Chaplin et al. (2002) studied the mechanical properties of crude oil-contaminated sand and concluded that a decrease in strength and permeability, and an increase in compressibility. Al-Aghbari et al. (2013) experimentally researched oil-contaminated sand. They found that the internal friction angle and strength of oil-contaminated sand decreased. With the increase of oil content, the shear strength of sand decreased to some extent as concluded by Abousnina et al. (2015). In the above studies, the change laws of mechanical properties of oil-contaminated sand are relatively consistent.

Furthermore, based on the above studies on the mechanical properties of oil-contaminated sand, some researchers have carried out tests on the mechanical properties of other different types of oil-contaminated soils. Khamsehchiyan et al. (2007) studied the mechanical properties of clay soil polluted by crude oil. Their results indicated a decrease in the maximum dry density, optimum water content, permeability, and strength. Rahman et al. (2010) prepared oil-contaminated soil specimens by mixing air-dried residual soil and oil, and subjected them to laboratory tests. They found that oil contamination led to deterioration of mechanical properties of soil specimens, and that compared with clean residual soil, the maximum dry density, optimal water content, permeability and shear strength decreased. Nazir (2011) conducted unconfined compressive strength tests on overconsolidated clay under natural water content contaminated by crude oil. The results observed that the unconfined compressive strength of overconsolidated clay specimens were lower than those of clean soil specimens. Zheng et al. (2010; 2013) studied the mechanical properties of oil-contaminated silty clay by mixing air-dried silty clay with different oil contents. They reported that the maximum dry density, optimum water content, and permeability of specimens decreased with the increase of pollution degree, and the change of unconfined compressive strength was related to the oil content and water content of the specimens. Safehian et al. (2018) prepared contaminated soil specimens by mixing dried clay and diesel oil, carried out a series of laboratory tests, and found that the mechanical characteristics of clay were relatively complex under diesel pollution. Khosravi et al. (2013) examined contaminated kaolin specimens prepared by mixing dried kaolin with gasoline, and observed a decrease in the internal friction angle of gasoline-contaminated kaolin specimens, an increase in cohesion, and a slight change in shear strength. Xie et al. (2016), Li et al. (2015; 2017) performed unconfined compressive strength tests to study the strength and deformation characteristics of oil-contaminated coastal saline soil specimens by mixing oil with coastal saline soil of known water content. All the above studies indicate that the mechanical properties of different types of soil such as sandy soil, clay, fine-grained soil, kaolin soil, and illite soil are relatively complex.

However, in the above studies, the preparation method of oil-contaminated soil specimen is relatively single, and few studies on the comparative analysis of mechanical properties of soil with different modes of oil contamination have been conducted. In addition, little information

is available for dealing with the evaluation on the mechanical properties of oil-contaminated loess. The oil leakage pollutes the soil in the loess oil-production areas. As a typical organic contaminated soil, oil-spillage pollution is bound to have a certain impact on the mechanical behaviors of loess. Therefore, the mechanical behaviors of oil-contaminated loess under different modes of oil contamination are necessary to compare.

In the current work, the mechanical properties (i.e., compression properties, shear strength characteristics, and compressive strength characteristics) of clean loess and contaminated loess were evaluated through compression tests, direct shear tests, and unconfined compressive strength tests, respectively. The results can serve as a reference for evaluating the geotechnical properties and developing treatment and restoration methods for loess contaminated by oil leakage in the loess oil-production areas.

2. Experimental procedure

2.1 Materials

(1) Soil

The loess used in this study was obtained from the construction site of the slope engineering in the loess oil-production area of Northwest China. The depth of soil collection was 2.5–3.5 m. The main physical parameters of loess are shown in Table 1.

Table 1 Main physical parameters of loess

Soil	Natural water content(%)	Optimum water content (%)	Maximum dry density (g/cm ³)	liquid limit (%)	plastic limit (%)
Loess	12	19.6	1.77	32.18	20.51

(2) Oil

In this study, diesel oil was selected as a typical representative of petroleum oil, which was obtained from Sinopec. Compared with other light oil fluids such as gasoline, kerosene, engine oil, and lubricating oil, diesel oil has poor flammability and low solubility in water, and it is not volatile. Therefore, the laboratory tests are relatively safe. Viscosity of diesel oil is also lower than that of other light oil fluids, and it is generally 3–5 times higher than that of water. The physical properties of diesel oil at room temperature of 20 °C are shown in Table 2.

Table 2 Basic parameters of diesel

Oil	Density (g/cm ³)	Viscosity coefficient (mm ² /s)	Surface tension (mN/m)	PH	Freezing point (°C)
Diesel	0.846	3.9	1.77	7.4	-20

2.2 Specimen preparation

The process of oil contamination to loess may be long in nature, and it gradually reaches a certain oil-bearing state in loess under the influence of various factors. Loess has complex characteristics in the presence of diesel oil under different contamination modes. To study the effect of mechanical properties of diesel-contaminated loess, natural water content ($w=12\%$), different oil contents ($n=0\%, 2\%, 4\%, 8\%, 12\%$, and 16%), and different dry densities ($\rho_d=1.35, 1.45$, and 1.55 g/cm^3) were considered in this research. Oil content (n) refers to the percentage of diesel oil in a unit mass of loess, which is the ratio of the mass of diesel to the mass of dry loess (Kermani et al. 2012).

However, different specimen preparation methods have certain influences on the structure of loess and lead to various mechanical properties (Li et al. 2014). Different specimen preparation methods of diesel-contaminated loess represent different modes of oil contamination. In the present research, two different modes of diesel oil contamination were proposed and applied in compression tests, direct shear tests, and unconfined compressive strength tests. The specimen preparation methods of contaminated loess under two different modes of oil contamination are shown in Fig. 1.

Fig. 1(a) presents the specimen preparation method under the first diesel oil contamination mode. Air-dried clean loess is initially passed through a sieve and then dried at the temperature of 105 °C in an oven for 24 h. Diesel oil is added into a predetermined quantity of dried loess to ensure that the oil contents of contaminated loess specimens range from 0% to 16%, and that the mixture of diesel oil and loess come to equilibrium in a closed container at room temperature (20 °C) for 7 days. Then, water is sprayed onto a predetermined quantity of diesel-contaminated loess to ensure that the water content of diesel-contaminated loess is 12% (natural water content). The sample is mixed until homogeneity in a closed container at room temperature (20 °C) for 24 h. Finally, the diesel-contaminated loess specimens are molded and tested.

The specimen preparation method under the second mode of oil contamination is shown in Fig. 1(b). Air-dried clean loess is passed through a sieve. The natural water content (12%) is ensured by adding water to quantitative clean loess and allowing it to stand for 24 h to achieve homogeneity at room temperature (20 °C). A predetermined quantity of diesel oil is then added to loess to prepare contaminated specimens with different oil contents (0% to 16%). The diesel-contaminated specimens are placed in a closed container and allow to stand for 7 days at room temperature (20 °C). During this period, the container should be turned upside down to ensure the uniform mixing of diesel oil and loess. Finally, the diesel-contaminated loess specimens are molded and tested.

Fig. 1 Specimen preparation methods of loess under two different modes of oil contamination

187 2.3 Methods

188 To compare and analyze the mechanical properties of loess under the two different modes of
 189 oil contamination, compression tests, direct shear tests, and unconfined compressive strength
 190 tests were conducted on clean specimens and contaminated specimens according to SL237-
 191 2019(2019). Compression tests were conducted on loess with different oil contents and dry
 192 densities under two different modes of oil contamination, and the specimen size was $\Phi 79.8$
 193 mm $\times$ 20 mm (SL237-015-2019). Vertical loads of 50, 100, 200, 400, and 800 kPa were
 194 selected, and the deformation of samples under each level of load were recorded. Direct shear
 195 tests were performed in a shear box at a constant shear rate of 1 mm/min, and the specimen
 196 size was $\Phi 61.8$ mm $\times$ 20 mm (SL237-021-2019). Each test was performed on four different
 197 normal stresses of 100, 200, 300, and 400 kPa. According to SL237-020-2019, a series of
 198 unconfined compressive strength tests were conducted on loess specimens, and the specimen
 199 size was $\Phi 39.1$ mm $\times$ 80 mm. The coefficient of measuring ring was 1.0993 N/0.01 mm, and
 200 the rate was 0.368 mm / min. A deformation of 0.1 mm was taken as the interval to read the
 201 stress value, and the maximum axial stress was taken as the unconfined compressive strength
 202 of diesel-contaminated loess.

203 3. Results and Discussion

204 3.1 Compression tests

205 Soil compressibility is often evaluated with the compression coefficient (α_v) and compression
 206 modulus (E_s) through the following equations.

$$207 \quad \alpha_v = \frac{e_i - e_{i+1}}{P_{i+1} - P_i} \quad (1)$$

$$208 \quad E_s = \frac{1 + e_0}{\alpha_v} \quad (2)$$

209 where e_0 is the initial void ratio of the specimen, e_i is the void ratio after compression
 210 stabilization under vertical load (P_i), and e_{i+1} is the void ratio after compression stabilization
 211 under vertical load (P_{i+1}).

212 A series of one-dimensional compression tests were performed on clean and diesel-
 213 contaminated loess to evaluate the effect of diesel contamination on the compressibility of loess
 214 with the increase of oil content under two different modes of oil contamination. Compared with
 215 water, oil has different properties as a non-aqueous phase fluid (Safehian et al. 2018). Under
 216 the condition of two different modes of oil contamination, the compression coefficient and
 217 compression modulus of diesel-contaminated loess with different oil contents were determined,
 218 and results are shown in Figs. 2 and 3, respectively.

219 Under the first mode of oil contamination, it can be concluded from Fig. 2(a) that the
 220 compression coefficient of diesel-contaminated loess initially increases and then decreases
 221 gradually with increasing oil content at the same dry density. When the oil content is about 4%,
 222 it reaches the maximum value, and the compression coefficient increases from 0.13 MPa^{-1} to
 223 0.32 MPa^{-1} by adding 146% at $\rho_d = 1.35 \text{ g/cm}^3$. Diesel oil spillage significantly affected the
 224 compression coefficient of loess when the dry density of loess specimen is low. Owing to the
 225 lubrication of diesel, the compressibility of loess could be increased, as reported by Khosravi
 226 et al. (2013). Then, with increasing oil content ($n > 4\%$), the compression coefficient of diesel-
 227 contaminated loess decreases. In these tests, the compression coefficient of loess initially

increases and then decreases with the increase of oil content, consistent with the conclusion of some researchers (Shin et al. 1999; Singh et al. 2009). Fig. 2(b) indicates that the compression modulus of diesel-contaminated loess sharply decreases initially with the increase of oil content and then increases gradually ($n > 4\%$). Moreover, the trend of increasing amplitude is relatively slow. The compressive modulus of clean loess is larger than those of contaminated loess, which it can be concluded that diesel oil increases the ease of compression under this condition. Under the second mode of oil contamination, Fig. 3(a) shows that the compression coefficient of loess firstly decreases, and then increases before gradually decreasing again with the increase of oil content. The fluctuation in compression modulus of loess at $\rho_d = 1.35 \text{ g/cm}^3$ is larger than that of loess with $\rho_d = 1.45$ and 1.55 g/cm^3 . Compared with clean loess, the compression coefficient of diesel-contaminated loess fluctuates with increasing oil content. In Fig. 3(b), it can be also observed that the compression modulus of diesel-contaminated loess initially increases and then decreases with the increase of oil content before increasing again ($n > 8\%$). The variation in compression modulus trend of diesel-contaminated loess is contrary to the compression coefficient trend at the same condition. Comparative analysis of Figs. 2 and 3 reveals that the compression coefficient of oil-contaminated loess initially increases and then decreases with increasing oil content under the first mode of oil contamination. It reaches the maximum value with oil content approaching 4% at three different dry densities. Compared with the first mode of oil contamination, the compression coefficient of diesel-contaminated loess firstly decreases, and then increases before decreasing again with the increase of oil content under the second mode of oil contamination. It reaches the minimum with the oil content approaching 4% at the same dry density. Based on comparative analysis of the above studies, it can be observed that the compression characteristics of diesel-contaminated loess are not only related to the oil content, but also to the oil contamination mode.

Fig. 2 Compression characteristics of diesel-contaminated loess under the first mode of oil contamination

Fig. 3 Compression characteristics of diesel-contaminated loess under the second mode of oil contamination

3.2 Direct shear tests

Direct shear tests were conducted on clean loess and contaminated loess by using the cohesion and frictional angle to determine the shear strength characteristics of diesel-contaminated loess according to the Mohr-Coulomb criterion. To study the shear strength characteristics of loess contaminated by diesel oil spillage, different diesel oil contents, and the both modes of oil contamination were considered in these tests. Figs. 4 and 5 show the shear strength characteristics of loess with the increase of oil content under the two different modes of oil contamination respectively.

Under the first mode of oil contamination, the influence of diesel oil on the cohesion of loess is presented in Fig. 4(a). With the increasing oil content, the cohesion of contaminated loess initially decreases and then increases before decreasing at the same dry density. At three different dry densities ($\rho_d = 1.35, 1.45$, and 1.55 g/cm^3), diesel oil ($n=16\%$) was added to the clean loess specimens to reduce the cohesion value of loess by almost 60.7%, 57.6%, and 58.6% respectively. Owing to the pollution caused by diesel oil leakage, the cohesion values of contaminated loess with the three different dry densities decreased by more than half compared with clean loess. Decreased dielectric constant of the pore fluid in contaminated loess results in decreased cohesive value, as reported by Ratnaweera et al. (2006). Fig. 4(b) reveals the changes in friction angle of contaminated loess with increasing diesel oil content. The friction angles of contaminated loess decrease to the minimum at three different dry densities when the oil content is in a low level ($2\% < n < 4\%$) and then basically increase with increasing oil content ($n > 4\%$). The friction angles of contaminated loess with different oil contents are smaller than those of clean loess under the same condition.

Fig. 4 Direct shear test of diesel-contaminated loess under the first mode of oil contamination

Fig. 5 Direct shear test of diesel-contaminated loess under the second mode of oil contamination

Under the second mode of oil contamination, the influence of diesel oil on the cohesion of loess is presented in Fig. 5(a). It illustrates that the cohesion of loess reduces with the increase of diesel oil content at the same dry density. This finding shows no difference with the result of Safehian et al. (2018). Surrounding the soil particles was a double layer, whose thickness is sensitive to the dielectric constant of the pore fluid (Nasehi et al. 2016). Compared with water, diesel oil has a lower dielectric constant, and when it is added to soil, the dielectric constant of pore fluid decreases. A solvent with a lower dielectric constant reduces the thickness of the double-layer of the negatively charged clay (Murray et al. 1994). With the increase of diesel oil in the pore fluid of loess particles, the content of water decreases. Therefore, the double-layer's thickness of loess decreases, as shown in Fig. 6, thereby reducing the cohesion of contaminated loess. Fig. 5(b) shows the effect of diesel oil on the friction angle of loess. The friction angle of contaminated loess became larger than that of clean loess at the same dry density with the change in oil content.

It can be illustrated from Figs. 4 and 5 that the shear strength characteristics varied due to the different modes of oil contamination. Under the first mode of oil contamination, the shear strength of contaminated loess is lower than that of clean loess, for both the cohesion and friction angle of contaminated loess decrease with the increasing oil content. The friction angle of contaminated loess is larger than that of clean loess under the second mode of oil contamination, but it presents the opposite trend under the first mode of oil contamination.

Fig. 6 Schematic diagram of the effect of diesel oil on the thickness of double layer

3.3 Unconfined compressive strength tests

The effect of different diesel oil contents and modes of oil contamination on the compressive strength characteristics of loess was examined through unconfined compressive strength tests.

The relationships between the unconfined compressive strength of contaminated loess and diesel oil are presented in Figs. 7 and 8 under the two different modes of oil contamination. Under the first mode of oil contamination, Fig. 7 illustrates that diesel-contaminated loess has a larger unconfined compressive strength with the higher dry density at the same condition. With the increase of oil content, the unconfined compressive strength of diesel-contaminated loess all initially decreases and then slowly increases at three different dry densities ($\rho_d=1.35$, 1.45, and 1.55 g/cm³), reaching the minimum value with oil content approaching 5%. At $n=4\%$ oil content, the unconfined compressive strength of contaminated loess decreases the most at $\rho_d=1.55$ g/cm³, a 43% reduction, which is nearly half than that of clean loess. By comparing the contaminated loess specimen ($n=4\%$) with $\rho_d=1.55$ g/cm³, the maximum reduction values of unconfined compressive strength are 23.5% and 42.3% at $\rho_d=1.35$ and 1.45 g/cm³, respectively. Furthermore, the unconfined compressive strength of contaminated loess decreased in comparison with clean loess, because this sample was contaminated by diesel oil leakages, which changed its structure. These results are consistent with those of the compression test and direct shear test. With increasing oil content, the compression modulus, cohesion, and unconfined compressive strength of diesel-contaminated loess have the same trends at the same dry density, indicating that diesel oil spillage decreases the loess strength, as previously reported (Murray et al. 1994; Khosravi et al. 2013; Safedian et al. 2018). The results of the above three tests further show that most of the decline occurred in loess with low diesel oil content.

Fig. 7 Unconfined compressive strength of diesel-contaminated loess under the first mode of oil contamination

Under the second mode of oil contamination, Fig. 8 shows that with increasing oil content, the unconfined compressive strength of loess initially increases ($n < 2\%$) and then reduces before slowly increasing again ($n > 8\%$). The unconfined compressive strength value reaches the maximum value with oil content approaching 2% at the same dry density. Compared with clean loess, the unconfined compressive strength of oil-contaminated loess is greater, except for several oil contents. In these tests of specimen preparation method, clean loess is initially combined with water and then added with diesel oil to prepare contaminated loess. When the oil content of loess is in a low level, diesel oil fills the pores of soil particles, and its viscosity is greater than that of pore water among specimen particles, thereby increasing the viscosity of soil particles (Khomehchiyan et al. 2007). Accordingly, the cementation ability of contaminated loess is strengthened, and the unconfined compressive strength increases with low oil content. With increasing content of oil, it gradually fills the pores around soil particles. At this time, the viscosity of diesel oil is far less than its own lubrication effect, and the relative sliding of soil particles becomes relatively easy, which reduces the unconfined compressive strength of diesel-contaminated loess.

Fig. 8 Unconfined compressive strength of diesel-contaminated loess under the second mode of oil contamination

The contaminated loess specimens used in this tests were prepared by mixing soils with diesel oil using different contamination methods as above mentioned, which transformed the structure of loess. Comparison of Figs. 7 and 8 reveals that the unconfined compressive strength of diesel-contaminated loess in the second mode of oil contamination is larger than that in the first mode of oil contamination at the same condition. Under the second mode of oil contamination, loess is initially combined with water, and a double-layer formed around the soil particles. The water molecules close to the surface of the soil particles are greatly affected by the electric field force. Consequently, strong bound water formed on the surface of the soil particles, and the arrangement of the water molecules was approximately fixed; they gradually lost their liquid characteristics and approximated solid characteristics (Zhang et al. 2018), so the compressive strength of contaminated loess is relatively high. However, under the first mode of oil contamination, diesel oil combines with soil particles and initially surrounds the surface of soil particles, thereby preventing water molecules from combining with soil particles to form a double electric layer. Therefore, the unconfined compressive strength of diesel-contaminated loess greatly varies due to different modes of oil contamination.

4. Conclusions

A series of extensive laboratory tests were carried out on clean and diesel-contaminated loess to compare and analyze the effect of oil contents and dry densities on mechanical behaviors of diesel-contaminated loess by using two different modes of oil contamination. The conclusions drawn are as follows.

(1) The compression properties, shear strength characteristics, and compressive strength characteristics of loess are greatly affected by different modes of oil contamination, which leads to various mechanical behaviors of loess.

(2) Under the first mode of oil contamination, with increasing oil content, the changing law of compression modulus, cohesion, and unconfined compressive strength of diesel-contaminated loess are nearly identical at the same density. Due to diesel oil spillage, the compressibility of loess increases and its unconfined compressive strength and shear strength decrease. Most changes occur in loess with low oil content.

(3) By comparing the test results of the two different modes of oil contamination, it can be concluded that the compression modulus, friction angle, and unconfined compressive strength of diesel-contaminated loess subjected to the second mode of oil contamination are larger than those subjected to the first mode of oil contamination at the same oil content and dry density.

Data Availability

All the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest.

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