

# Impacts of petroleum spills on geotechnical properties of soils: A review

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**ABSTRACT:** Environmental pollution caused by crude oil spills had increased recently in Nigeria, due to increase in crude oil production and the activities of crude oil thieves. This review work was embarked upon to evaluate the impacts of crude oil petroleum products spills on the geotechnical properties of different soils found in Nigeria. The review tried to provide a summary on the influence of crude oil on the Atterberg limits, compaction, permeability, angle of internal friction, cohesion, and consolidation properties of soil samples. Findings from this review revealed that the geotechnical characteristics of soils can be remarkably altered by crude oil and petroleum products impaction. Most of the literatures reviewed indicated a reduction in the Atterberg limits, the compression index (Cc) and the permeability of the soils, as the volume of crude oil in the soils increased. The literature review depicted that the rate, at which the soils' geotechnical properties were altered, was a factor of the oil volume contained inside the soils and the impacted soil biochemical properties.

**Keywords:** Environmental impact, geotechnical properties, oil exploration, oil spill, petroleum.

## INTRODUCTION

Petroleum is an organic compound, which contains numerous aromatic hydrocarbons, heavy metals, asphaltenes, etc. (Moubasher *et al.*, 2015), obtained through underground exploration processes (Uguru and Udubra, 2021). Globally, petroleum production is on the increase, despite its widely some of their negative consequences on the ecosystems (Akpomrere and Uguru, 2020a). Petroleum production has three major sections; the exploration and production, the refining and marketing section, and the infrastructure/transportation section (Walls, 2010; Akpokodje *et al.*, 2019a).

Petroleum production and the utilization of its derivatives, can lead to environment pollution (spills) if not properly managed. Crude oil spills have become major menace in most oil producing countries. In Nigeria most of the crude oil spills are linked to activities of vandals (crude oil thieves) (Akpomrere and Uguru, 2020a). Shell Petroleum Development Company (SPDC), a major oil production company in Nigeria, stated that approximately 80% of oil spills incidences occurring in the country can be

linked to the activities of saboteurs (Uguru *et al.*, 2020; SPDC, 2021). National Oil Spill Detection and Response Agency (NOSDRA), an environmental protection agency of the Nigeria government, reported more than 1,100 crude oil spill incidences in Nigeria, between 2019 and 2021, resulting in about 62,678 barrels of crude oil into the adjoining ecosystem (Saadoun, 2015; NOSDRA, 2021; Uguru and Udubra, 2021).

Crude oil pollution has adverse effects on the surrounding soil physical, mechanical and biochemical properties; affecting building foundations, road pavements and earth retaining structures within the vicinity (Hong *et al.*, 2005; Youdeowei, 2008). Khamehchiyan *et al.* (2007) reported that when soils are impacted by lower quantity of oil (<16%), the likelihood of this oil draining out from the soil is quite remote. Akinwumi *et al.* (2014) stated that one of the major effects of oil impacted soils is the alterations in the soils' engineering properties; resulting in significant increment in the soil's plasticity and settlement rate, reduction in the soil load bearing capacity, etc.

Environmental pollution resulting from oil spills cannot be ignored or disregarded; as one of these environmental impacts is the alterations in the soils' engineering properties and behavior. It has been reported (Elisha, 2012; Al-Obaidy *et al.*, 2019) that oil has the capability of increasing the petroleum hydrocarbons and toxic metals concentrations in the soil; thus causing significant modification to the soils' chemical, mechanical, physical and biological properties (Puri, 2000; Chang *et al.*, 2014; Akpokodje *et al.*, 2019a).

### **IMPACT OF PETROLEUM ON SOIL GEOTECHNICAL PROPERTIES**

Generally, hydrocarbons polluted fines are posed to have a flocculating fabric with more Edge-to-Face contacts; on the contrary, uncontaminated fines are posed to have predominant Face-to-Face and Edge-to-Edge contacts that produce a widespread and familiarized fabric (Izdebska-Mucha *et al.*, 2011; Trzciński *et al.*, 2015; Rajabi and Sharifipour, 2018). Izdebska-Mucha and Trzciński (2021) reported that petroleum impaction of soil resulted to changes in the soils' microstructural pattern, from an extremely anisotropic pattern to a uniform matrix pattern. The rate at which petroleum alters the geotechnical properties of soils is a factor of; the volume and concentration of the crude oil discharged into the soil, the climatic conditions, the physical characteristics of the soil, the vegetative cover of the spatial extent impacted and the chemical properties of the soil (Fine *et al.*, 1997; Akpomrere and Uguru, 2020b; Uguru *et al.*, 2020).

Nudelman *et al.* (2002) stated that the rate at which oil alters the soil's behavior is predisposed to the soil properties, such as its permeability, adsorption rate, partition coefficient, etc. Evgin and Das (1992) also revealed in their findings (finite-element analysis), that the rate of soil settlement in structures (footings) can be increased, as a result of oil presence in the soil. Evaporation of the oil from the soils surfaces can institute alterations in the oil physiochemical properties; thus restoring the altered soils' geotechnical properties (Ostovar *et al.*, 2020).

#### **Atterberg limits (consistency limits)**

Tse and Eshiemomo (2016) and Evgin and Das (1992) in their investigation on some geotechnical properties of soils, observed that, oil contamination had substantial effects on the soils' Atterberg limits and strength parameters. Khamehchiyan *et al.* (2007) investigated the geotechnical properties of oil adulterated clayey and sandy soils in Iran, and their findings revealed a generally decline in the strength, permeability, maximum dry density (MDD), optimum water content (OWC) and Atterberg limits of the

soil. Amir and Amir (2021) and Youdeowei (2008) in their studies concluded that, soil liquid limits and plastic limits declined notably after oil pollution. Youdeowei (2008) reported that the soils' liquid limits declined by 8%, while the plastic limits and plasticity indices declined by 9% and 40 %, respectively after the petroleum contamination. Furthermore, Rahman *et al.* (2010) and Rasheed *et al.* (2014) studied the consequence of hydrocarbons on soil geotechnical properties, and their findings depicted that the as the oil volume in the soil increases, a decline in the soil's liquid limit and plastic limit values were observed.

In contrary, Khosravi *et al.* (2013), Akinwumi *et al.* (2014) and Al-Obaidy *et al.* (2019) stated that high petroleum content (>12%) in fine grained soils, resulted in a dramatic reduction in the soils' plastic limits, but the liquid limits and plastic indices increased dramatically. Irregularities in the Atterberg's limits can be attributed to characteristics of the soils' particle sizes. The liquid and plastic limits of fine grained size soil tend to reduce after contamination, resulting from the non-polarity of oil molecules and the particle sizes distribution of the soils. Fine grained size soil do not show plasticity with non-polar fluids (Kaya and Fang, 2000; Ratnaweera and Meegoda, 2006; Rajabi and Sharifipour, 2018).

#### **Compaction and permeability**

Puri (2000) and Yazdi and Teshnizi (2021) reported that petroleum impaction caused meaningful alteration in soil compaction and permeability. Likewise, Yazdi and Teshnizi (2021) stated that petroleum caused significant changes in the soils' internal friction angle and constrained modulus; as these parameters decrease non-linearly as the petroleum quantity increases (from 0 to 12%). According to Nazir (2011) oil pollution generally reduced granular soils' permeability; but the effect of oil pollution on the permeability of clayey soils was not noticeable, which can be attributed to the poor dielectric constant value, initiated in the fines in the soil by the contaminant. Clay particle soils experience a drop in their double-layer thickness, and the volume of the free water will rise after the petroleum pollution (Safehian *et al.*, 2018; Ostovar *et al.*, 2020).

Iloeje and Aniago (2016) reported that petroleum altered the permeability property of soils from a silty clay state to a clayey soil state, as the permeability decreased drastically, as the oil content increased by 8%. Petroleum significantly affects the density of the soil samples (Shah *et al.*, 2003; Khamehchiyan *et al.*, 2007; Yazdi and Teshnizi, 2021). This affirmed the negative impact of oil on the engineering properties of soils. Rehman *et al.* (2007) studied the impact of petroleum on the compaction characteristics of clay soils, and observed that polluted clay soils tend to have higher MDD at lower soil water content. This is because the oil acts as an additional

lubricating agent, as well as a binding material for the soil aggregates, gluing the soil particles together; thus increasing the soil MDD; although higher petroleum content (>16%) revealed reduction in the soil MDD. Similarly, Kermani and Ebadi (2012) and Nasehi et al. (2016) observed a reduction in soils' MDD, as the petroleum volume and concentration in soils increases. According to Udonne and Onwuma (2014), the soil bulk density increased by 4.4%, and the capillarity rate declined by 900%, after oil spill. Ostovar *et al.* (2020) in their investigation into oil spills impacted soils, noted strong variations in the soils' permeability coefficient, as the later tends to increase initially, at lower petroleum volume, and then increased sharply as the petroleum volume is increased above 12%. Khomehchiyan *et al.* (2007) in their studies justified the fall in the permeability coefficient of sandy soil, under severe oil contamination, attributing it to a reduction in the void sizes in the sand samples, which rose from excess oil in the soil. Additionally, the research findings of Walia *et al.* (2013) confirm the results of previous researchers, as it stated that soil MMD tends to decline after exposure to hydrocarbon compounds and other organic oils.

Furthermore, Safehian et al. (2018), Akinwumi et al. (2014) and Akpokodje and Uguru (2019b) in their exclusive researched into the impact of petroleum on soils' geotechnical properties, reported reductions in the soils' MDD, OWC and permeability after contamination. The declined in soils' permeability can be linked to the clogging of the soil voids, initiated by the petroleum impactation (Akpokodje and Uguru, 2019b). Srivastava and Pandey (1998) reported that increment (0% to 12%) of petroleum in alluvial soils tends to cause a continuously decline in the soils' MDD and OMC. However, Singh et al. (2009) stated that the OMC of soils samples increased by almost by 45%, as the volume of the petroleum in the soil samples increased from 0 to 9%.

### Soil hydraulic conductivity

According to Shin and Das (2000) the hydraulic conductivity of oil spill impacted soils tends to decline continuously and directly proportionally to the concentration of crude oil in the soil samples. Moreover, Rojas *et al.* (2003) investigated the influence petroleum on soils' kinematic viscosity and hydraulic conductivity, and recorded a decline in the soils' hydraulic conductivity as the petroleum quantity increases. Rojas *et al.* (2003) observed that oil spill impacted soils recorded higher kinematic viscosities.

In related development, Chew and Lee (2006) examined the impact of organic oil spills on the hydraulic conductivity of coarse grained particles soils, and reported that the hydraulic conductivity of the soils decreased, as the oil quantity increased; attributing this action to the occupation

of the soils' voids by the organic oil, which hinder the free flow of water within the soils.

### Angle of internal friction and cohesion

Youdeowei (2008) investigated the effect of petroleum on soils' mechanical properties, and reported that petroleum caused significant decline in the soils' cohesion and frictional angle. Relatively, Alsanad *et al.* (1995), Alsanad and Ismail (1997) and Rahman *et al.* (2010) studied the impact of oil on soils geotechnical properties, and reported that the soils' shear parameters, compressibility, permeability and compaction were altered by the oil's presence. Also, Alsanad *et al.* (1995) indicated significant drop in soils' strength and permeability parameters, as a results of the oil contamination; though the soils exhibited increments in their compressibility.

Evgin and Das (1992) stimulated the impact of oil spills on quartz sand's shear strength, and recorded a decline in soil friction angle as the oil volume increases. Abousnina et al. (2015) in their research, looked at the impacts of petroleum on soils particles, and their observations revealed that oil pollution led to increment in the cohesion and decrement in the angle of internal friction angle. Furthermore, Khosravi *et al.* (2013) and Nasehi *et al.* (2016) in their investigation into the effects of oil on clay soils observed that, the oil initiated a reduction in the internal friction angle of the soils, while soil cohesion increased progressively, as the oil volume increased to 7%. The increase in cohesion of contaminated clay must have been caused by the increase in bonding by oil particles (Elisha, 2012). According to Al-Shayea (2001), the decline noticed in the contaminated soil friction angle may be caused by the reduction in the frictional resistance between the soil particles, triggered by the existence of adequate oil in the soil.

Granular soils are mostly non-cohesive and have a considerable friction angle (Jia *et al.*, 2011; Ostovar *et al.*, 2020). Oils tend to increase soils' coefficient of compression, although, there is no strong correlation relationship between the soils' shear strength and the oil quantity (Jia *et al.*, 2011; Khosravi *et al.*, 2013). According to Evgin and Das (1992), stimulated oil spills instigated a momentous reduction soils' friction angle, irrespective of their texture; even though there was dramatic increment in the soils' volumetric strain. Shin *et al.* (2002) stated that oil content in the soils increases, internal modification tends to occur between the particles of the contaminated soils, leading to alterations in the soils' friction angle (Rajabi and Sharifipour, 2018). The impact of oil spills on river bed soils was carried out by Puri *et al.* (1994), and it was observed that the river bed soils showed a remarkable reduction in their friction angle, as oil content increases.

In a study carried by Al-Sanad *et al.* (1995) and Onyelowe (2015) on the consequence of oil on the

geotechnical properties of poorly-graded soils, a continuous decline was observed in the soils' shear strength as the oil volume was increased by 68 %wt. Khomehchiyan *et al.* (2007) and Srivastava and Pandey (1998), stated that oils are capable of creating minute amounts of cohesion in large-grained size soil particles, due to good adhesion capacity of these large-grained size soil particles. Generally, imposed alterations in the van der Waals force and suction between the soil particles, couple with formation of moist hydrocarbon circumstances in the soil microstructure, could be accountable for the cohesion reduction observed in hydrocarbon contaminated fine-grained soil (Rajabi and Sharifipour, 2018).

Ostovar *et al.* (2020) reported that the cohesion values of poorly-graded soils samples increases as the oil content increases; while cohesion values recorded in the clayey sand sample reduces, when the quantity of oil present in soil increases. Additionally, it was detected in results obtained by Ostovar *et al.* (2020) that although the cohesion recorded in clayey sand sample generally diminishes with rise in the soil oil content, it still remains higher than the cohesion values for the sandy soil samples. In addition, Alfach and Wilkinson (2020) stated that oil contamination of poorly graded soils caused alterations in the maximum internal forces (bending moment and normal force) of corner piles, and the load–displacement pattern was directly proportional to the volume of oil in the soil.

Generally, as a result of the contamination, there was a reduction in the angle of internal friction of sandy, bentonite-rich and pure kaolin soils; although the cohesion of the sandy, bentonite-rich and pure kaolin soils tends to increase with oil contamination (Khomehchiyan *et al.*, 2007; Khosravi *et al.*, 2013). On the contrary, it was observed that for the clayey and silty soils, the samples angle of friction tends to increase, while the cohesion tend to decrease after the oil pollution (Kermani and Ebadi, 2012; Khomehchiyan *et al.*, 2007).

### Consolidation

Consolidation is the process of applying a long duration static load to a large body of soil, in order to minimize the voids inside the soil mass (Talukdar and Saikia, 2013). Matteo (2011) studied the influence of oil on the compression index of kaolinitic soil samples, and observed a non-linear decline in of void ratio and compressibility of the soil samples as the oil volume increased. Khosravi *et al.* (2013) in their experimental works recorded general reduction in soil compression index ( $C_c$ ), after simulated oil spill; though the soil swelling index ( $C_s$ ) was observed to increase at a slow pace, as the oil volume increases. According to Safedian *et al.* (2018) and Salimnezhad *et al.* (2021), oil pollution caused significant increment in soils free swelling rate; while the swelling pressure declined the

oil contamination.

Additionally, Talukdar and Saikia (2013) in their investigation into the geotechnical properties of fine grained size soils reported that, soil  $C_c$  tends to decrease as the oil volume from the oil spill increases. In contrast, Srivastava and Pandey (1998) reported in their study that soil  $C_c$  tends to increase as the oil volume in the soil increases. Furthermore, Elsharief *et al.* (2015) noted that soils swelling pressure diminished, as the oil content increased, which can be linked to the reduction in the soils moisture content, caused by the increase in the soils oil content (Akpokodje Uguru, 2019b). Murat and Mustafa (2010), reported that consolidation parameters of fine grained soils are posed to decline as oil adulteration increases. Petroleum has the ability of causing serious alteration in the consolidation characteristics ( $C_c$  and  $C_v$ ) of soils, and these alterations are highly dependent on the soil type, the biochemical properties of the soil and the nature of the hydrocarbon impactation Al-Sanad *et al.*, 1995; Alhassan and Fagge, 2013; Uguru *et al.*, 2020).

### CONCLUSION AND RECOMMENDATIONS

This review work embarked upon focusing on recorded previous literatures on the impact of crude oil (petroleum) on the geotechnical properties of soils. The following itemized conclusions can be made from the review.

1. Petroleum pollution adversely affects the geotechnical properties of the soil, irrespective of the soil type.
2. Petroleum can significantly decline soils LL and PL, although some authors stated contrary views.
3. Most literatures reported that the coefficient of permeability of soils decreased gradually as the soils oil volume increases.
4. It was observed from the literatures that crude oil reduces soils' OMC and MDD.
5. Most literatures reported a general decline in the soils' compression index ( $C_c$ ) as a results of oil spillage.
6. Regarding soils' internal friction angle, literatures reviewed revealed that petroleum generally caused a reduction in the internal friction angle of soils.
7. It was observed that the rate at which soil geotechnical properties are altered, is dependent on the quantity of oil in the soils.

### CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

### REFERENCES

- Abousnina, R. M., Manalo, A., Shiau, J., & Lokuge, W. (2015). Effects of light crude oil contamination on the physical and

- mechanical properties of fine sand. *Soil and Sediment Contamination: An International Journal*, 24(8), 833-845.
- Adejumo, T. E. (2012). Effect of crude oil contamination on the geotechnical properties of soft clay soils of Niger Delta Region of Nigeria. *Electronic Journal of Geotechnical Engineering*, 17, 1929-1938.
- Akinwumi I. I., Diwa, D., & Obianigwe, N. (2014). Effects of crude oil contamination on the index properties, strength and permeability of lateritic clay. *International Journal of Applied Sciences and Engineering Research*, 3(4), 1-10.
- Akpokodje, O. I., & Uguru, H. (2019a). phytoremediation of petroleum products contaminated soil. *Archives of Current Research International*, 18(1), 1-8.
- Akpokodje, O. I., Uguru, H., & Esegbuyota, D. (2019) Evaluation of phytoremediation potentials of different plants' varieties in petroleum products polluted soil. *Global Journal of Earth and Environmental Science*, 4(3), 41-46.
- Akpokodje, O.I. & Uguru, H. (2019b). Bioremediation of hydrocarbon contaminated soil: assessment of compost manure and organic soap. *Transactions on Machine Learning and Artificial Intelligence*, 7(5), 13-23.
- Akpomrere, O. R., & Uguru, H. (2020a). Ecotoxicity effect of illegal refineries on the environment: A case study of Delta State, Nigeria. *International Journal of Innovative Agriculture & Biology Research* 8(2), 40-49.
- Akpomrere, O. R., & Uguru, H. (2020b). Spatial distribution of residual petroleum hydrocarbons in an oil spill site located at Isoko South LGA, Delta State, Nigeria. *Journal of Environment and Waste Management*, 7(1), 312-317.
- Alfach, M. T., & Wilkinson, S. (2020). Effect of crude-oil-contaminated soil on the geotechnical behaviour of piles foundation. *Geotechnical Research* 7(2), 76-89.
- Alhassan, H. M., & Fagge, S. A. (2013). Effects of crude oil, low point pour fuel oil and vacuum gas oil contamination on the geotechnical properties sand, clay and laterite soils International. *Journal of Engineering Research and Applications*, 3,1947-1954.
- Al-Obaidy, N., Al-Shueli, A., Sattar, H., Majeed, Z., & Hamid, N. A. H. (2019). An experimental study on geotechnical and electrical properties of an oil-contaminated soil at thi-qar governorate/Iraq. *International Review of Civil Engineering*, 10(3), 148-154.
- Al-Sanad, H. A., & Ismael, N. F. (1997). Aging effects on oil-contaminated Kuwaiti sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 123(3), 290-293.
- Al-Sanad, H. A., Eid, W. K., & Ismael, N. F. (1995). Geotechnical properties of oil-contaminated Kuwaiti sand. *Journal of Geotechnical Engineering*, 121(5), 407-412.
- Al-Shayea, N. A. (2001). The combined effect of clay and moisture content on the behavior of remolded unsaturated soils. *Engineering Geology*, 62(4), 319-342.
- Chang, S. E., Stone, J., Demes, K., & Piscitelli, M. (2014). Consequences of oil spills: a review and framework for informing planning. *Ecology and Society*, 19(2), 26.
- Chew, S., & Lee, C. (2006). Simple shear behaviour of palm biodiesel contaminated soil. *Journal of Engineering and Applied Sciences*, 5, 12.
- Elsharief, A. M., Zumrawi, M. M. & Salam, A. M. (2015). Experimental study of some factors affecting swelling pressure. *University Of Khartoum Engineering Journal*, 4(2), 1-6.
- Evgin, E., & Das, B. M. (1992). Mechanical behaviour of oil-contaminated sand. In: Usmen, M. A., & Acar, Y. B. (eds.). *Environmental geotechnology*. Balkema Publishers, Rotterdam, Netherlands. Pp. 101-108.
- Hong, J. H., Kim, J., Choi, O. K., Cho, K. S., & Ryu, H. W. (2005). Characterization of a diesel-degrading bacterium, *Pseudomonas aeruginosa* IU5, isolated from oil-contaminated soil in Korea. *World Journal of Microbiology and Biotechnology*, 21(3), 381-384.
- Iloje, A. F., & Aniago, V. (2016). Effect of crude oil on permeability properties of the soil. *International Journal of Trend in Scientific Research and Development*, 1(1), 39-43.
- Izdebska-Mucha, D., & Trzciński, J. (2021). Clay soil behaviour due to long-term contamination by liquid petroleum fuels: microstructure and geotechnical properties. *Bulletin of Engineering Geology and the Environment*, 80(4), 3193-3206.
- Izdebska-Mucha, D., Trzciński, J., Żbik, M. S., & Frost, R. L. (2011). Influence of hydrocarbon contamination on clay soil microstructure. *Clay Minerals*, 46(1), 47-58.
- Jia, Y. G., Wu, Q., Shang, H., Yang, Z. N., & Shan, H. X. (2011). The influence of oil contamination on the geotechnical properties of coastal sediments in the Yellow River Delta, China. *Bulletin of Engineering Geology and the Environment*, 70(3), 517-525.
- Karimi, A. H., & Hamidi, A. (2021). Effect of Phytoremediation on Geotechnical Characteristics of Oil Contaminated Sands. *Soil and Sediment Contamination: An International Journal*, 30(8), 943-963.
- Kaya, A., & Fang, H. Y. (2000). The effects of organic fluids on physicochemical parameters of fine-grained soils. *Canadian Geotechnical Journal*, 37(5), 943-950.
- Kermani, M., & Ebadi, T. (2012). The effect of oil contamination on the geotechnical properties of fine-grained soils. *Soil and Sediment Contamination: An International Journal*, 21(5), 655-671.
- Khamehchiyan, M., Charkhabi, A. H., & Tajik, M. (2007). Effects of crude oil contamination on geotechnical properties of clayey and sandy soils. *Engineering Geology*, 89(3-4), 220-229.
- Khosravi, E., Ghasemzadeh, H., Sabour, M. R., & Yazdani, H. (2013). Geotechnical properties of gas oil-contaminated kaolinite. *Engineering Geology*, 166, 11-16.
- Nasehi, S. A., Uromeihy, A., Nikudel, M. R., & Morsali, A. (2016). Influence of gas oil contamination on geotechnical properties of fine and coarse-grained soils. *Geotechnical and Geological Engineering*, 34(1), 333-345.
- Moubasher, H. A., Hegazy, A. K., Mohamed, N. H., Moustafa, Y. M., Kabiell, H. F., & Hamad, A. A. (2015). Phytoremediation of soils polluted with crude petroleum oil using *Bassia scoparia* and its associated rhizosphere microorganisms. *International Biodeterioration & Biodegradation*, 98, 113-120.
- Nazir, A. K. (2011). Effect of motor oil contamination on geotechnical properties of over consolidated clay. *Alexandria Engineering Journal*, 50(4), 331-35.
- NOSDRA (2021). Crude oil spill. Retrieved June, 2021 from <https://nosdra.oilspillmonitor.ng/>.
- Nudelman, N. S., Rios I. S. & Katusich, O. (2002) Fate of the oil residuals in Patagonian soils effects of the environmental exposure time. *Journal of Environmental Risk Assessment and Remediation*, 3, 1-8.
- Olgun, M., & Yıldız, M. (2010). Effect of organic fluids on the geotechnical behaviour of a highly plastic clayey soil. *Applied Clay Science*, 48(4), 615-621.
- Onyelowe, K. C. (2015). Pure crude oil contamination on Amaoba

- lateritic soil. *Electronic Journal of Geotechnical Engineering*, 20(3), 1129-1142.
- Ostovar, M., Ghiassi, R., Mehdizadeh, M. J., & Shariatmadari, N. (2020). Effects of crude oil on geotechnical specification of sandy soils. *Soil and Sediment Contamination: An International Journal*, 30(1), 58-73.
- Puri, V. K. (2000). Geotechnical aspects of oil-contaminated sands. *Soil and Sediment Contamination*, 9(4), 359-374.
- Puri, V. K., Das, B. M., Cook, E. E., & Shin, E. C. (1994). Geotechnical properties of crude oil contaminated sand. *ASTM Special Technical Publication*, 1221, 75-88.
- Rahman, Z. A., Mohd, U. H., & Taha, R. (2010). Influence of oil contamination on geotechnical properties of basaltic residual soil. *American Journal of Applied Sciences*, 7(7), 954-961.
- Rajabi, H., & Sharifipour, M. (2019). Geotechnical properties of hydrocarbon-contaminated soils: A comprehensive review. *Bulletin of Engineering Geology and the Environment*, 78(5), 3685-3717.
- Rasheed, Z. N., Ahmed, F. R., & Jassim, H. M. (2014). Effect of crude oil products on the geotechnical properties of soil. Witpress Ltd.
- Ratnaweera, P., & Meegoda, J. N. (2006). Shear strength and stress-strain behavior of contaminated soils. *Geotechnical Testing Journal*, 29(2), 133-140.
- Rojas, J., Salinas, L., & Garnica, I. (2003). Influence of the kinematic viscosity of oil contaminants in the compaction and hydraulic conductivity in certain type of soils. In *Groundwater engineering: recent advances: Proceedings of the International Symposium on Groundwater Problems Related to Geo-environment*, Okayama, Japan, 28-30 May, 2003. Taylor & Francis (Vol. 373).
- Saadoun, I. M. K. (2015). Impact of oil spills on marine life, emerging pollutants in the environment - Current and further implications. Larramendy, M. L., & Soloneski, S. (eds.). IntechOpen, Retrieved from <https://www.intechopen.com/chapters/48738>.
- Safehian, H., Rajabi, A. M., & Ghasemzadeh, H. (2018). Effect of diesel-contamination on geotechnical properties of illite soil. *Engineering Geology*, 241, 55-63.
- Salimnezhad, A., Soltani-Jigheh, H., & Soorki, A. A. (2021). Effects of oil contamination and bioremediation on geotechnical properties of highly plastic clayey soil. *Journal of Rock Mechanics and Geotechnical Engineering*, 13(3), 653-670.
- Shah, S. J., Shroff, A. V., Patel, J. V., Tiwari, K. C., & Ramakrishnan, D. (2003). Stabilization of fuel oil contaminated soil—A case study. *Geotechnical & Geological Engineering*, 21(4), 415-427.
- Shin, E. C., & Das, B. M. (2000). Some physical properties of unsaturated oil-contaminated sand. In *Advances in Unsaturated Geotechnics* (pp. 142-152).
- Shin, E. C., Omar, M. T., Tahmaz, A. A., Das, B. M., Atalar, C., & De Mello, L. G. (2002, August). Shear strength and hydraulic conductivity of oil-contaminated sand. In *Proceedings of the Fourth International Congress on Environmental Geotechnics, Rio de Janeiro, Brazil* (Vol. 1, pp. 9-13). AA Balkema Publishers Lisse.
- Singh, S. K., Srivastava, R. K., & John, S. (2009). Studies on soil contamination due to used motor oil and its remediation. *Canadian Geotechnical Journal*, 46(9), 1077-1083.
- SPDC (2021). Crude oil spills. Retrieved June 2021 from <https://www.shell.com.ng/sustainability/environment/oil-spills/january-2020.html>.
- Srivastava, R. K., & Pandey, V. D. (1998). Geotechnical evaluation of oil contaminated soil. In: Sarsby, R. W (ed.). *The proceeding of CREEN 2 in the second international symposium on Geotechnics Related to the Environment Krakow, Poland* Thomas Telford, London.
- Talukdar, D. K., & Saikia, B. D. (2013). Effect of crude oil on some consolidation properties of clayey soil. *International Journal of Emerging Technology and Advanced Engineering*, 3(2), 117-120.
- Trzciński, J., Williams, D. J., & Žbik, M. S. (2015). Can hydrocarbon contamination influence clay soil grain size composition? *Applied Clay Science*, 109, 49-54.
- Tse, A. C., & Eshiemomo, A. U. (2016). Geotechnical properties of soils in a crude oil impacted site in the Niger Delta, Nigeria. *IOSR Journal of Applied Geology and Geophysics*, 4(2), 69-76.
- Udonne, J. D., & Onwuma, H. O (2014). A study of effects of waste lubricating oil on the physical/chemical properties of soil and the possible remedies. *Journal of Petroleum and Gas Engineering*, 5(1), 9-14.
- Uguru, H., & Udubra, E. A. (2021). Optimizing the bioremediation of petroleum hydrocarbons contaminated soil. *International Journal of Innovative Environmental Studies Research*, 9(3), 47-53.
- Uguru, H., Akpokodje, O. I., & Esegbuyota, D. (2020). Remediation potency of charcoal block and sawdust in petroleum products contaminated soil. *Trends in Technical & Scientific Research*, 4(4), 131-140.
- Ur-Rehman, H., Abduljawwad, S. N., & Akram, T. (2007). Geotechnical behavior of oil-contaminated fine-grained soils. *Electronic Journal of Geotechnical Engineering*, 12, 1-12.
- Walls, W. D. (2010). Petroleum refining industry in China. *Energy Policy*, 38(5), 2110-2115.
- Yazdi, A., & Sharifi Teshnizi, E. (2021). Effects of contamination with gasoline on engineering properties of fine-grained silty soils with an emphasis on the duration of exposure. *SN Applied Sciences*, 3(7), 1-24.
- Youdeowei, P. O. (2008). The effect of crude oil pollution and subsequent fire on the engineering properties of soils in the Niger Delta. *Bulletin of Engineering Geology and the Environment*, 67(1), 119-121.