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Sensitivity Analysis of Crude Oil and Soil Properties on Diffusion Rate

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Abstract- Crude oil diffusion in soil is influenced by both the physical properties of the crude oil and the characteristics of the receiving soil. This study investigated the sensitivity of crude oil diffusion to API gravity and soil porosity using a numerical sensitivity-analysis approach. API gravity was varied from heavy to light crude-oil conditions, while soil porosity was varied from 0.25 to 0.55 to represent conditions ranging from relatively low- to high-porosity soils. The effect of each parameter on crude-oil concentration distribution was evaluated in the lateral and longitudinal directions after a simulation period of 35 days. The results showed that increasing API gravity resulted in a gradual reduction in localized crude-oil concentration. In the lateral direction, concentration decreased from approximately 3.54×10^4ppm at 10° API to 3.25×10^4ppm at 50° API, while the longitudinal concentration decreased from 4.28×10^4to 4.07×10^4ppm. In contrast, increasing soil porosity from 0.25 to 0.55 increased concentration from approximately 2.98×10^4to 3.34×10^4ppm in the lateral direction and from 3.91×10^4to 4.13×10^4ppm in the longitudinal direction. The response to porosity was more pronounced than the response to API gravity, indicating that soil pore structure exerts a stronger influence on simulated crude-oil diffusion under the investigated conditions. Concentrations were consistently higher in the longitudinal direction than in the lateral direction, indicating directional differences in diffusion behaviour. The findings demonstrate that both crude-oil characteristics and soil properties influence diffusion, with soil porosity exhibiting greater sensitivity within the investigated parameter ranges.

Keywords: Crude oil diffusion; sensitivity analysis; API gravity; soil porosity; petroleum hydrocarbons; contaminant transport; Niger Delta; soil contamination.

I. INTRODUCTION

Crude oil contamination of soil remains an important environmental problem in petroleum-producing regions because accidental releases from exploration, production, transportation, storage, refining, and pipeline infrastructure can introduce large quantities of petroleum hydrocarbons into terrestrial environments. Following a spill, crude oil can migrate through the soil profile and subsequently contaminate groundwater, surface water, vegetation, and soil ecosystems. The environmental fate of petroleum hydrocarbons is controlled by interconnected processes including diffusion, advection, dispersion, volatilisation, dissolution, sorption–desorption, and biodegradation ([1], [2], [3]). Recent reviews have emphasized that the movement of petroleum hydrocarbons cannot be adequately described without considering both the properties of the contaminant and the physical and chemical characteristics of the receiving soil.

The environmental significance of crude-oil contamination is particularly pronounced in the Niger Delta of Nigeria, where petroleum exploration and production have occurred for several decades. The region contains extensive wetlands, agricultural land, mangrove ecosystems, rivers, and shallow groundwater systems that can facilitate the movement and redistribution of petroleum contaminants. Recent field investigations have demonstrated that petroleum contamination remains widespread in parts of the Niger [4], for example, reported TPH concentrations ranging from 129 to 20,600 mg/kg in surface sediments and from 15.5 to 729 mg/kg in subsurface sediments within an investigated Niger Delta sub-catchment. Petroleum hydrocarbons were also detected in surface water and groundwater, demonstrating the potential for contaminants to migrate beyond the original spill locations. Similarly, recent studies have documented substantial hydrocarbon contamination in crude-oil-impacted soils within the Niger Delta. A 2023 investigation of crude-oil-impacted soils reported elevated concentrations of priority PAHs and identified a predominantly petrogenic source, with concentrations sufficiently high to present ecological concerns [5]. In another recent study, [6] found substantial TPH concentrations in both surface and subsurface soils from Ogoniland, with polluted surface soil containing approximately 36,775 ppm TPH compared with approximately 479.67 ppm in unpolluted soil. The study also identified petroleum hydrocarbons at depth, demonstrating the persistence and vertical distribution of petroleum contamination within the soil profile.

The movement of crude oil through soil is governed by several transport mechanisms. Diffusion refers to the movement of molecules resulting from concentration gradients, whereas advection involves the bulk movement of dissolved or mobile contaminants with flowing water. Dispersion results from variations in flow velocity and pore-scale heterogeneity. In actual contaminated soil systems, these processes can occur simultaneously and interact with sorption, dissolution, volatilisation, and biodegradation. [7] emphasized that diffusion is particularly relevant to mass transfer in porous media and that contaminant migration in the subsurface is strongly affected by heterogeneity and anisotropy. The authors further identified accurate determination of transport parameters as an important requirement for reliable contaminant-transport modelling.

The diffusion rate of crude oil is therefore not a constant property of the contaminant alone. It depends on the characteristics of the crude oil as well as the properties of the medium through which it migrates. [8] identified viscosity and volatility as important petroleum-hydrocarbon characteristics, while porosity, hydraulic properties, water status, soil organic matter, and atmospheric conditions were identified as important environmental controls. The study therefore established that petroleum-hydrocarbon behaviour results from an interaction between contaminant characteristics and soil properties rather than from a single controlling variable. Crude-oil viscosity is one of the most important properties influencing its movement through porous media. Viscosity represents the resistance of a fluid to deformation and flow, and an increase in viscosity generally reduces the mobility of liquid hydrocarbons.[9] reported that the viscosity and density of petroleum hydrocarbons influence their dispersal following surface spills, with increasing viscosity reducing the intrinsic infiltration rate of liquid hydrocarbons into fine-textured soils. Experimental evidence from the Niger Delta also supports the importance of viscosity. [10] found that crude oils with lower kinematic viscosity exhibited higher diffusion rates in loamy-sand soil, whereas the crude oil with the highest viscosity exhibited the lowest diffusion rate.

The composition of crude oil can also influence its migration because crude oil is a complex mixture of saturated hydrocarbons, aromatic hydrocarbons, resins, and asphaltenes. These components differ in molecular size, polarity, volatility, solubility, and resistance to degradation. Recent research in Ogoniland has demonstrated the persistence of long-chain hydrocarbons in contaminated soil, with C20–C28 compounds being prominent in polluted surface soils [11]. Long-chain hydrocarbons generally have lower water solubility and may interact more strongly with soil organic matter and mineral surfaces than more mobile low-molecular-weight fractions.Soil characteristics constitute another major group of variables controlling crude-oil diffusion. Soil texture, particle-size distribution, porosity, permeability, bulk density, moisture content, organic-matter content, mineral composition, and pore connectivity influence the movement and retention of hydrocarbons. [12] identified porosity, hydraulic properties, water status, and organic matter as major factors controlling petroleum-hydrocarbon behaviour in soil. The interaction of these properties determines the size and connectivity of pores available for contaminant migration and the extent to which petroleum compounds are retained within the soil matrix. Soil texture is particularly important because it determines the distribution and connectivity of pore spaces. Coarse-textured soils generally contain larger pores and can permit relatively rapid movement of mobile hydrocarbons, whereas fine-textured soils contain smaller pores and greater specific surface area, which can enhance contaminant retention. The effects of soil texture can therefore produce significant differences in diffusion rate even when the same crude oil is introduced under similar experimental conditions.

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This interaction is important when comparing diffusion behaviour among different soil environments.Soil moisture also affects hydrocarbon migration because water occupies part of the soil-pore system and modifies effective porosity, hydraulic conductivity, contaminant partitioning, and microbial activity. Changes in water content can therefore alter the pathways through which petroleum hydrocarbons migrate. [13] identified water status as one of the major factors controlling petroleum-hydrocarbon fate and transport, while [14] emphasized the importance of hydraulic conditions and subsurface characterization when predicting crude-oil migration.
Soil organic matter is another important controlling variable because petroleum hydrocarbons are predominantly hydrophobic and can partition into organic phases within the soil. Increased organic-matter content may enhance sorption and reduce the fraction of hydrocarbon available for immediate migration. Recent research has demonstrated that soil organic matter and texture can influence the vertical migration potential of petroleum hydrocarbons with different carbon-chain lengths. Consequently, the same crude oil can exhibit different migration patterns when introduced into soils having different organic-matter contents and particle-size distributions.The influence of soil properties is not restricted to physical transport. Petroleum contamination can also alter the physicochemical and biological characteristics of soil. [15], for example, demonstrated that oil contamination can affect the physicochemical and thermal characteristics of sandy-loam soils. Such changes may subsequently influence porosity, moisture behaviour, microbial activity, and contaminant retention, creating feedback between the contaminant and the soil environment. Biological processes can further modify the concentration gradient responsible for diffusion. Petroleum-hydrocarbon-degrading microorganisms can consume hydrocarbon constituents and consequently reduce their concentration within contaminated zones. Recent research in the Niger Delta has demonstrated that petroleum contamination can significantly alter soil microbial communities. For example, a 2024 investigation reported differences in microbial community composition between contaminated and uncontaminated soils and detected oil contamination at depth. The authors also identified hydrocarbon-degrading functional genes within the contaminated environment, indicating the potential contribution of indigenous microorganisms to petroleum-hydrocarbon transformation. The persistence of petroleum hydrocarbons in Niger Delta soils has also been demonstrated by recent research on chronically contaminated sites. [16] reported substantially higher TPH and total organic carbon in polluted surface and subsurface soils from Ogoniland than in unpolluted soil. The presence of long-chain hydrocarbons at depth further demonstrates that contaminant distribution is affected by both migration and degradation processes. These findings reinforce the need to distinguish between the processes responsible for contaminant movement and those responsible for contaminant removal or transformation. The interaction between crude-oil properties and soil properties makes the prediction of diffusion rate particularly challenging. A reduction in viscosity may increase oil mobility, while increased soil organic matter may simultaneously increase hydrocarbon retention. Similarly, increased soil moisture may alter pore connectivity and hydraulic conditions, while soil texture may determine the extent to which the contaminant is retained or transmitted. Consequently, the overall diffusion response may result from several competing mechanisms rather than from one independent parameter.

Recent reviews have highlighted the importance of developing improved models for petroleum-hydrocarbon migration.[17] reviewed petroleum-pollutant migration in soil and water and identified adsorption, desorption, biological processes, and numerical transport modelling as important components of contaminant-migration assessment. The review further emphasized that improved understanding of migration mechanisms is necessary for risk assessment and pollution-control strategies. [18] similarly identified inadequate high-resolution characterization of soil and subsurface conditions as an important limitation in petroleum-contamination investigations in Nigeria. The need for improved understanding is particularly important in the Niger Delta because recent investigations indicate that petroleum contamination may extend beyond the immediate spill location and into subsurface environments. [19] demonstrated the occurrence of TPH and PAHs in surface sediment, subsurface sediment, surface water, and groundwater within a Niger Delta sub-catchment. Their findings highlight the importance of understanding the pathways and controlling parameters governing contaminant migration. Similarly, recent geoelectrical investigations in the Central Niger Delta have identified subsurface hydrocarbon-contaminated zones and possible contaminant flow pathways, further demonstrating the spatial complexity of petroleum contamination. [20] investigated the three-dimensional diffusion behaviour of different crude oil types in soil. The findings demonstrated that crude oil type significantly affects its rate and spatial pattern of diffusion through soil. The study showed that crude oils with different physical properties exhibited different levels of lateral, longitudinal, and vertical migration. Overall, lighter crude oil exhibited greater mobility and wider spatial dispersion, while heavier crude oil tended to remain more concentrated around the source region because of its relatively higher viscosity. The study also demonstrated that diffusion was anisotropic, meaning that the extent of crude-oil movement differed among the three spatial directions. The work therefore established that crude-oil physical properties, particularly viscosity and density-related characteristics, play an important role in determining contaminant migration in soil. These findings provide useful experimental evidence for understanding and predicting the movement of different crude-oil types following spills in soil environments. This work provides the experimental foundation for subsequent modelling and sensitivity-analysis studies on crude-oil diffusion.

Despite the growing body of research on petroleum contamination, an important gap remains in quantitatively determining the relative sensitivity of crude-oil and soil properties to diffusion rate. Much of the existing literature has examined individual factors such as viscosity, soil texture, organic matter, contamination concentration, or moisture content. However, comparatively less attention has been given to systematically evaluating how changes in several crude-oil and soil parameters affect the diffusion response under a common experimental or mathematical framework. Such an assessment is important because the parameter exerting the greatest influence on diffusion may differ according to the crude-oil type and soil environment.

Sensitivity analysis provides a useful approach for addressing this research gap. It enables the influence of individual parameters on diffusion rate to be quantified while other parameters are systematically varied or controlled. Consequently, sensitivity analysis can identify dominant parameters, reveal interactions between variables, support parameter estimation, and improve the reliability of mathematical models for contaminant transport. This is particularly relevant because accurate transport parameters are required for predicting petroleum-hydrocarbon migration and evaluating potential environmental risks.

Therefore, the present study focuses on the sensitivity analysis of crude-oil and soil properties on diffusion rate. The study considers the effects of selected crude-oil properties and soil characteristics on the rate of crude-oil movement through soil and seeks to establish the relative importance of these parameters. The results are expected to improve understanding of crude-oil diffusion behaviour, support the development and calibration of predictive transport models, and provide useful information for environmental assessment and remediation planning in petroleum-contaminated soils, particularly within the Niger Delta region of Nigeria.

II. MATERIALS AND METHODS

2.1 Materials

The materials used in this study includes

i. MATLAB R2024b
ii. Datafit version 9
iii. Microsoft excel

2.2 Methods

2.2.1 Perform sensitivity analysis of crude oil and soil properties on the diffusion rate.

The sensitivity analysis was conducted to evaluate the influence of API gravity (crude oil property) and soil porosity (soil property) on crude oil diffusion in soil at a simulation time of 25 days. The analysis focused on concentration distribution in both longitudinal (x-direction) and lateral (y-direction).

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2.2.1.1 API Gravity Sensitivity by Keeping soil Porosity Constant

A range of API gravity values representing crude oil types from heavy to light was selected and varied using a fixed step size:

i. Range: 10° API (heavy) to 45° API (light)
ii. Step size: 5° API
iii. Values used: 10, 15, 20, 25, 30, 35, 40, 45, For each API value:

The corresponding diffusion coefficient was evaluated using the adopted correlation:

$$D = 3.0752 \times 10^{-2} - 2.6988 \times 10^{-4} X_1 - 3.3203 \times 10^{-5}/X2 + 7.5499 \times 10^{-5} X_1^2 + 590.5674/{X_2}^2 - 0.3736\, X_1/X_2 \quad (1)$$

Where D = Diffusivity of crude oil, X_1 = API gravity of the crude oil, X_2 = Porosity of Soil. Equation (1) is the empirical correlation model that was generated by DataFit software version 9.1 The diffusion model was solved over 0–35 days.At t = 35 days, concentration profiles were extracted along:Longitudinal direction (x-axis) and Lateral direction (y-axis). The resulting profiles were compared to determine how crude oil type affects diffusion spread and penetration depth.

2.2.1.2 Soil Porosity Sensitivity by Keeping API Gravity of Crude Constant

Soil types were represented using porosity ranges typical of clay, loamy, and sandy soils, and varied with a defined step size:

i. Clay soil: 0.25 – 0.35
ii. Loamy soil: 0.35 – 0.45
iii. Sandy soil: 0.45 – 0.55
iv. Step size: 0.05
v. Values used: 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55

For each porosity value:

i. The effective diffusion coefficient was adjusted accordingly.
ii. The model was simulated over 0–35 days.
iii. At t = 35 days, concentration distributions were obtained along:

Longitudinal direction (x-axis) and Lateral direction (y-axis). The results were compared to evaluate the effect of soil structure on crude oil diffusion.

III. RESULTS AND DISCUSSION

3.1 Sensitivity Analysis Results

Sensitivity analysis was conducted to evaluate how variations in key parameters influence the diffusion behavior of crude oil in soil over time. In this study, particular attention was given to two critical factors: API gravity, representing crude oil properties, and soil porosity, representing the characteristics of the porous medium. These parameters were selected due to their direct impact on diffusion mechanisms, fluid mobility, and contaminant transport in subsurface environments. For the crude oil property analysis, API gravity was varied from heavy to light crude to examine how changes in density and viscosity affect the rate and extent of diffusion. Conversely, soil porosity was varied across a range representative of clay, loamy, and sandy soils to assess how pore space availability influences crude oil migration and retention.

3.1.1 Effect of Varying API gravity of Crude on the final concentration of crude oil in soil in the lateral and longitudinal direction of flow

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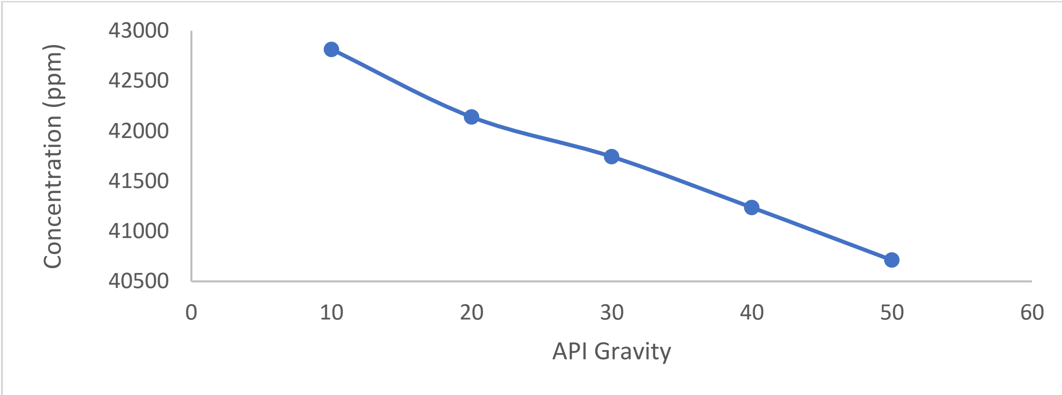

Figure 1: Effect of API Gravity of Crude Oil on Longitudinal Flow Direction

Figure 1 shows that concentration decreases as API gravity increases. The concentration decreases from approximately 42,800 ppm at an API gravity of 10° to about 40,700 ppm at 50° API. This indicates an inverse relationship between API gravity and crude-oil concentration in the longitudinal flow direction. The higher concentration associated with lower API gravity suggests that heavier crude oils, which generally have higher viscosity and lower API gravity, tend to exhibit greater retention and slower longitudinal movement through the soil. Conversely, higher-API-gravity crude oils are lighter and less viscous, allowing them to migrate more readily through the soil, resulting in lower residual concentrations along the longitudinal direction. Overall, the figure demonstrates that crude-oil properties, particularly API gravity, influence its longitudinal transport and distribution in soil.

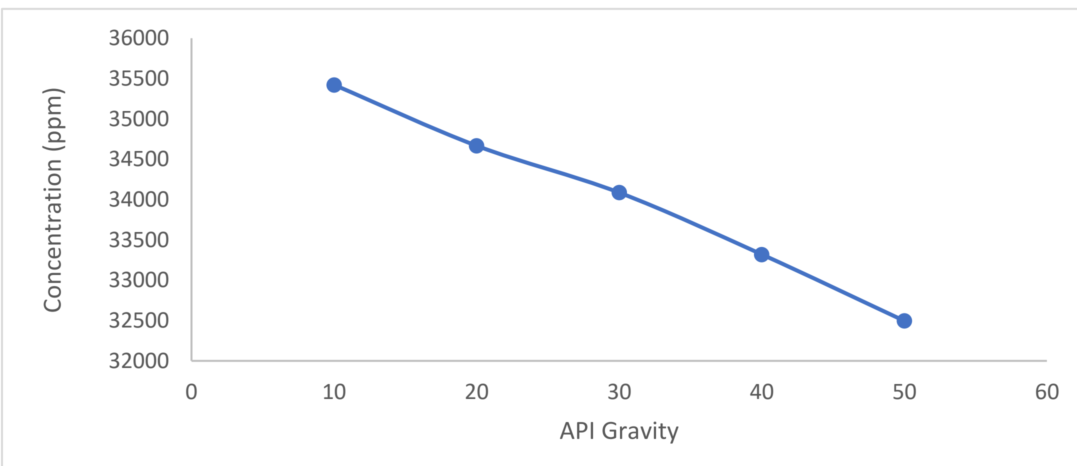

Figure 2: Effect of API Gravity of Crude Oil on Lateral Flow Direction

Figure 2 shows a clear inverse relationship between API gravity and crude-oil concentration in the lateral flow direction. The concentration decreases progressively from approximately 35,400 ppm at 10° API to about 32,500 ppm at 50° API.The higher concentrations observed at lower API gravities indicate that heavier crude oils tend to remain more concentrated within the soil, largely because of their higher viscosity and reduced mobility. As API gravity increases, the crude oil becomes lighter and generally less viscous, facilitating greater migration through the soil and consequently reducing the residual concentration along the lateral direction.Overall, the figure demonstrates that API gravity significantly influences the lateral distribution of crude oil in soil, with lower-API (heavier) crude oils exhibiting higher

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retained concentrations than higher-API (lighter) crude oils.

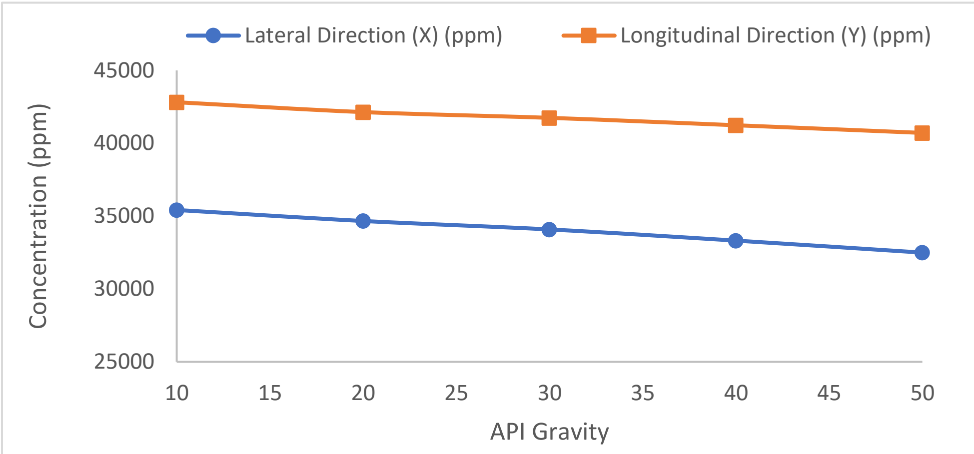

Figure 3: Combined Plot of Crude API gravity on flow directions

Figure 3 presents the sensitivity of crude oil diffusion in soil to variations in API gravity after a simulation period of 35 days. API gravity values ranging from 10° to 50° were considered to represent heavy to light crude oils, and their effects on concentration distribution were analyzed in both the lateral (x-direction) and longitudinal (y-direction).The results indicate a consistent decrease in crude oil concentration with increasing API gravity in both directions. In the lateral direction, concentration decreased from 3.54×10^4 ppm at 10° API to 3.25×10^4 ppm at 50° API, while in the longitudinal direction, it reduced from 4.28×10^4 ppm to 4.07×10^4 ppm over the same range. This trend reflects enhanced diffusion and mobility associated with lighter crude oils, which typically exhibit lower viscosity and density. Additionally, higher concentrations were consistently observed in the longitudinal direction compared to the lateral direction, suggesting anisotropic diffusion behavior influenced by soil structure or model boundary conditions. The rate of decrease in concentration was gradual, indicating moderate sensitivity of diffusion to API gravity, with slightly higher sensitivity observed in the lateral direction.Overall, the findings demonstrate that lighter crude oils tend to spread more extensively, resulting in lower localized concentrations, whereas heavier crude oils remain more concentrated and localized within the soil matrix. These results highlight the importance of crude oil properties in predicting contamination spread and suggest that while API gravity plays a significant role, other factors such as soil properties may exert a stronger influence on diffusion behavior.

3.1.2 Effect of Varying Porosity of Soil on the final concentration of crude oil in soil in the lateral and longitudinal direction of flow

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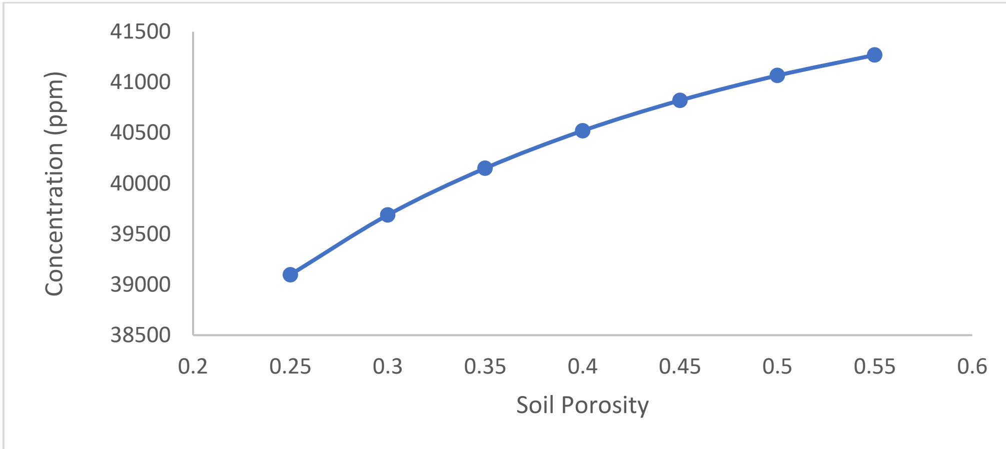

Figure 4: Effect of Soil Porosity on Longitudinal Flow Direction

Figure 4 shows a positive relationship between soil porosity and crude-oil concentration in the longitudinal flow direction. As soil porosity increases from approximately 0.25 to 0.55, the concentration increases from about 39,100 ppm to 41,250 ppm.The increase in concentration with increasing porosity indicates that more porous soil conditions influence the longitudinal transport and retention of crude oil. Higher porosity provides greater interconnected pore spaces through which crude oil can migrate, thereby facilitating its movement along the longitudinal direction. The relatively gradual increase in concentration also suggests that porosity is an important soil property controlling crude-oil distribution. Overall, Figure 4 demonstrates that increasing soil porosity is associated with increased crude-oil concentration in the longitudinal direction, indicating that soil structure and pore-space characteristics play an important role in crude-oil transport through soil.

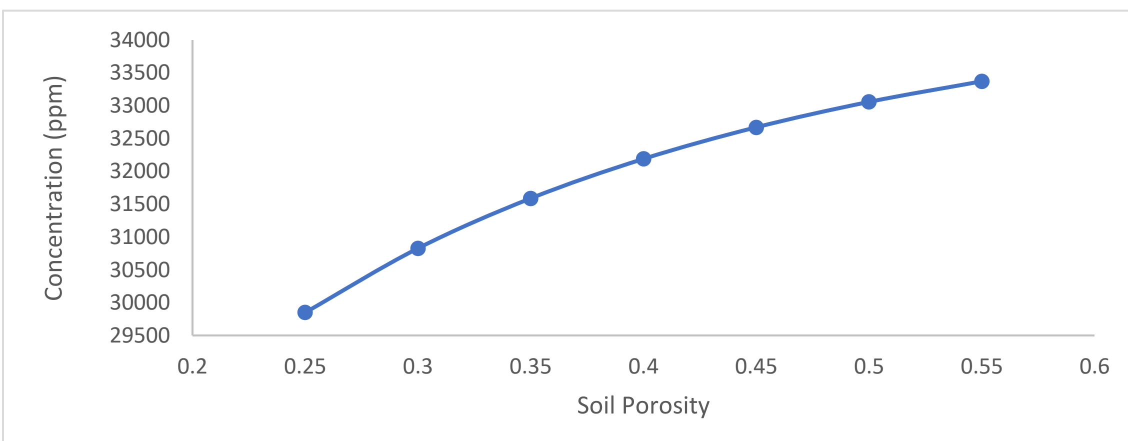

Figure 5: Effect of Soil Porosity on lateral Flow Direction

Figure 5 shows a positive relationship between soil porosity and crude-oil concentration in the lateral flow direction. As soil porosity increases from approximately 0.25 to 0.55, the concentration increases progressively from about 29,850 ppm to 33,350 ppm.This trend indicates that increasing soil porosity enhances the movement and distribution of crude oil through the lateral direction. Higher porosity provides more interconnected pore spaces, allowing crude oil to migrate more readily and resulting in higher concentrations being observed along the lateral flow path. The gradual reduction in the rate of increase at higher porosity values suggests that the influence of porosity may become less pronounced as the pore space becomes increasingly available.Overall, Figure 5 demonstrates that soil porosity is an important factor controlling lateral crude-oil transport, with higher porosity associated with increased crude-oil concentration along the lateral flow direction.

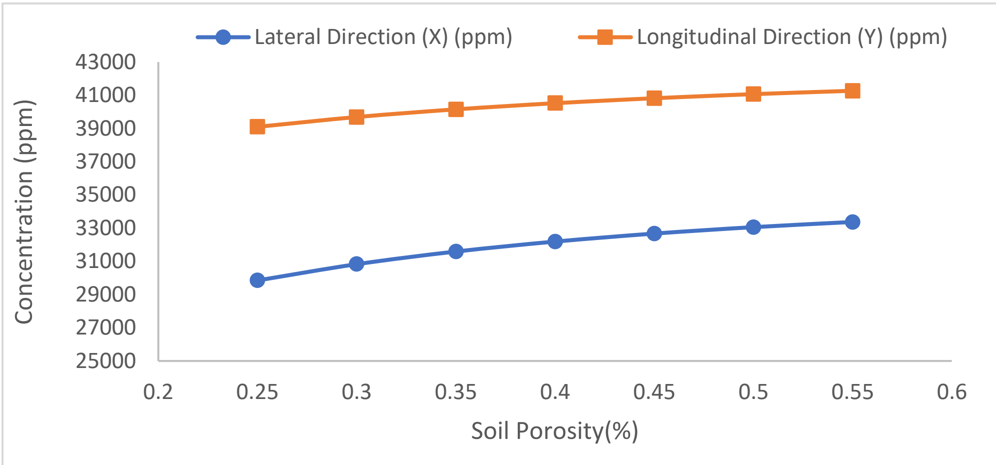

Figure 6: Combined Plot of Soil Porosity on flow directions

Porosity values ranging from 0.25 to 0.55 were considered to represent different soil types, from clayey to sandy formations, and their effects on concentration distribution were analyzed in both the lateral (x-direction) and longitudinal (y-direction) as shown in figure 6. The results show a consistent increase in crude oil concentration with increasing porosity in both directions. In the lateral direction, concentration increased from 2.98×10^4 ppm at a porosity of 0.25 to 3.34×10^4 ppm at 0.55, while in the longitudinal direction, it rose from 3.91×10^4 ppm to 4.13×10^4 ppm over the same range. This trend indicates that higher porosity enhances the effective diffusion and storage capacity of the soil, allowing greater crude oil penetration and accumulation. Furthermore, concentration values in the longitudinal direction were consistently higher than those in the lateral direction, suggesting anisotropic diffusion behavior likely influenced by soil structure or directional permeability. The increase in concentration with porosity is gradual but more pronounced than in the API gravity case, indicating that soil porosity exerts a stronger influence on diffusion behavior. Overall, the findings reveal that soils with higher porosity (e.g., sandy soils) facilitate greater crude oil migration and retention, leading to higher concentration levels, whereas low-porosity soils (e.g., clay) restrict fluid movement and limit diffusion. This highlights soil porosity as a critical controlling parameter in predicting crude oil transport and environmental contamination in subsurface systems.

IV. CONCLUSION

The sensitivity analysis demonstrated that both crude-oil API gravity and soil porosity influence crude-oil diffusion behaviour, although their effects differed in magnitude. Variation in API gravity from heavy to light crude-oil conditions produced a gradual reduction in localized crude-oil concentration in both the lateral and longitudinal directions. The reduction was from approximately 3.54×10^4to 3.25×10^4ppm in the lateral direction and from 4.28×10^4to 4.07×10^4ppm in the longitudinal direction. Soil porosity exhibited a comparatively stronger influence on diffusion behaviour. Increasing porosity from 0.25 to 0.55 resulted in an increase in crude-oil concentration from approximately 2.98×10^4to 3.34×10^4ppm in the lateral direction and from 3.91×10^4to 4.13×10^4ppm in the longitudinal direction. This indicates that increasing pore-space availability facilitates greater crude-oil penetration and accumulation within the soil medium. Comparison of the two sensitivity analyses indicates that soil porosity produced a stronger diffusion response than API gravity within the investigated ranges. The relatively gradual response to API gravity suggests moderate sensitivity to crude-oil density-related characteristics, whereas the more pronounced response to porosity demonstrates the importance of the physical structure of the soil in controlling crude-oil movement. The consistently higher concentrations obtained in the longitudinal direction compared with the lateral direction further indicate directional or anisotropic diffusion behaviour. This observation suggests that soil structure and directional transport characteristics should be considered when assessing crude-oil migration in contaminated soil. Overall, the findings establish that soil porosity is an important sensitivity parameter governing crude-oil diffusion, while API gravity also contributes to changes in diffusion behaviour. The sensitivity analysis therefore provides a quantitative basis for identifying the parameters that should receive greater attention when predicting crude-oil migration and assessing petroleum-contaminated soils in the Niger Delta.

REFERENCES

[1] M. A. Adeniran, M. A. Oladunjoye, and K. O. Doro, "Soil and groundwater contamination by crude oil spillage: A review and implications for remediation projects in Nigeria," *Frontiers in Environmental Science*, vol. 11, Art. no. 1137496, 2023. Frontiers

[2] M. Balseiro-Romero, C. Monterroso, and J. J. Casares, "Environmental fate of petroleum hydrocarbons in soil: Review of multiphase transport, mass transfer, and natural attenuation processes," *Pedosphere*, vol. 28, no. 6, pp. 833–847, 2018. ScienceDirect

[3] S. A. Ganiyu, O. T. Olurin, D. O. Morakinyo, M. O. Olobadola, and J. A. Rabiu, "Physico-chemical and thermal characteristics of sandy loam soils contaminated by single and mixed pollutants (mineral and vegetable oils)," *Environmental Monitoring and Assessment*, vol. 194, Art. no. 454, 2022. Springer

[4] I. Ola, C. Drebenstedt, R. M. Burgess, M. Mensah, N. Hoth, P. Okoroafor, and C. Küls, "Assessing petroleum contamination in parts of the Niger Delta based on a sub-catchment delineated field assessment," *Environmental Monitoring and Assessment*, vol. 196, Art. no. 585, 2024. Springer

[5] A. Ola, C. Drebenstedt, R. M. Burgess, M. Mensah, N. Hoth, and C. Külls, "Remediating oil contamination in the Niger Delta region of Nigeria: Technical options and monitoring strategies," *The Extractive Industries and Society*, vol. 17, Art. no. 101405, 2024. ScienceDirect

[6] A. U. Okoye, R. Selvarajan, C. B. Chikere, G. C. Okpokwasili, and K. Mearns, "Characterization and identification of long-chain hydrocarbon-degrading bacterial communities in long-term chronically polluted soil in Ogoniland: An integrated approach using culture-dependent and independent methods," *Environmental Science and Pollution Research*, vol. 31, pp. 30867–30885, 2024. Springer

[7] L. Wang, Y. Cheng, R. Naidu, and M. Bowman, "The key factors for the fate and transport of petroleum hydrocarbons in soil with related in/ex situ measurement methods: An overview," *Frontiers in Environmental Science*, vol. 9, Art. no. 756404, 2021. Frontiers

[8] M. Wang, "Migration rules of petroleum pollutants in water and soil: A review," *Petroleum Science and Technology*, vol. 42, no. 25, pp. 4281–4296, 2023. Taylor & Francis

[9] N. O. Ahmed, N. N. Nik Daud, and I. A. Okunlola, "Geoelectrical soil mapping for subsurface hydrocarbon contaminant characterization and remediation site zoning at Alode, Central Niger Delta, Nigeria," *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 136, Art. no. 103726, 2024. ScienceDirect

[10] A. E. Futughe, H. Jones, and D. Purchase, "A novel technology of solarization and phytoremediation enhanced with biosurfactant for the sustainable treatment of PAH-contaminated soil," *Environmental Geochemistry and Health*, vol. 45, pp. 3847–3863, 2023.

[11] I. B. Ahmed, E. O. Nwaichi, E. Ugwoha, J. N. Ugbebor, and S. B. Arokoyu, "Cost reduction strategies in the remediation of petroleum hydrocarbon contaminated soil," *Open Research Africa*, vol. 5, Art. no. 21, 2022. PubMed

[12] S. A. Ganiyu, O. T. Olurin, D. O. Morakinyo, M. O. Olobadola, and J. A. Rabiu, "Physico-

chemical and thermal characteristics of sandy loam soils contaminated by single and mixed pollutants," *Environmental Monitoring and Assessment*, vol. 194, Art. no. 454, 2022.

[13] K. M. Oghenejoboh and Y. T. Puyate, "Experimental investigation of the effects of crude oil physical properties on its diffusion rate in soil medium," *Journal of Industrial Pollution Control*, vol. 26, no. 2, pp. 131–137, 2010.

[14] K. M. Oghenejoboh, Y. T. Puyate, and M. F. N. Abowei, "Concentration distribution of spilled crude petroleum in different soils I: Effects of volume of oil on diffusion rate," *Pollution Research*, vol. 28, no. 3, pp. 321–327, 2009.

[15] K. M. Oghenejoboh, M. F. N. Abowei, and Y. T. Puyate, "Sorption mechanism of Nigerian crude petroleum into soil medium," *Journal of Pollution Research*, vol. 27, no. 1, pp. 7–12, 2008.

[16] M. O. Benka-Coker and J. A. Ekundayo, "Effects of an oil spill on soil physico-chemical properties of a spill site in the Niger Delta area of Nigeria," *Environmental Monitoring and Assessment*, vol. 36, pp. 93–104, 1995.

[17] P. Fine, E. R. Graber, and B. Yaron, "Soil interactions with petroleum hydrocarbons: Abiotic processes," *Soil Technology*, vol. 10, no. 2, pp. 133–153, 1997.

[18] L. Wang, Y. Cheng, R. Naidu, and M. Bowman, "The key factors for the fate and transport of petroleum hydrocarbons in soil with related in/ex situ measurement methods: An overview," *Frontiers in Environmental Science*, vol. 9, Art. no. 756404, 2021. Frontiers

[19] M. Wang, "Migration rules of petroleum pollutants in water and soil: A review," *Petroleum Science and Technology*, vol. 42, no. 25, pp. 4281–4296, 2023. Taylor & Francis

[20] Z. Jaja, J. G. Akpa, K. K. Dagde, and T. O. Goodhead, "Experimental Investigation of Three-Dimensional Diffusion Behavior of Crude Oil Types in Soil Environment," *Journal of Dalian University of Technology*, vol. 33, no. 8, pp. 71–87, 2026.