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Biobased Materials and Their Composites for Oil Spill Treatment

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Contents

Impacts of Oil Spill on Geotechnical Properties of Soil

Imtiyaz Akbar Najar, Raudhah Ahmadi, Showkat Ahmad Bhawani, Murtala Namakka, and Nur Hisyam Ramli

Abstract The escalation of environmental pollution in the world is attributed to the recent increase in crude oil spills, mainly due to the increase in crude oil production and the activities of individuals involved in crude oil theft. In oil and gas, the likelihood of soil pollution from petroleum products soars as oil exploration, production, and transportation of substantial oil volumes via pipelines across vast distances continue to dilate. Recent findings divulge a plethora of instances of oil spills occurring in various locations, attributed to damage within the infrastructure of the oil industry. These spills have resulted in soil contamination, giving rise to significant environmental risks and degradation of both the soil and its engineering characteristics. Herein we explore the changes in geotechnical properties of soil resulting from oil contamination. Beyond understanding the detrimental effects, the chapter explores numerous treatment methodologies, both established and emerging, offering a roadmap for restoring the geotechnical integrity of oil-contaminated soil. The advantages of employing geotechnical approaches, including sustainability, cost-effectiveness, and long-term efficacy, are highlighted, looking ahead, we identify key areas emphasizing the need for long-term monitoring, exploration of emerging contaminants and technologies like nanotechnology, for the development of scalable and cost-effective solutions.

Keywords Geotechnical · Oil spill · Pollution · Soil · Contamination

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1 Introduction

An oil spill refers to the release or discharge of liquid petroleum hydrocarbons, commonly known as oil, into the environment [1]. These spills can occur in various locations, including land, water bodies (such as oceans, seas, rivers, or lakes), or even underground. Oil spills are typically the result of human activities, accidents, or natural disasters, and they can have detrimental effects on ecosystems, wildlife, and human communities [2]. The most common type of oil spills occurs in marine environments, where crude oil or refined petroleum products are released into the water [1–3]. These spills may be the consequence of incidents involving offshore drilling platforms, pipelines, oil tankers, or other oil-related infrastructure. Additionally, spills on land can occur during transportation, storage, or industrial processes. The consequences of oil spills are extensive and include environmental pollution, damage to aquatic and terrestrial ecosystems, harm to wildlife, and economic losses for industries such as fishing and tourism [4]. Cleanup efforts for oil spills involve various techniques and technologies [5], including containment booms, skimmers, dispersants, and in-situ burning [2–4]. Preventing oil spills and developing effective response strategies are crucial for minimizing the environmental impact and protecting both natural ecosystems and human activities that rely on clean water and land [3–5].

Consequentially, oil spills can have significant impacts on the geotechnical parameters of soil, influencing its mechanical and hydraulic properties [6]. The extent of these impacts depends on various factors such as the type and amount of oil spilled, the characteristics of the soil, and the environmental conditions [7]. Table 1 outlined some of the influence of oil spills on the performance and properties of the affected terrain.

It is crucial to note that the use of remediation methods, such as soil washing or bioremediation, can also influence geotechnical parameters [7, 8]. Moreso, some methods may further disturb the soil structure that the specific impact of an oil spill on soil will vary based on site-specific conditions [9]. Hence, proper assessment and monitoring are essential to understand the full extent of the effects and to implement appropriate remediation strategies [2–7]. Additionally, local regulations and guidelines may dictate the required actions for mitigating the impact of oil spills on soil quality.

An oil spill on soil can have profound effects on its geotechnical properties, introducing significant challenges for environmental and geotechnical engineers [5]. The spilled oil permeates the soil, leading to changes in its physical and mechanical characteristics. The hydrophobic nature of oil can alter the soil's porosity [10], reducing water infiltration and impeding natural drainage processes [11]. This, in turn, may affect the soil's shear strength, compaction, and overall stability. The oil's interaction with soil particles can lead to increased soil hydrophobicity, causing shifts in aggregate size distribution [11–19]. Furthermore, the contamination may result in changes to the Atterberg limits, such as an increase in liquid limit [6], plastic limit [4, 28], and plasticity index [13]. These alterations in geotechnical properties pose challenges

Table 1 Effects and mechanisms of oil spill on geotechnical properties if oil contaminated soil

Oil spill affected material type	Mechanism	Effect on soil geotechnical properties
Oil contaminated soil	Coat soil particles, making them hydrophobic	Reduces water infiltration and affects the soil's ability to retain moisture
Oil contaminated soil	Clog soil pores	Reducing permeability and altering the flow of water through the soil. This can lead to increased runoff and erosion
Oil contaminated soil	Reduction in shear strength	Instability of slopes and foundations
Oil contaminated soil	Alter the compaction characteristics of soil	Affecting oil density and porosity
Contaminated soil	Oil components-to-soil minerals interactions, imbalance in soil chemical compositions	Alters the soil's mineralogy and potentially affects its engineering properties
Oil contaminated soil	Microbial decomposition	Production of byproducts which alter the soil structure and composition
Oil contaminated soil	Root penetration and growth	Instability of vegetation and increasing the risk of erosion

for construction projects in affected areas, necessitating a thorough understanding of the specific impacts of oil contamination on soil behavior [14]. Remediation efforts to restore the geotechnical integrity of the soil often require a multidisciplinary approach, combining environmental science, engineering, exploration of the potential utilization of nanotechnology [32], and regulatory compliance.

2 State-Of-The-Art and Oil Spill Sources

The primary sources of surface contamination by crude oil include leakages from pipelines, oil wells, underground storage tanks, and spills from accidents like the Gulf War oil spills and the Valdez tanker incident. Notably, Saudi Aramco (2005) reported that over half the world's crude oil comes from the Arabian Gulf, where a staggering 550 spills totalling 14,000 barrels occurred between 1995 and 1999, followed by another 11,000 barrels between 2000 and 2003 [5]. This oil contamination poses not only environmental threats but also geotechnical challenges due to its impact on soil properties, as documented by numerous studies over the past decade [7–12].

Despite its detrimental environmental consequences [15], petroleum, a complex organic mixture of aromatic hydrocarbons, asphaltenes, and heavy metals [13], extracted through underground exploration [14], continues to be a globally increasing resource [15]. Petroleum production primarily encompasses exploration and extraction, refining and marketing, and transportation [15, 16]. However, mismanagement of both petroleum production and its derivatives can lead to significant environmental pollution, particularly through oil spills [15]. This poses a major threat in oil-producing regions like Nigeria, where vandalism and crude oil theft often contribute to a high incidence of spills [14–20]. The resulting crude oil pollution negatively impacts the physical, mechanical, and biochemical properties of surrounding soil, potentially affecting nearby structures like building foundations, road pavements, and earth-retaining structures [21, 22]. Interestingly, Khamehchiyan et al. [23] suggest that with lower oil contamination (<16%), the likelihood of natural drainage from the soil diminishes significantly.

kinwumi et al. [24] and Al-Obaidy et al. [25] highlight the multifaceted impact of oil spills on soil properties, emphasizing both alterations in engineering behavior and environmental ramifications. Spilled oil elevates hydrocarbons as well as toxic metals in soil [25], triggering substantial modifications in its chemical, mechanical, physical, and biological characteristics [9, 16, 26]. The extent of these alterations depends on the oil volume and type, as well as the soil's inherent features [17, 24]. Significant consequences include reductions in Atterberg limits, compaction, permeability, angle of internal friction, cohesion, and consolidation properties [17, 24]. Oil disrupts internal structure, decreasing frictional resistance and influencing compression characteristics, particularly in sandy soils [2, 9, 27]. Furthermore, oil pollution alters particle surface texture and promotes the formation of atypical pores within the soil matrix [4], further compromising its engineering behavior and contributing to environmental concerns.

3 Influence of Oil Spill on Soil Geotechnical Properties

Hydrocarbon-contaminated soils typically exhibit a denser, flocculated structure with increased Edge-to-Face contacts amongst particles [17, 18]. In contrast, uncontaminated fines tend to display a more open and recognizable fabric characterized by prevalent Face-to-Face and Edge-to-Edge arrangements [28]. This shift in microstructure, as Izdebska-Mucha and Trzciński observed, transforms the soil's initially anisotropic pattern into a uniform matrix upon petroleum exposure [28]. The degree to which this transformation affects soil's geotechnical properties depends on multiple factors, including the volume and concentration of the contaminant, climatic conditions, soil's physical characteristics, vegetation cover, and its chemical composition [2, 17, 18].

Nudelman et al. [29] illuminate the crucial role of soil properties, such as permeability, adsorption rate, and partition coefficient, in dictating the rate at which oil modifies soil behavior. Evgin and Das [8] further utilize finite-element analysis to demonstrate how oil presence in soil amplifies settlement, particularly in footings. Notably, oil evaporation from the soil surface can alter the oil's physiochemical properties, facilitating restoration of the geotechnical characteristics of the affected soil [30]. This interplay between oil and soil highlights the dynamic nature of their interaction and its significant impact on geotechnical properties.

3.1 Impact on Atterberg Limits

In their studies on various geotechnical properties of soils, Tse and Eshiemomo, [31] and Evgin and Das, [8] observed significant impacts of oil contamination on the Atterberg limits and strength parameters of the soils. Khamehchiyan et al. [23] investigated the geotechnical properties of clayey and sandy soils contaminated with oil in Iran. Their findings indicated a general decline in the strength, permeability, maximum dry density (MDD), optimum water content (OWC), and Atterberg limits of the soil due to oil contamination. Youdeowei [21] concluded in their respective studies that soil liquid limits and plastic limits exhibited a notable decrease following oil pollution. According to Youdeowei [21], the liquid limits of the soils decreased by 8%, while the plastic limits and plasticity indices witnessed declines of 9% and 40%, respectively, after petroleum contamination. Additionally, Rahman et al. [32] and Rasheed et al. [33] investigated the impact of hydrocarbons on soil geotechnical properties. Their findings indicated that with an increase in the volume of oil in the soil, there was a corresponding reduction in the soil's liquid limit and plastic limit values. Contrarily, Akinwumi et al. [24], Al-Obaidy et al. [25], and Khosravi et al. [34] argued that when fine-grained soils contained a substantial amount of petroleum, specifically exceeding 12%, there was a notable decrease in the soils' plastic limits. Contrarily, they noted a significant rise in both the liquid limits and plasticity indices. According to their findings, these anomalies in the Atterberg's limits were linked to the particle size characteristics of the soils. The presence of oil molecules, which exhibit non-polarity, and the distribution of particle sizes in the soils were identified as key factors contributing to the observed reduction in both liquid and plastic limits of fine-grained soils following contamination. Fine-grained soils do not exhibit plasticity with non-polar fluids [35, 36].

3.2 Impact on Permeability and Compaction

Puri [9] and Yazdi and Teshnizi [37] demonstrate that petroleum contamination significantly alters soil behavior, with profound reductions in compaction, permeability, and internal friction angle observed as petroleum content increases [37]. Notably, while Nazir [38] reports diminished permeability in granular soils, clayey soils exhibit minimal change due to reduced electrostatic interactions between clay particles and the non-polar oil [30, 39]. This interplay between petroleum and soil type highlights the multifaceted nature of contamination, emphasizing the need for tailored remediation strategies based on soil composition. Petroleum's detrimental impact on soil engineering properties is evident in its ability to alter permeability and density. Ilojeje and Aniago [40] observed a shift from silty clay to clayey soil behavior, accompanied by an 8% permeability decrease with increasing oil content. Similarly, studies by [2, 23, 37, 41] confirmed a significant oil-induced decrease in soil density. Rehman et al. [20] shed further light on this phenomenon, demonstrating that oil acts as a lubricating agent and binder in clay soils, leading to higher Maximum Dry Density (MDD) at lower water content. This interplay between oil and soil highlights the substantial modifications petroleum can induce, compromising the critical engineering properties of soil. However, it is noteworthy that higher petroleum content (>16%) resulted in a reduction in the soil MDD.

Moreover, in their respective studies on the influence of petroleum on soil geotechnical properties, Akinwumi et al. [24], Safehian et al. [39], and Akpokodje and Uguru [42] observed decreases in the Maximum Dry Density (MDD), Optimum Water Content (OWC), and permeability following soil contamination. The reduction in soil permeability is explained by the clogging of soil voids resulting from petroleum impact, as highlighted by Akpokodje and Uguru [42]. Additionally, Srivastava and Pandey, [43] found that an increase (from 0 to 12%) in petroleum content in alluvial soils leads to a consistent decrease in both the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the soils. Contrastingly, Singh et al. [44] asserted that the Optimum Moisture Content (OMC) of soil samples exhibited an increase of nearly 45% with the rise in the volume of petroleum in the soil samples, ranging from 0 to 9%.

3.3 Impact on Hydraulic Conductivity of Soil

Corroborating findings from Shin and Das [11] and Rojas et al. [45], Chew and Lee [46] solidify the notion that oil contamination directly and steadily diminishes the hydraulic conductivity of soils [2, 11, 45, 46]. Rojas et al. [45] further elucidate this relationship by demonstrating a concurrent rise in kinematic viscosity alongside decreased hydraulic conductivity [45]. This observed reduction in permeability is attributed to the physical obstruction of soil pores by oil, impeding water flow [46]. This consistent evidence across varied soil types and oil concentrations [11, 45, 46] underscores the profound impact of oil spills on soil's fundamental hydraulic properties.

3.4 Impact on Soil Consolidation

Consolidation refers to the prolonged application of a static load to a substantial soil mass with the aim of minimizing voids within the soil structure [47]. Also, the influence of oil on kaolinitic soil samples, a non-linear decline in void ratio and compressibility of the soil samples was observed as the volume of oil increased. Khosravi et al. [34] observed a general reduction in the soil compression index (Cc) in their experimental work after simulating an oil spill. However, the soil swelling index (Cs) was noted to increase at a gradual pace as the volume of oil increased. According to Safehian et al. [39] and Salimnezhad et al. [48], oil pollution led to a significant increase in the free swelling rate of soils, while the swelling pressure decreased due to oil contamination. Additionally, Talukdar and Saikia [47], in their examination of the geotechnical properties of fine-grained soils, found that the soil compression index (Cc) tends to decrease with an increase in the volume of oil resulting from an oil spill. In contrast, Srivastava, and Pandey [43] reported in their research that the soil compression index (Cc) tends to increase as the volume of oil in the soil rises.

4 Oil Treatment Methodologies

Oil spill treatment involves a combination of mechanical, chemical, and biological methods to contain, recover, and mitigate the impact of spilled oil on the environment. The choice of methods depends on factors such as the type of oil, environmental conditions, and the scale of the spill. Common methods used for oil spill treatment are depicted in Fig. 1.

4.1 Treatment of Oil Spill on Soil Through Geotechnical Approaches

The treatment of oil spills on soil through geotechnical approaches involves a combination of physical, chemical, and biological methods aimed at mitigating the environmental impact and restoring the geotechnical properties of the affected soil. Some key geotechnical strategies for oil spill treatment on soil are summarized in Table 2.

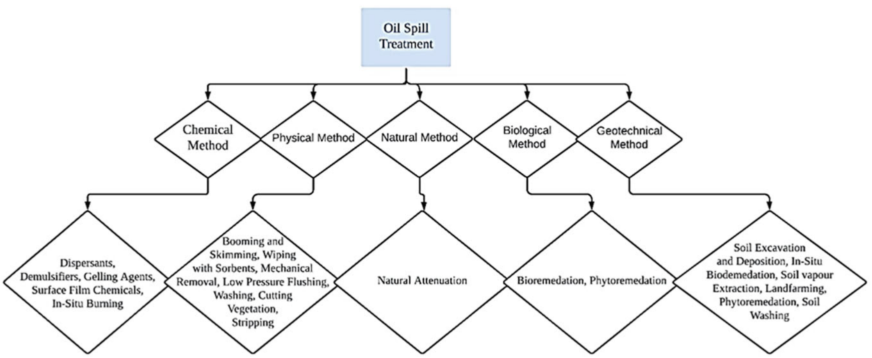

Fig. 1 Methods of oil spill treatment

Table 2 Oil contaminated soil treatment methods, applications, and mechanism

Treatment methods	Mechanisms	Applications
Soil excavation and disposal	Remove and dispose of the contaminated soil to prevent further spreading of the oil	For heavily contaminated areas. Excavated soil may be substituted with clean soil
In-situ bioremediation	Stimulate the activity of indigenous microorganisms in the soil to naturally break down and degrade the oil. Bioremediation can be boosted by adding nutrients, oxygen, or microbial agents to accelerate the degradation process	Lightly contaminated soil
Soil vapor extraction	Use soil vapor extraction systems to remove volatile organic compounds from the soil. This technique involves the extraction of air and contaminants from the soil, followed by treatment and monitoring	Lower to mid-level oil contaminated soil
Landfarming	Encourage the natural degradation of oil in the soil by incorporating it into the top layer and providing optimal conditions for microbial activity	Lower-level contamination
Phytoremediation	Utilize plants with the ability to absorb and gather contaminants, a process known as phytoremediation. Certain plant species can enhance the degradation of oil in the soil	Mid-level contamination
Soil washing	Washing the soil with water or other washing agents and separating the contaminated components	Lower-level contamination

However, effective oil spill treatment on soil through geotechnical approaches requires a site-specific assessment, considering factors such as soil type, contamination levels, and the surrounding environment. Integrating these geotechnical methods with environmental and regulatory considerations ensures a comprehensive and sustainable remediation process.

4.2 Advantages of Treatment of Oil Spill on Soil Through Geotechnical Approaches

Treating oil spills on soil through a geotechnical approach offers several advantages, leveraging principles of soil mechanics and engineering to mitigate the environmental impact. Here are some key advantages:

- Geotechnical approaches often allow for in situ treatment, diminishing the need for excavation or removal of contaminated soil. This decreases disturbance to the natural environment and facilitates a more sustainable remediation process.
- Geotechnical methods aim to preserve the physical structure of the soil. Techniques such as soil vapor extraction and bioventing can be applied to remediate soil without causing significant disruption to the soil matrix, maintaining its integrity and fertility.
- Traditional excavation methods can lead to soil erosion and disruption of the natural landscape. Geotechnical methods, by contrast, can be designed to minimize such disturbances, preventing erosion and the potential for downstream impacts on water bodies.
- Geotechnical methods can enhance natural biodegradation processes by optimizing conditions for microbial movement in the soil. This includes adjusting factors such as moisture content, aeration, and nutrient levels to promote the growth of indigenous microorganisms that can break down the contaminants.
- Certain geotechnical techniques involve the use of alterations or barriers to immobilize contaminants in the soil. This prevents the migration of impurities to groundwater or other sensitive receptors, offering a long-term solution to contamination.
- In many cases, geotechnical approaches can be more cost-effective compared to extensive excavation and off-site disposal. Treating the contamination in place reduces transportation and disposal costs associated with excavated soil.
- The geotechnical approach, particularly in situ treatments, minimizes the disruption of the affected site. This is particularly advantageous in urban or ecologically sensitive areas where preserving the existing landscape is a priority.
- Geotechnical methods can be customized based on the specific characteristics of the contaminated site, allowing for a targeted and efficient remediation strategy. This adaptability is crucial for addressing diverse soil types, hydrogeological conditions, and contaminant compositions.
- Geotechnical methods are designed to meet environmental regulations and guidelines. Implementing a geotechnical approach ensures that the remediation process aligns with regulatory requirements, promoting responsible and sustainable practices.
- When appropriately designed and implemented, geotechnical methods can provide long-term effectiveness in treating oil-contaminated soil. This helps prevent the recurrence of contamination and promotes the restoration of the soil ecosystem.

In summary, the geotechnical approach to oil spill treatment on soil offers a suite of advantages, including in situ treatment, preservation of soil structure, cost-effectiveness, and tailored remediation strategies that make it a valuable and environmentally conscious option for addressing soil contamination.

5 Conclusion and Future Perspectives

In this Chapter we explored the intricate relationship between oil spills and the geotechnical properties of soil. We have delved into the multifaceted effects and mechanisms at play (outlined in Table 1), analyzed the impact of petroleum on soil characteristics, and examined several promising oil treatment methodologies (see Table 2). Notably, the advantages of employing geotechnical approaches for oil spill remediation have been highlighted, emphasizing their potential for efficient and sustainable restoration.

Future Perspectives:

Despite significant advancements in discerning and mitigating oil spill impacts on soil, several key areas assure further exploration:

- Long-term monitoring and assessment: Long-term monitoring of treated sites is crucial to assess the effectiveness and sustainability of remediation strategies. Developing robust predictive models to anticipate the long-term evolution of oil-contaminated soil will be essential for effective management.
- Emerging contaminants: With the increasing use of unconventional hydrocarbons and complex oil mixtures, research on their specific interactions with soil and the effectiveness of existing treatment methods is necessary.
- Nanotechnology: Exploring the potential of nanomaterials for targeted contaminant removal as revealed in the study of Namakka et al. [49], and investigating synergistic combinations of these technologies hold promising opportunities for enhanced efficacy and environmental footprint reduction.
- Cost-effective and scalable solutions: Developing cost-effective and scalable treatment solutions, while considering local soil conditions and resource availability, is critical for wider adoption of geotechnical approaches in real-world spill situations.
- Policy and regulatory frameworks: Establishing robust policies and regulatory frameworks that encourage preventive measures, prioritize geotechnical approaches, and promote responsible land management practices will play a crucial role in minimizing the long-term impacts of oil spills.

By tackling these future research directions, we can further enhance our understanding of oil-soil interactions, optimize existing remediation technologies, and develop innovative solutions.

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