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The impact of organic pollutants on the geotechnical environmental properties of soils in the western region of Bandar Abbas, West of Iran

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Abstract The presence of petrochemicals in the western region of Bandar Abbas has been a significant contributor to oil pollution. Most of the factories and refineries in this area are situated on marl formations. Marl soil exhibits favorable characteristics in terms of load-bearing capacity and resistance to dry conditions; however, it becomes turbid when in contact with water. The high sensitivity of marl soils to climatic conditions poses challenges for engineering projects. Petroleum pollutants such as gasoline and crude oil often leak due to factors like tank ruptures, aging pipelines, and industrial accidents. These pollutants alter the geotechnical properties of the soil, thereby affecting slope stability and load-bearing capacity.In this study, varying amounts (0, 2, 5, 10, 15, 20, and 30% by dry weight) of diesel and crude oil were added to marl soil. The results indicated that pH and electrical conductivity (EC) did not significantly change in samples contaminated with either diesel or crude oil. However, as the level of contamination increased, the soil's compaction coefficient and settlement potential rose by 32% and 27%, respectively. The presence of oil pollutants was found to improve the stability of marl soil against sedimentation. Microstructural monitoring using X-ray diffraction (XRD) analysis revealed that increased concentrations of diesel and crude oil did not significantly alter the main peaks of the clay minerals.

Keywords: *soil pollution, organic pollutants, soil characteristic*

Introduction

To utilize natural resources and sustain life on Earth, humans have continuously introduced various pollutants into the environment, both intentionally and unintentionally (Yu et al., 2020). Human activities have led to the contamination of not only air but also soil. Oil pollution, in particular, can arise from diverse incidents such as oil tanker accidents, damaged pipelines during drilling, and anthropogenic events, including those that occurred during the Persian Gulf War (Wang, 2020). Petroleum hydrocarbons present in soil can infiltrate the food chain or reach groundwater, thereby posing serious threats to human health and the environment (Tajik, 2013). Contamination of soil with petroleum hydrocarbons is widely recognized as a major environmental crisis. A branch of geotechnical engineering investigates how soil mineralogy and the nature of pore fluids affect the structural and mechanical behavior of soils (Shahidi et al., 2015; Sen, 2016). These properties are inherently linked to the soil's composition and texture.One key factor influencing soil behavior is the type of pore fluid present (Seluki, 2018). Changes in pore fluid chemistry can lead to variations in soil permeability, consolidation, and settlement behavior (Ahmadi, 2010). Pollution from petroleum-based products not only contaminates groundwater but also holds significant implications for environmental geotechnics (Bojnordi et al., 2020). The interaction between soil and pollutants can alter the soil's strength parameters, potentially reducing the bearing capacity of foundations and causing uneven settlement in infrastructure associated with oil facilities (Arifuzman et al., 2017).

Marl is a problematic soil type that exists globally, including along the northern shores of the Persian Gulf, as well as in parts of Europe and Canada. In Iran, it is prevalent in both central and rural regions and has been documented in the Persian Gulf, East Azarbaijan Province, Hormozgan Province, and Qeshm Island (Ohadi et al., 2015). In these areas, widespread soil issues have been observed, such as erosion, cracking of foundations and slopes, tensile cracks, and instability of natural and artificial slopes. Reports also mention severe cases of soil leaching (Rajaei, 2017). Marl soil is generally composed of 20–65% clay and carbonate. The clay fraction often contains polygorskite and sepiolite (Safhian et al., 2018), which are key contributors to soil swelling and reduced stability. These minerals are typically interconnected with other clay minerals and non-silicate constituents such as carbonates and sulfates (Rahimi et al., 2014). While marl soil possesses desirable load-bearing and dry-condition resistance properties in its natural, stone-like state, its structure is highly sensitive to moisture. Exposure to water significantly weakens its structure and turns it turbid (Salimnejad et al., 2020).

According to oil reserve statistics as of 2022, Iran ranks third globally—after Venezuela and Saudi Arabia—with approximately 14.98% of the world's proven oil reserves (Zhang et al., 2020). Additionally, as reported by the Oil and Energy Information Network (Shana) in 2023, Iran annually produces over 35 million tons of petrochemical products and hosts more than 14,000 kilometers of oil and gas pipelines, 3,800 petrol stations, and 11,000 oil tankers. These extensive operations make Iranian soils, particularly those near petrochemical zones, highly vulnerable to petroleum pollution.

The west of Bandar Abbas, home to major petrochemical industries and oil refineries, is situated on marl formations. This geographical overlap highlights the urgent need to assess the geotechnical and environmental responses of marl soil in this region. Therefore, the present study aims to investigate the impact of organic pollutants on the geotechnical properties of marl soil in the western part of Bandar Abbas.

Materials and methods

The soil used in this research was marl soil collected from the western region of Bandar Abbas, specifically around the railway station and the northern shoreline of the Persian Gulf (coordinates: 561503.3 53.2′16°27). This area has reported instances of soil erosion, subsoil cracking, slope failure, and tensile cracking on roads. Marl soil naturally occurs in a rocky state and offers good bearing capacity and durability in dry conditions. To minimize experimental error, samples were prepared under consistent conditions. For each testing stage, the soil was dried in a greenhouse at 80 °C for 24 hours. Diesel and crude oil were used as pollutants, and the soil samples were artificially contaminated accordingly.

Due to the location of Iran's main petrochemical refinery in this area and its operation atop marl deposits, studying the geotechnical and environmental behavior of the region was deemed necessary. As crude oil is the base material for petroleum products, it is the most common source of soil pollution. The following steps were taken to artificially contaminate the soil:

1. Measuring the required amount of dry soil
2. Weighing diesel and crude oil according to target contamination levels (2%, 5%, 10%, 15%, 20%, and 30% of soil dry weight)
3. Spraying pollutants uniformly over the soil to ensure homogeneity

After thorough mixing, the contaminated soils were transferred to clean nylon bags and weighed for control.

Atterberg Limit Test

The Atterberg limit test was conducted to assess the plasticity of contaminated marl soil. Due to challenges in performing the test directly on oil-contaminated samples, the soils were first dried at 80 °C for 24 hours prior to testing. This helped eliminate surface oil layers and ensure proper water interaction. The test involved adding specific amounts of diesel or crude oil before the drying process, with evaporated volumes calculated separately for each contamination level.

Permeability Testing

To measure the permeability coefficient, a falling head permeameter was designed and built at the Engineering Faculty of Hormozgan University, following ASTM D2434-87 standards. The device included a circular PVC chamber (10 × 5 cm) to resist corrosion. Permeability tests were performed on natural and contaminated soils with varying levels of diesel exposure.

Soil samples were contaminated with diesel or crude oil at 0%, 2%, 5%, 10%, 15%, 20%, and 30% of dry weight. Each sample was compacted in four layers at optimum moisture content and tested using the constructed permeameter. Filter paper and marble were placed at both ends of the chamber to maintain structural integrity. Permeability changes were assessed after a 14-day period.

Consolidation Test

The consolidation behavior of contaminated marl soil was evaluated using ASTM D2435-90 standards, with a measurement accuracy of 0.01 mm. The samples were prepared in three layers, and vertical deformation data were recorded at regular intervals. The test aimed to observe changes in compressibility under different levels of oil contamination.

pH Test

pH is a critical chemical property in contaminated soils. pH levels were measured according to ASTM D4972. A 1:4 soil-to-water ratio was used (10 g soil + 40 g distilled water), and samples were shaken in a vibrator for 2 hours. After 24 hours of resting, they were re-shaken for another 2 hours to ensure full ion exchange. pH values were recorded using a Lovibond PH110 meter.

Electrical Conductivity (EC) Test

Electrical conductivity was measured to determine the concentration of water-soluble ions. The test followed the method described by Seluki et al. (2009) using saturated soil extracts. The preparation steps mirrored those of the pH test. Conductivity values were recorded in millisiemens per centimeter using a digital EC meter.

X-ray Diffraction (XRD) Analysis

XRD analysis was performed to evaluate changes in mineralogy. Samples were first dried at 80 °C for 24 hours. Then, 10%, 15%, and 30% diesel-contaminated soils were stored in sealed, dark bags for 14 days before undergoing another 24-hour drying cycle.

Powdered samples were placed into flat sample holders using a solvent to ensure even distribution. XRD patterns were obtained using an advanced Bruker D-series diffractometer and analyzed with X'Pert 3 software.

Scanning Electron Microscopy (SEM)

SEM imaging was used to investigate soil microstructure and particle arrangement. A TESCAN-Vega 3 microscope was employed. Samples were coated with a 10 nm gold layer to enhance conductivity and resolution. Only a thin, uniform powder layer was used.

SEM sample preparation involved cleaning, drying, mounting, and establishing electrical contacts. All SEM and XRD samples were fully dried and ground according to the standardized procedure described earlier.

Results and discussion

The Impact of Oil Pollutants on Soil pH

Petroleum hydrocarbons have the potential to increase the total organic carbon content in soil and can also influence pH levels. In this study, only minimal variations in pH were observed in diesel-contaminated samples compared to clean soil. These changes were not statistically significant but can be attributed to the nearly neutral nature of diesel and crude oil, which have pH values of approximately 7.54 and 7.52, respectively.

When these hydrocarbons came into contact with the soil, they slightly altered the pH level, following an increasing trend (Taghvaian et al., 2007). This slight rise in pH is commonly associated with the accumulation of exchangeable base cations, which occurs as a result of reduced exchange acidity and changes in the effective cation exchange capacity (CEC) of the soil. Such mechanisms may explain the observed increase in pH in oil-contaminated soils.

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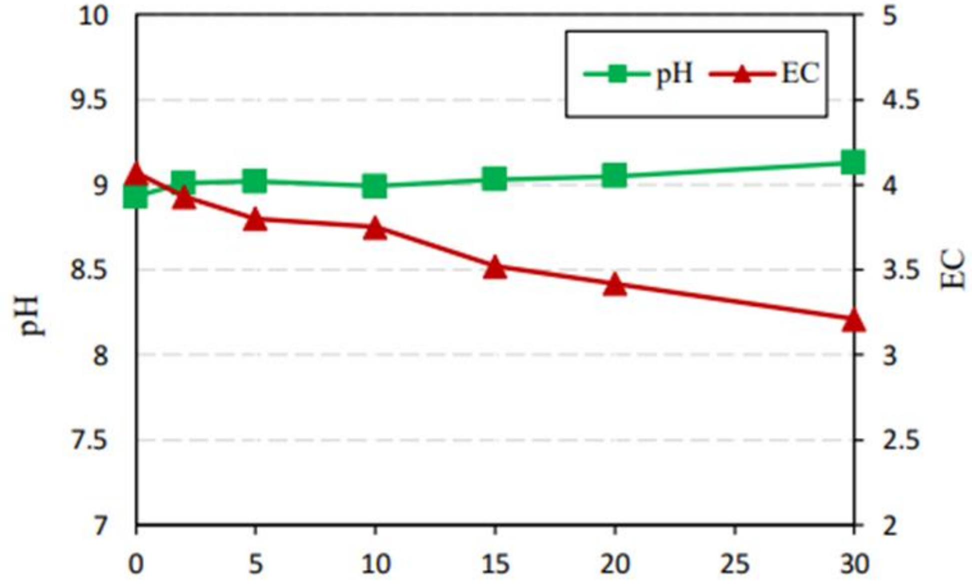

Figure 1: Variation curves of pH and EC at different percentages of diesel.

The Impact of Oil Pollutant Changes on EC

The incorporation of organic compounds into the soil can influence its dielectric properties and, consequently, reduce its electrical conductivity (EC). In this study, the EC of soil was observed to decrease in the presence of petroleum pollutants—by approximately 21% for diesel contamination and up to 33% for crude oil. This decline is primarily attributed to the dielectric characteristics of the contaminants.

At 20 °C, the dielectric constants of water, diesel, and oil are approximately 80, 2.1, and 2.3, respectively. Similarly, the EC values for water, diesel, and oil are reported to be around 44, 1.1, and 10.9 mS/cm, respectively. Because diesel and crude oil are poor conductors of electricity, their presence in soil reduces the number of free ions capable of carrying electrical current.

As contamination levels increased—particularly at 15% diesel—the soil's EC values decreased slightly, ranging from 3.52 to 3.21 mS/cm. Despite these reductions, the overall trend indicated that electrical conductivity did not decrease significantly beyond a certain pollution threshold, likely due to the insulating nature of petroleum hydrocarbons.

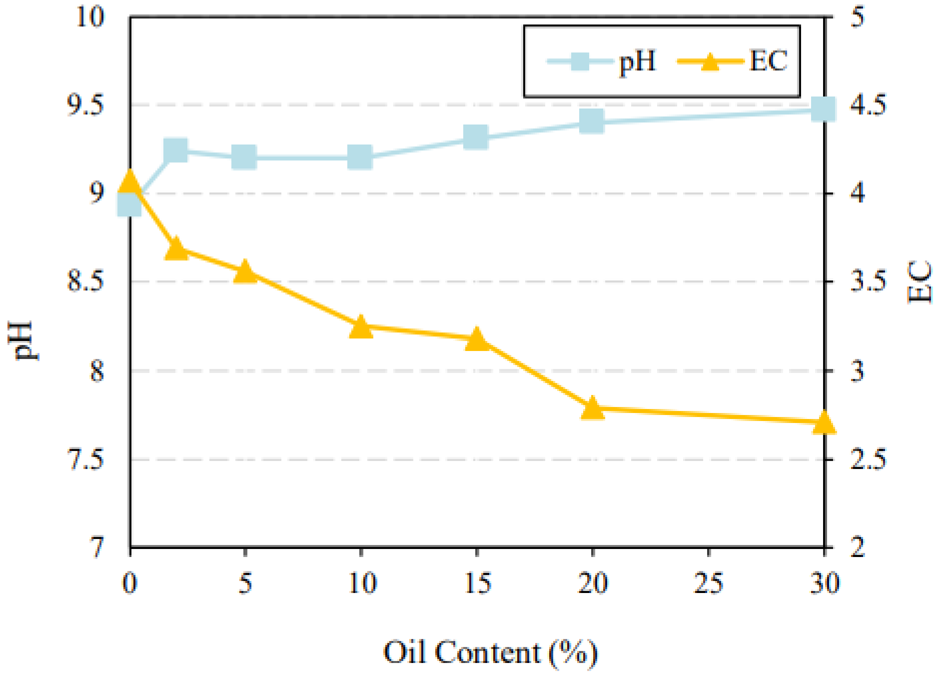

Figure 2. The curve of changes in pH and EC at different percentages of crude oil.

Impact of Oil Pollution on XRD Analysis

In coarse-grained soils, engineering behavior can often be associated with the mineralogical composition of the particles. However, in fine-grained soils, understanding mineralogy becomes essential for interpreting their mechanical and microstructural behavior (Young and Ohaidi, 2003). X-ray diffraction (XRD) analysis is widely used to evaluate the mineral structure of soils and assess microstructural changes.

In this study, XRD analyses were conducted on uncontaminated marl soil and marl samples contaminated with varying percentages of diesel to investigate changes at the microstructural level. The natural marl soil primarily contained clay minerals such as palygorskite, kaolinite, and sepiolite. Non-clay minerals included quartz, calcite, and dolomite.

XRD analyses of diesel-contaminated marl were performed at contamination levels of 10%, 15%, and 30% by dry weight. The first significant diffraction peak corresponded to quartz, located at $2\theta \approx 33.3°$, with intensity values of 229, 331, and 372 for the 10%, 15%, and 30% diesel samples, respectively.

The primary peaks related to the carbonate minerals—calcite and dolomite—were observed at approximately $2\theta \approx 3.02°$ and $2\theta \approx 2.898°$, respectively. For calcite, the corresponding peak intensities were recorded as 345, 364, and 341 for the 10%, 15%, and 30% diesel-contaminated soils. For dolomite, the intensities were 74, 92, and 72, respectively.

Additionally, in the natural marl soil, the intensity values for dolomite, sepiolite, and kaolinite were measured as 78, 74, and 53, respectively. These results indicate that increasing diesel content did not lead to significant shifts or deformations in the major diffraction peaks, suggesting that the crystalline structure of the primary clay and non-clay minerals remained largely unchanged.

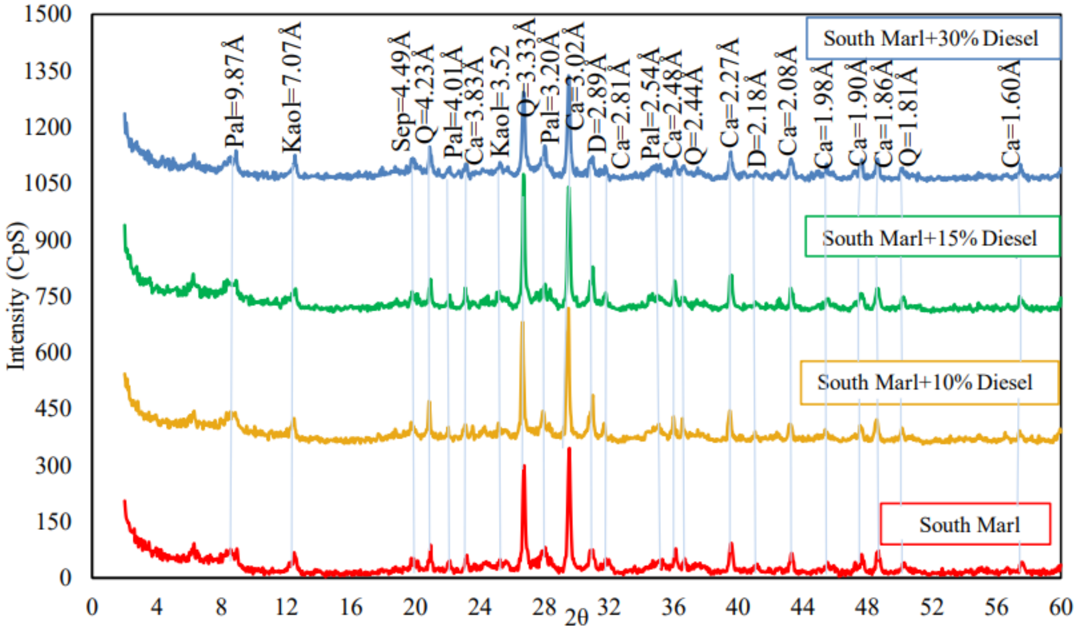

Figure 3. X-ray diffraction analysis of marl soil from the south and marl soil containing varying percentages of diesel: Sep: Sepiolite, Pal: Palygorskite, Kaol: Kaolinite, D: Dolomite, Q: Quartz, Ca: Calcite.

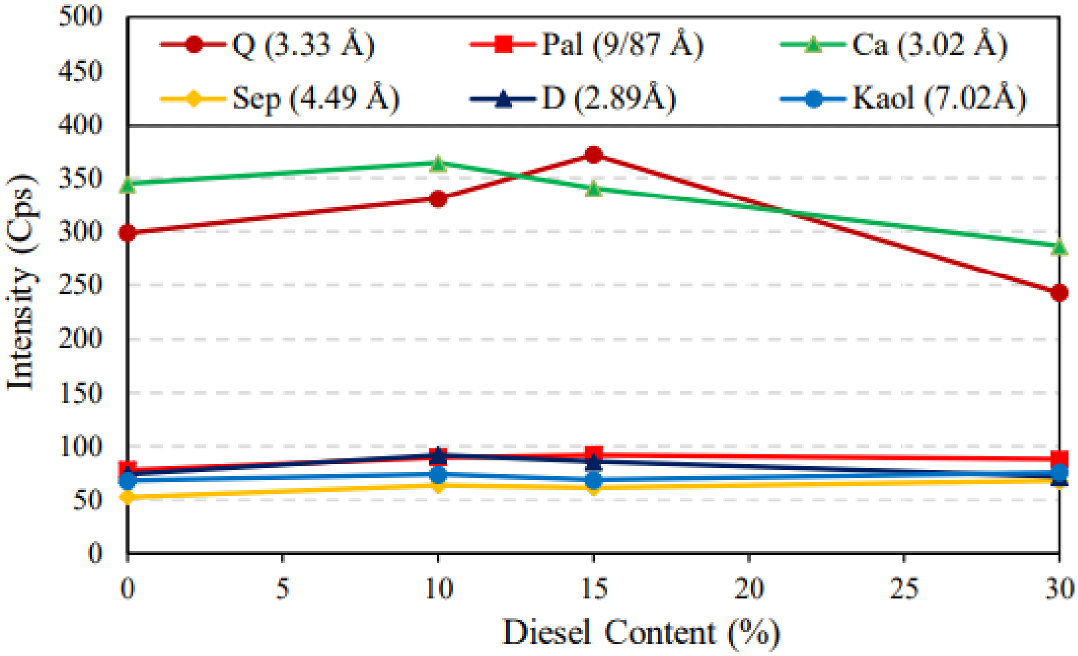

Figure 4. Analysis of X-ray diffraction of marl soil from the south and marl soil containing varying percentages of diesel: Sep: Sepiolite, Pal: Palygorskite, Kaol: Kaolinite, D: Dolomite, Q: Quartz, Ca: Calcite.

Scanning electron microscopy (SEM) was employed to examine microstructural changes in clay samples exposed to varying concentrations of diesel oil. The SEM images of the natural (uncontaminated) soil revealed a layered and irregular morphology, typical of marl soil.

As diesel content increased—particularly at the 15% contamination level—the soil structure exhibited visible deformation and bending. These observations confirmed that diesel contamination influenced the microstructure of the soil. Specifically, with higher diesel concentrations, the soil developed a denser and more complex internal arrangement.

The emergence of complex structures and fossil-like formations in diesel-contaminated samples is likely linked to the reduced dielectric constant of diesel (approximately 2.1), which is significantly lower than that of water. This reduction in dielectric constant causes a decrease in the thickness of the diffuse double layer surrounding clay particles, thereby allowing particles to move closer together.

Previous studies have shown that certain organic compounds—particularly long-chain hydrocarbons—can be strongly adsorbed by clay surfaces, promoting particle aggregation. This process transforms a dispersed clay structure into a more compact and interconnected microstructure. The findings from SEM imaging in this study are consistent with these mechanisms.

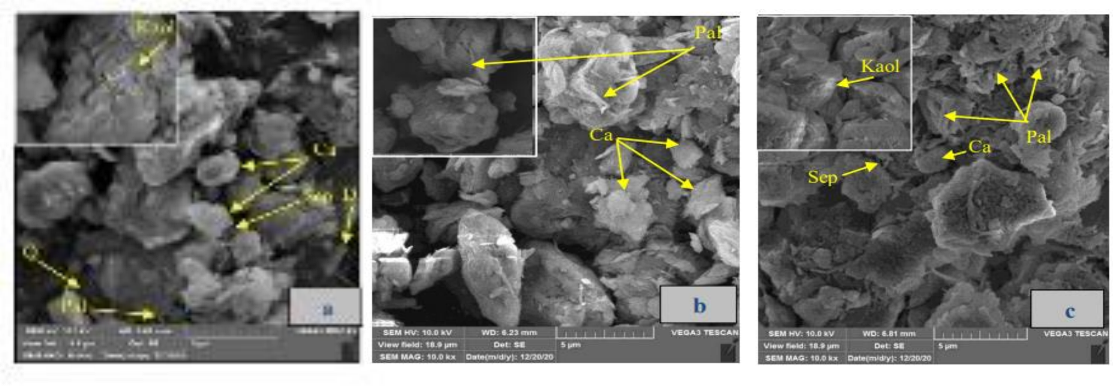

Figure 5. a) Scanning electron microscopy image of marl soil from the south, b) Scanning electron microscopy image of marl soil from the south containing 92% diesel, c) Scanning electron microscopy image of soil containing 39% diesel.

The impact of oil pollutants on Atterberg limits

As the percentage of petroleum contamination increased in the soil samples, a significant rise in the liquid limit (LL) was observed. The natural marl soil in the southern region had an LL of 53%. Upon contamination with 2% to 15% diesel (by dry weight), the LL increased from 63.9% to 69.16%, and reached a maximum of 75% at 30% diesel content—representing an overall increase of 22 units.

Similarly, the plastic limit (PL) showed a notable rise. For uncontaminated marl soil, the PL was 28%. With increasing diesel contamination levels of 2%, 15%, and 30%, the PL values rose to 33%, 39.5%, and 45%, respectively—reflecting an increase of 17 units. These changes are generally explained by variations in the diffuse double layer thickness surrounding clay particles (Sen et al., 2016). The liquid limit, which represents the maximum amount of water retained around a particle before it transitions to a liquid-like state, is closely related to the thickness of this layer (Tongwei Zhang et al., 2019).

Organic fluids that enter the soil environment can be categorized into two distinct types:

- **Water-soluble fluids** (e.g., ethylene glycol, propylene glycol), which substantially alter the chemical composition of pore fluids.
- **Water-insoluble fluids** (e.g., crude oil, diesel, kerosene), whose impact is primarily physical—affecting parameters like viscosity and specific gravity rather than pore fluid chemistry.

The observed increases in LL and PL in this study are attributed mainly to the higher viscosity of oil-based contaminants. For example, at 20 °C, the kinematic viscosity of water is about 1 centistoke (cSt), while diesel and crude oil have viscosities of approximately 4.35 cSt and 3.8 cSt, respectively—nearly four times that of water.

The elevated viscosity of petroleum fluids increases interparticle adhesion among clay particles. As the soil approaches its liquid limit, more water is needed to overcome this resistance, leading to a higher LL. Other studies (e.g., Salimnezhad et al., 2020) have also reported that diesel contamination increases the Atterberg limits of clay soils.

In crude oil-contaminated samples, the LL increased to 70% at 30% contamination. The PL values at 2%, 15%, and 30% crude oil were recorded as 27.27%, 35.8%, and 38%, respectively, indicating an increase of approximately 11.9 units compared to uncontaminated soil. The addition of oil also altered the soil microstructure, forming an intermediate layer between clay particles. Crude oil adhered to the surface of clay minerals and covered the adsorbed water layer, modifying the double layer thickness, which likely contributed to the increased LL and PL.

Moreover, diesel had a greater effect than crude oil. At 30% diesel, the LL was approximately 5% higher and the PL about 7% greater than in the crude oil-contaminated sample. This is consistent with the higher viscosity of diesel compared to crude oil.

Based on plasticity charts, natural marl soil from the CII region was classified as highly plastic. As diesel contamination increased, the soil's classification shifted from clay-like to silt-like behavior, eventually moving into the MH category. This shift indicates that the increased diesel content affected both the soil's plasticity and particle arrangement—potentially reclassifying clay particles closer to silt or fine sand. For example, soil contaminated with 2% oil fell into the CH-MH classification, while samples with higher oil levels were categorized as MII.

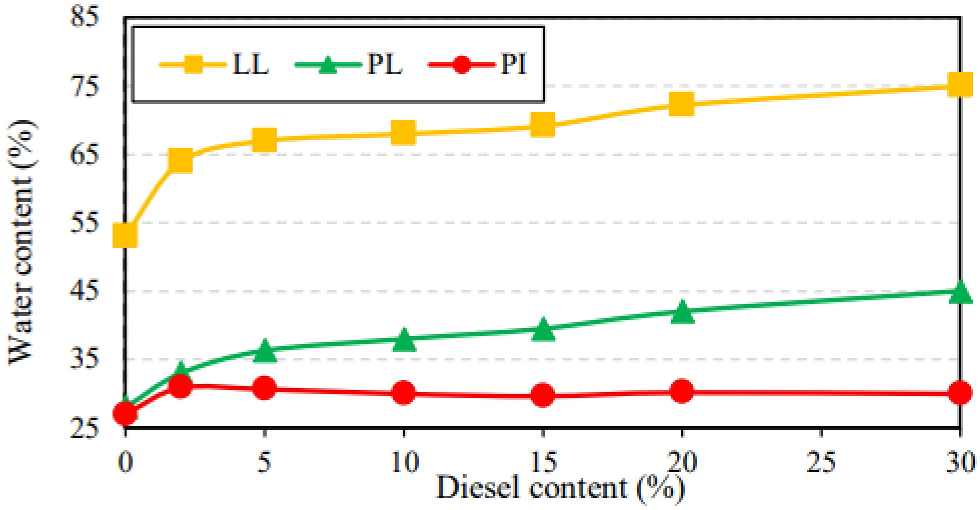

Figure 6. Results of Atterberg limits for Maran soil in the south containing various percentages of diesel.

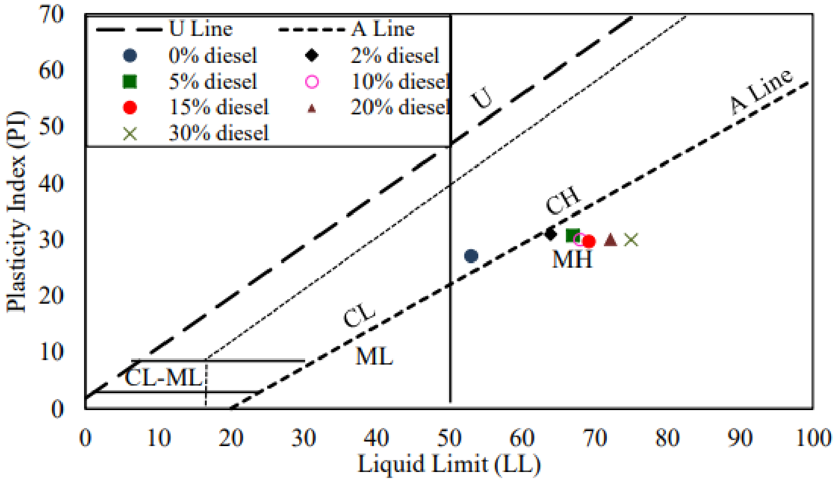

Figure 7. Changes in the plasticity of marl soil in the south and samples containing varying percentages of diesel.

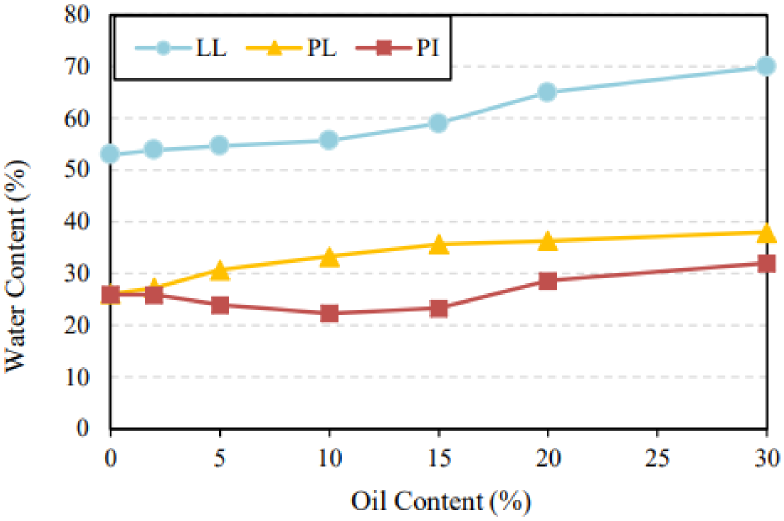

Figure 8. Results of the Atterberg limits of Maran South soil containing various percentages of oil.

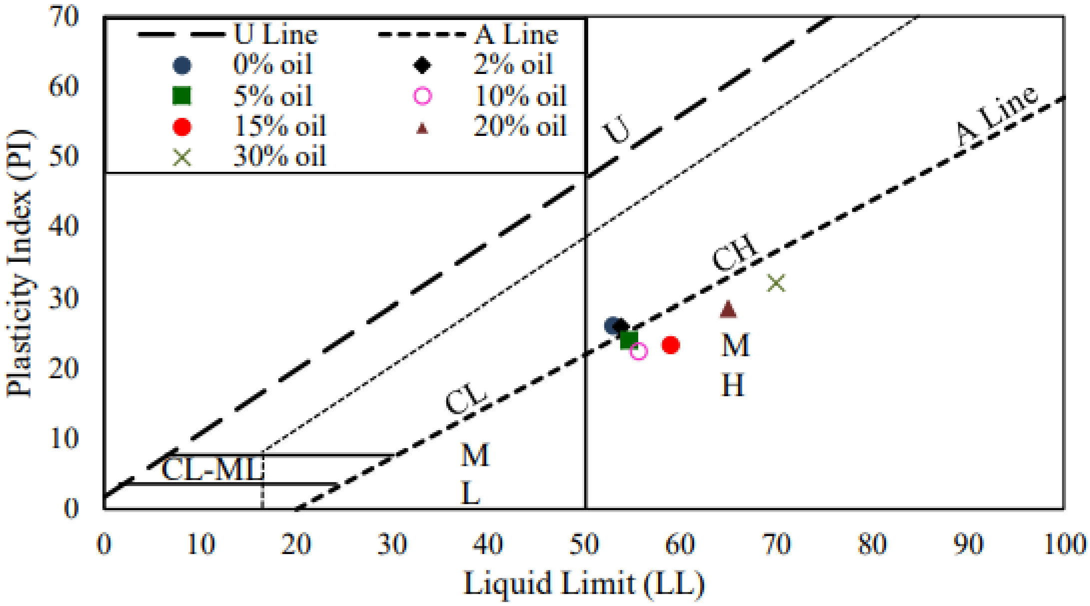

Figure 9. Changes in the plasticity of marl soil in the south and samples containing various percentages of crude oil.

The Impact of Oil Contaminants on Permeability Testing

This section presents the results of permeability testing conducted on southern marl soil samples contaminated with varying percentages of petroleum pollutants, using water as the permeating fluid. The permeability coefficient was measured for each level of contamination.

The findings showed that increasing oil contamination led to a noticeable reduction in soil permeability. Specifically, the addition of 5% crude oil resulted in a 6% decrease in permeability compared to uncontaminated soil. As oil content increased to 15% and 30%, the permeability further decreased by approximately 26% and 30%, respectively.

The permeability coefficient for natural soil was measured at approximately 1.0×10^{-5} m/s. With 15% and 30% oil contamination, the coefficients dropped to around 6.6×10^{-6} m/s and 7.0×10^{-6} m/s, respectively.

This reduction in permeability can be attributed to the presence of oil blocking the interconnected void spaces within the soil structure. As diesel or crude oil enters the soil, it coats the pore surfaces and occupies interparticle voids, thereby hindering the movement of water molecules through the soil matrix. This obstruction becomes more pronounced with higher contamination levels.

In addition, the higher viscosity of oil compared to water plays a significant role in impeding water flow. The dynamic viscosity of diesel oil is considerably greater than that of water at the same temperature, making it more difficult for water to percolate through the soil's pore spaces. Studies by Ekin Voomi et al. (2014) and Jadaari et al. (2014) support this observation, indicating that the presence of diesel can reduce soil permeability by approximately 4–30%, depending on the concentration and soil type.

Overall, the decline in permeability is primarily governed by two mechanisms: (1) physical obstruction of pores by oil, and (2) increased fluid resistance due to the high viscosity of the petroleum contaminants.

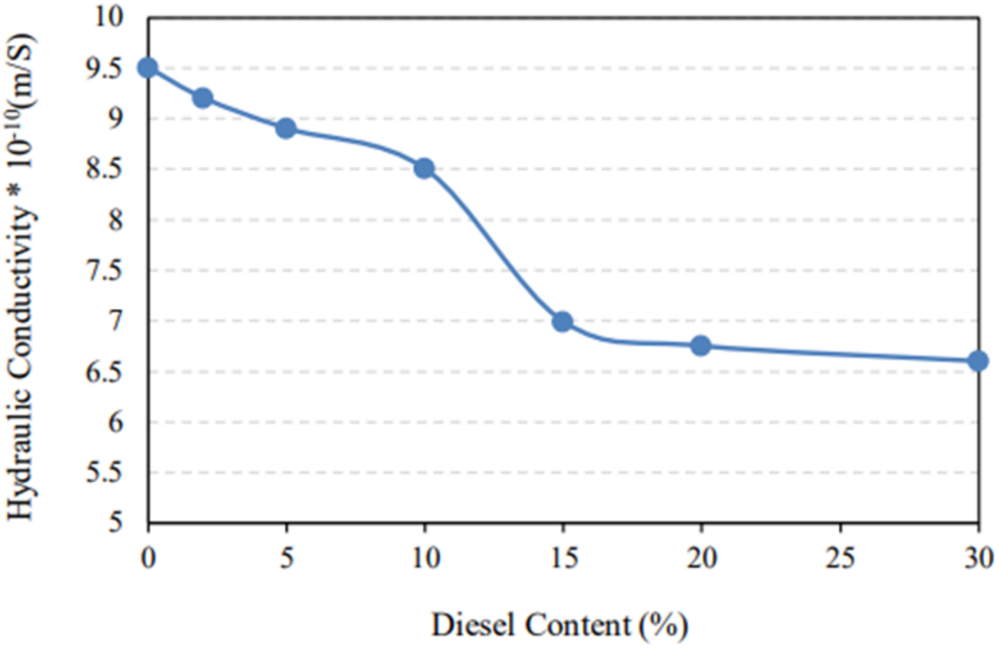

Figure 10. Changes in the permeability coefficient of marl soil in the south containing varying percentages of diesel.

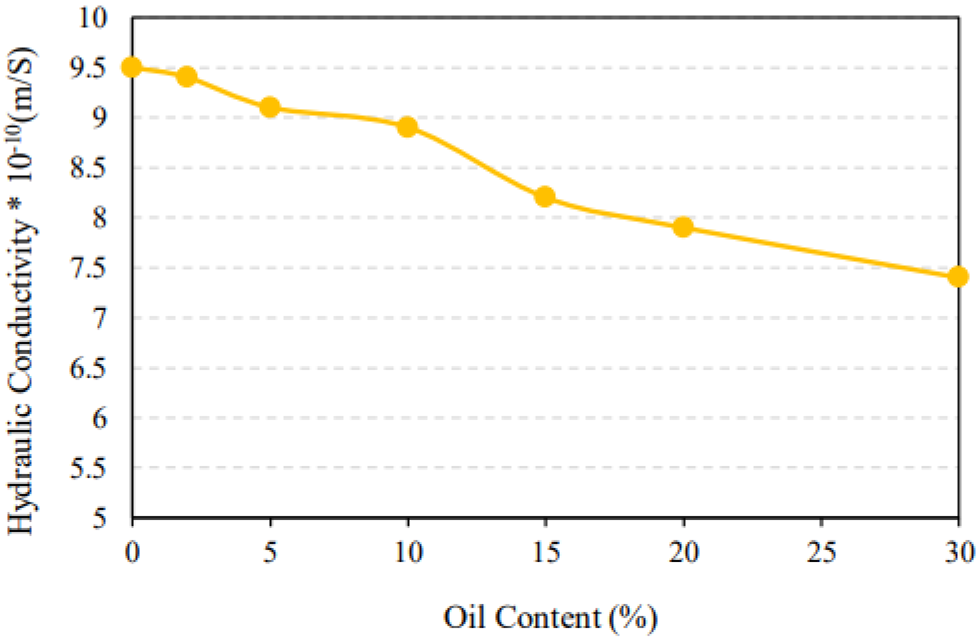

Figure 11. Changes in the permeability coefficient of marl soil in the south containing varying percentages of crude oil.

The Impact of Oil Contamination on Soil Consolidation

Consolidation tests were conducted on marl soil samples containing varying percentages of diesel fuel to assess their settlement characteristics. A semi-logarithmic plot illustrating porosity variations with respect to contamination levels was generated. Pre-consolidation pressure was determined using the Casagrande graphical method.

The load–displacement analysis revealed that increasing diesel concentration was associated with greater consolidation settlement. This was reflected in the steeper porosity and compressibility curves. The compression index (Cc) values for diesel-contaminated marl samples at 5%, 10%, 15%, 20%, and 30% contamination levels were approximately 0.293, 0.302, 0.310, 0.320, and 0.370, respectively. Settlement increased by up to 32% in the sample contaminated with 30% diesel.

For natural marl soil with a dry unit weight of 1.57 g/cm^3, the initial porosity was approximately 0.70, and the pre-consolidation pressure was around 220 kPa. In uncontaminated samples, water molecules form a cohesive network among clay particles, promoting interparticle interaction. However, diesel molecules disrupt this structure, weakening the bonds between clay particles. As a result, contaminated clay behaves more like silt due to reduced cohesion.

Scanning Electron Microscopy (SEM) images supported these findings. In the presence of diesel, the interparticle bonding weakened, and diesel acted as a lubricant, preventing clay particles from retaining water. This facilitated faster water expulsion, leading to increased compressibility. The compression coefficient (Cc) values for oil-contaminated samples at 0%, 2%, 5%, 10%, 15%, 20%, and 30% were 0.280, 0.290, 0.300, 0.320, 0.300, 0.340, and 0.355, respectively. Settlement increased by approximately 27% in the sample contaminated with 30% oil.

Overall, settlement was more pronounced in diesel-contaminated samples than in those contaminated with crude oil. This was attributed to diesel's higher viscosity, which makes it more difficult to escape from soil pores, resulting in higher settlement coefficients.

The porosity also increased with rising contaminant concentration. At 15% diesel contamination, porosity reached 0.85, and at 30%, it rose to 0.965. In comparison, oil-contaminated soils exhibited porosity values of 0.815 at 15% and 0.91 at 30%. SEM images of natural marl soil showed a relatively loose structure with small, irregular pores. As diesel content increased, the soil structure became more compact, but the voids between particles also grew larger, forming wider, more defined pores and resulting in higher total porosity.

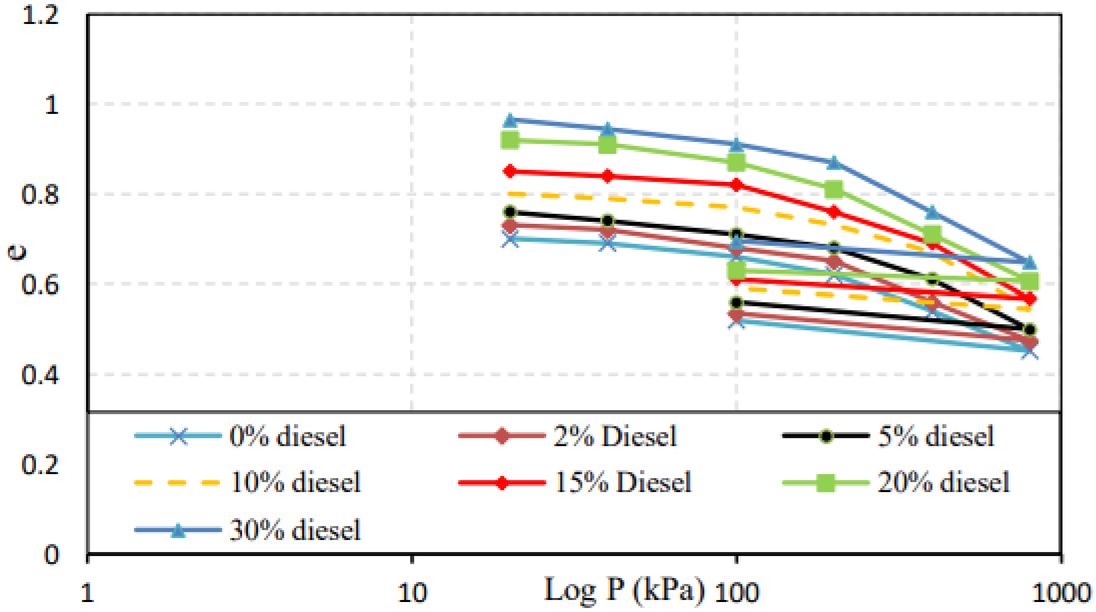

Figure 12. Changes in the soil porosity of marl soil containing varying percentages of diesel.

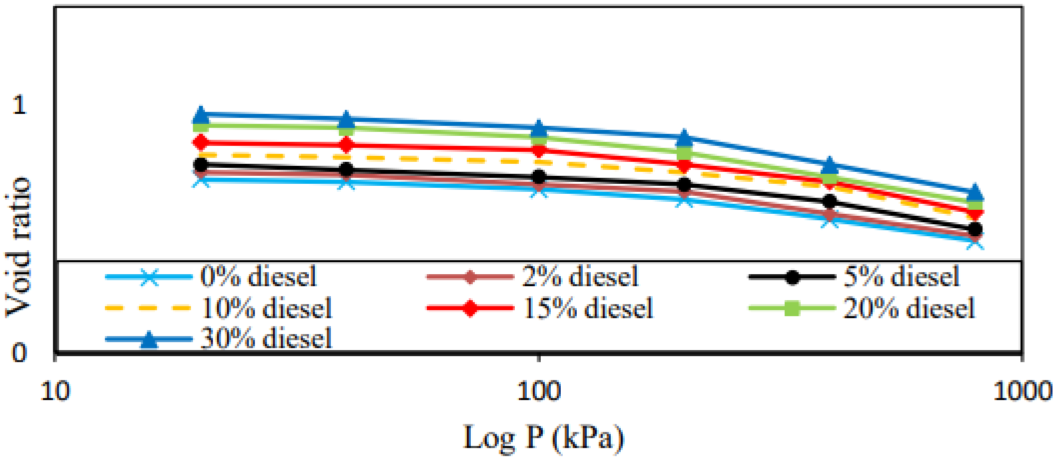

Figure 13. Changes in the soil porosity of marl in the south containing varying percentages of diesel.

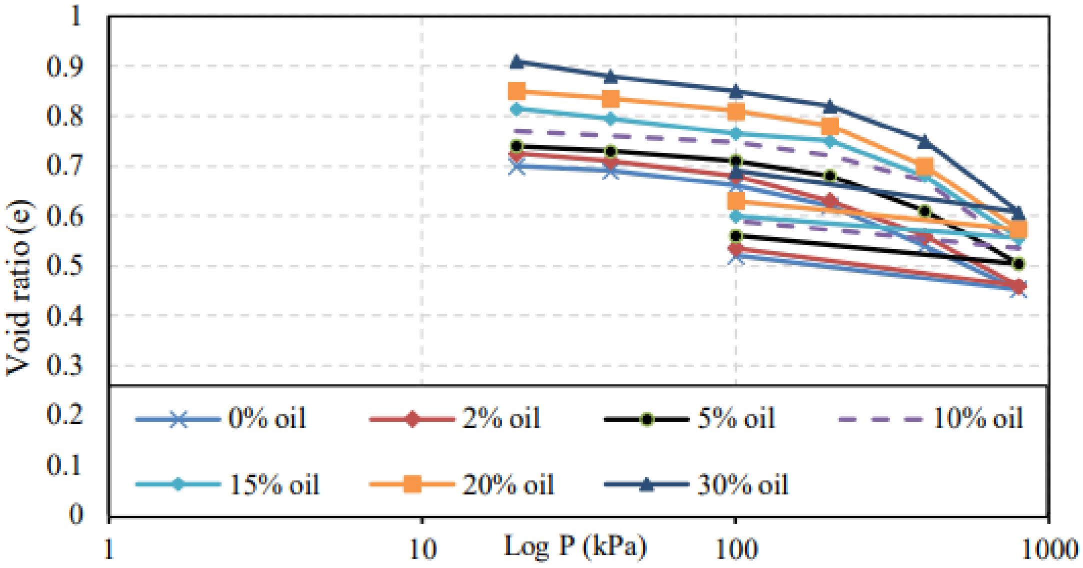

Figure 14. Changes in the soil porosity of marl from the south containing varying percentages of crude oil.

Conclusion

In general, the presence of petroleum pollutants in soil significantly reduced its permeability. For instance, the measured permeability coefficient of untreated marl soil (Nam Huu soil) was approximately 9.0×10^{-6} cm/s. As the diesel concentration increased to 15% and 30%, the ability of water to flow through soil pores declined considerably. This reduction was attributed to the occupation of pore spaces by diesel, which inhibited water movement.

X-ray diffraction (XRD) analysis indicated that oil contamination had no substantial effect on the peak intensity of clay minerals, suggesting minimal structural changes at the crystalline level.

According to the Atterberg limit test results, increasing the percentage of diesel contamination led to a notable rise in both the liquid limit (LL) and plastic limit (PL) of marl soil. Specifically, adding 5% diesel increased the LL and PL by 14 and 8 units, reaching 67% and 36.3%, respectively. At higher contamination levels (30%), the LL reached 75%, and the PL reached 45%, corresponding to increases of 22 and 17 units.

Moreover, the findings showed that consolidation settlement in marl soil also increased as diesel or oil contamination levels rose. This enhancement in compressibility was accompanied by accelerated changes in porosity and the soil's density curves. These results suggest that petroleum pollutants negatively impact the structural stability of marl soils, particularly under compressive loading.

Statements and Declarations

Competing Interests

The authors declare that they have no competing interests

Abbreviations

(SEM) :scanning electron microscopy

(XRD):- X-ray diffraction test

(EC): electrical conductivity

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