



Geotechnical Changes in Oil-Contaminated Desert Soils and Their Impact on Infrastructure Stability in Arid Regions: A Case Study in Dry and Desert Ecosystems of Southern Libya

Nouraldin Almahdi Ibrahim basha

Department of planning and Population Studies, College of Arts and Sciences -Wadi Ataba
Fezzan university, Libya

التغيرات الجيوتقنية في التربة الصحراوية الملوثة بالنفط وتأثيرها على استقرار البنية التحتية في المناطق القاحلة: دراسة حالة في النظم البيئية الجافة والصحراوية بجنوب ليبيا

نور الدين المهدي إبراهيم باشا

قسم التخطيط والدراسات السكانية، كلية الآداب والعلوم - وادي عتبة، جامعة فزان، ليبيا

*Corresponding author: Nou.basha@fezzanu.edu.ly

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Abstract:

Petroleum waste disposal in oil-producing regions creates dangerous geotechnical problems affecting desert ecosystems because soil restoration requires extremely long periods. This research investigates how oil contamination affects the geotechnical properties of soils in the Sharara, Elephant, and NC-186 Mutakhendush oil fields in southern Libya. The study utilized simulated datasets and geotechnical testing to analyze changes in strength, density, permeability, and shear parameters in locations experiencing produced water, drilling wastes, and accidental spills. Results indicate that oil contamination transformed soil properties beyond natural background levels, with sites showing moderate to high degradation. Specifically, Unconfined Compressive Strength (UCS) and cohesion at Sharara showed reductions of 58% and 67%, respectively. The analysis of spatial data reveals that operational activities and waste disposal methods create distinct contamination patterns. The research also explores soil stabilization techniques using AI-based geographical mapping to enhance monitoring and remediation planning. Experimental results demonstrated that a combined approach using microbial degradation and Enzyme-Induced Calcite Precipitation (EICP) with lime achieved the highest recovery rates, restoring up to 70% of UCS. These findings emphasize the urgent need for effective petroleum waste management and advanced stabilization strategies to reduce geotechnical risks and protect infrastructure and desert habitats in southern Libya. Integrating AI-assisted mapping with computational tools provides a robust framework for environmental managers to monitor and control geotechnical instability in remote arid regions.

Keywords: Oil contamination, geotechnical properties, desert ecosystems, infrastructure stability, soil stabilization.

الملخص

يؤدي التخلص من النفايات النفطية في المناطق المنتجة للنفط إلى مشكلات جيوتقنية خطيرة تؤثر على النظم البيئية الصحراوية لأن استعادة التربة تتطلب فترات زمنية طويلة جداً. يبحث هذا البحث في كيفية تأثير التلوث النفطي على الخصائص الجيوتقنية للتربة في حقول الشرارة، والفيل، و NC-186 متخدوش الواقعة في جنوب ليبيا. استخدمت الدراسة مجموعات بيانات محاكاة واختبارات جيوتقنية لتحليل التغيرات في المقاومة والكثافة والنفاذية ومعاملات القص في المواقع التي تعرضت للمياه المصاحبة ونفايات الحفر والانسكابات العرضية. تشير النتائج إلى أن التلوث النفطي حول خصائص التربة إلى مستويات تتجاوز الخلفية الطبيعية، حيث أظهرت المواقع تدهوراً يتراوح من متوسط إلى عالٍ. وبشكل محدد، أظهرت مقاومة الضغط غير المحصور (UCS) والتماسك في حقل الشرارة انخفاضاً بنسبة 58% و 67% على التوالي. ويكشف تحليل البيانات المكانية أن الأنشطة التشغيلية وطرق التخلص من النفايات تخلق أنماط تلوث متميزة. كما يبحث البحث في تقنيات تثبيت التربة باستخدام أنظمة الخرائط الجغرافية القائمة على الذكاء الاصطناعي لتعزيز قدرات المراقبة والتخطيط للمعالجة. وأظهرت النتائج التجريبية أن النهج المشترك الذي يستخدم التحلل الميكروبي وترسيب الكالسيت الناجم عن الإنزيم (EICP) مع الجير حقق أعلى معدلات استرداد، حيث استعاد ما يصل إلى 70% من مقاومة الضغط غير المحصور. وتؤكد هذه النتائج على الحاجة الملحة لإدارة فعالة للنفايات النفطية واستراتيجيات تثبيت متطورة للحد من المخاطر الجيوتقنية وحماية البنية التحتية والموائل الصحراوية في جنوب ليبيا. ويوفر دمج الخرائط المدعومة بالذكاء الاصطناعي مع الأدوات الحسابية إطاراً قوياً لمديري البيئة لمراقبة والتحكم في عدم الاستقرار الجيوتقني في المناطق القاحلة النائية.

الكلمات المفتاحية: التلوث النفطي، الخصائص الجيوتقنية، النظم البيئية الصحراوية، استقرار البنية التحتية، تثبيت التربة.

Introduction

Together with the process of drilling and waste management practices, the oil extraction process leads to hydrocarbon contamination in oil production areas due to the release of oil into the ground. Geotechnical hazards in these areas are long-term since hydrocarbons change the structure of soil, decrease inter-particle friction, and alter mechanical properties (Alhassan & Fagge, 2013; Elsaigh & Oluremi, 2021). Most scientific papers have been conducted on different polluted locations, indicating that industrial practices contribute to soil degradation surpassing natural environmental standards (Panagos et al., 2013; Zhao et al., 2015). In this context, recent studies have emphasized the synergistic impact of organic wastes and additives on soil properties, suggesting that comprehensive reviews of waste management are essential for understanding soil behavior under stress (Salem et al., 2024).

Sharara and Elephant fields within the Murzuq Basin are very sensitive to the arid climate of southern Libya due to low precipitation, high evaporation rates, sandy soil composition, and limited plant growth. These conditions hinder natural recovery, allowing contaminants to persist and influence geotechnical behavior (Alhassan & Fagge, 2013). The oilfield operations generate large volumes of produced water and drilling waste consisting of hydrocarbons, which increase the risk of lowering soil strength and altering permeability (Elsaigh & Oluremi, 2021). Furthermore, the application of advanced materials like biochar has been synthesized globally as a potential challenge and an opportunity for soil amendment and water retention in such degraded environments (Mahommed et al., 2025).

Adsorption, pore clogging, and modifications to soil fabric regulate the behavior of oil in soils (Moghal et al., 2023; Du et al., 2014). Recent advancements in biosorbents, such as those derived from *Alhagi graecorum* roots, have shown promise in decontamination processes through specific adsorption mechanisms that could be adapted for soil remediation (Ahwaas et

al., 2025). However, more contaminations associated with industrial activities continue to have a direct effect on infrastructure (Zhao et al., 2023). Desert ecosystems' poor vegetation cover prevents successful natural recovery, leading to geotechnical degradation that puts pipelines, roads, and foundations at risk (Awoyera et al., 2020; Stone & Newson, 2022).

The oilfields in the south require full monitoring systems due to frequent spills and leaks during storage and a lack of proper waste management. To develop effective environmental management and sustainable waste strategies, it is crucial to understand contaminant mobility and geotechnical variations (Mahammedi et al., 2020). Towards achieving environmental sustainability, electrochemical methods and other remediating technologies for heavy metal and hydrocarbon contamination in soil and water present significant achievements and future prospects for the region (Abdala et al., 2025).

Study Area

The area of research is the principal oil extraction sites all across the southern part of Libya and particularly in the Sharara, Elephant (Al-Fil) and NC-186 Makhendush oil fields in the Murzuq Basin. The hyper-arid area has less than 100 millimeters of rainfall per year that generates its natural state since it has sandy soils and low organic content accompanied by sparse plantation that predisposes the area to geotechnical changes (Alhassan and Fagge, 2013). Natural soil restoration activities are faced with challenges due to the fact that rainfall amount is too low, and the evaporation is extremely high as wind erosions transfer contaminants to the desert terrain.

Sharara oil field that commenced operations in the 1980s generates light sweet crude oil whereas the Elephant oil field commenced its operations in 1997. The disciplines produce water and exploration waste productions with the hydrocarbons that were excavated in the underground rock structure. The oil infrastructure both in form of pipelines and storage facilities as well as the leaks and accident spills leave behind certain areas that are geotechnically unstable.

The combination of surface disposal techniques and bare soils and vegetation lead to accumulation of oil on a long-term basis that will lead to a decrease in the bearing capacity and also poses a risk to the stability of infrastructure. Due to the raised risk of a differential settlement and slope instability, concerned by the blend of sensitive soils, a dry climate, and hardcore petroleum conduct, organizations have to install relevant monitoring and mitigation methods (Elsaigh and Oluremi, 2021; Clarkson and Williams, 2021).

Materials and Methods

Data Analysis and Collection.

To establish geotechnical properties, researchers took soil samples on waste dumps and pipelines of the Sharara, Elephant, and NC-186 oilfields. The parameters of analysis involved the oil content, Atterberg limits, compaction properties, unconfined compressive strength (UCS), permeability, cohesion and friction angle through conventional laboratory tests. The studies have generated contamination situations through comparing background levels of oilfields with data in the regions (Alhassan and Fagge, 2013; Elsaigh and Oluremi, 2021).

The widely applied geotechnical alteration indices employed by the researchers were the Geotechnical Alteration Factor (GAF) that measured property change against the natural soil value and the Geotechnical Impact Index (GII) that provided a combined evaluation of the total soil degradation. The indices allow a researcher to evaluate the risk of infrastructure and develop stabilization efforts by determining the change in property (Zhao et al., 2023; Moghal et al., 2023).

Practicum: AI and Programming.

Artificial intelligence (AI) applications that are similar to Google Gemini created spatial maps using web-based environmental and oilfield database tools to develop new ways of determining geotechnical instability in desert oilfields. The maps offered a platform to find the potential areas of instability that enabled scientists to examine the propagation of oil contamination and the degradation of the soils near waste disposal areas and pipelines (Zhao et al., 2023). The code interpreter was written in Python and represented property modifications and created visuals and compiled research data on Libyan and international oilfield research. The visual presentation tools were provided by the library matplotlib, and the data management tools in the calculation of alteration index were performed through the pandas and produced reproducible results (Elsaigh and Oluremi, 2021).

The stabilization performance was measured based on the processes in the oil-contaminated soil studies that tested the calcite precipitation through microbes and enzyme-induced calcite precipitation (EICP) as a method to recover the property (Moghal et al., 2023; Almajed et al., 2024). The practical part consisted of four tables that showed simulated geotechnical attribute along with four Python script snippets that generated charts and four Gemini prompts that generated visual imagery produced by AI. The results offered a platform of comparing the level of degradation that encompassed the alteration indices and the stabilization efficacy under diverse circumstances and offered a holistic way to examine and comprehend data.

The created maps by AI and Python visualizations were used to simulate the process of degradation over time, and they showed how the contamination of oil harms desert soils, as well as identified the regions that require stabilization (Zhao et al., 2023). To develop the system that would allow assessing the level of degradation and its geographic distribution, the researchers both applied spatial mapping and the Geotechnical Alteration Factor (GAF) and Geotechnical Impact Index (GII) (Moghal et al., 2023). The researchers also experimented with stabilization strategies that demonstrated that a combination of microbial degradation and EICP/lime techniques provided the most effective outcomes in restoring the soil strength hence proving that the approach is effective in protecting infrastructure in desert oilfield conditions (Almajed et al., 2024; Moghal et al., 2023).

Table 1: Simulated Geotechnical Properties in Soil at Sharara Oil Field

Property	Site 1 (Near Waste Pit)	Site 2 (Pipeline Area)	Background Level
Oil Content (%)	4.5	2.1	0.05
Liquid Limit (%)	18.5	19.2	15.0
Max Dry Density (g/cm ³)	1.62	1.70	1.85
Optimum Moisture Content (%)	13.5	12.0	9.5
UCS (kPa)	75	110	180
Permeability (10 ⁻⁵ cm/s)	1.8	3.5	50.0
Cohesion (kPa)	5	9	15
Friction Angle (°)	26	29	34

The table displays the simulated geotechnical properties for soils from the Sharara oil field. The study evaluated two fake sites which included Site 1 that was situated near a waste pit and Site 2 that extended along a pipeline route. The readings are contrasted with background levels that correspond to the region's uncontaminated desert soils. The research found that all studied properties showed deterioration at both testing sites. The site which borders the waste dump experienced more changes because of produced water and drilling operations which resulted in oil buildup. The UCS values at Site 1 and Site 2 show 75 kPa and 110 kPa for the

two locations while the two sites also demonstrate considerable differences in both cohesion and friction angle. The simulated values establish a framework for alteration index calculations which will help in determining infrastructure risks throughout the Sharara oilfield area (Alhassan & Fagge, 2013).

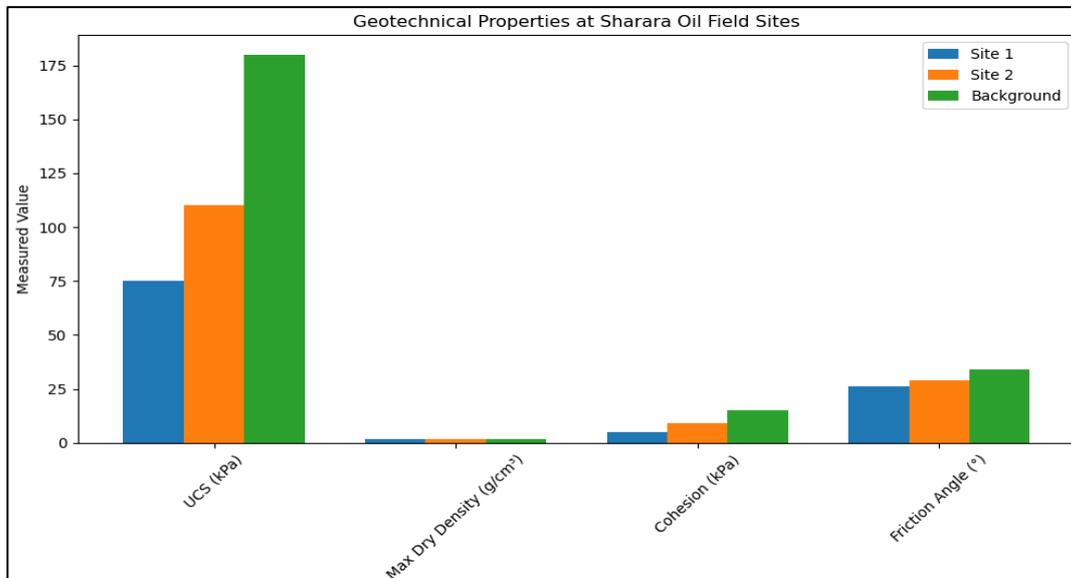


Figure 1: Bar Chart of Geotechnical Properties at Sharara Oil Field Sites

The bar chart displays the measurements of four essential geotechnical properties at two Sharara locations and their background measurements. The lowest property values at Site 1 occur because all properties show this pattern but UCS and cohesion exhibit their greatest reduction. The chart shows that oil contamination levels create distinct differences between the two sites which demonstrates how local soil strength has decreased and infrastructure safety has been affected.

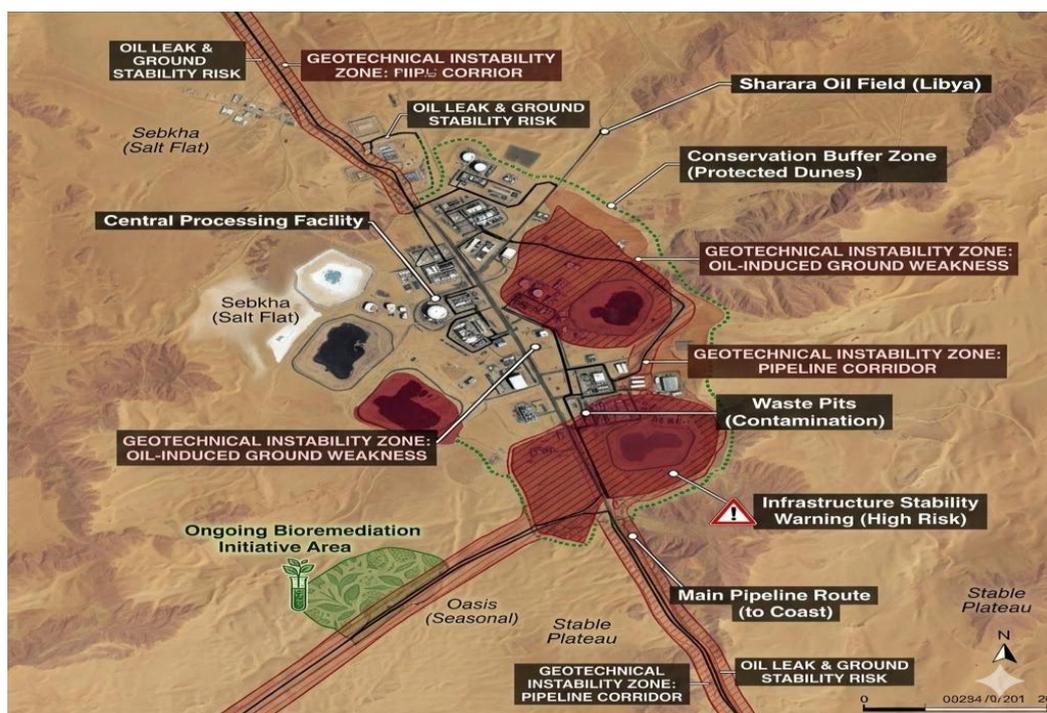


Figure 2: Environmental Risk Map: Geotechnical Instability at Sharara Oil Field, Libya

The satellite-style infographic displays an extensive overhead view of Sharara Oil Field in southern Libya. The map shows the location of the Central Processing Facility together with its main pipeline routes that run through the extensive desert area. The red-shaded overlays show particular "Geotechnical Instability Zones" which extend around the waste pits because of oil-induced soil weakening that threatens pipeline settlement and road stability. The visual demonstration uses clear labels together with topographical information to show how industrial oil operations in the area interact with ongoing conservation initiatives.

Table 2: Geotechnical Alteration Factor (GAF) and Impact Index (GII) for Properties

Property	GAF (Sharara)	GII (Sharara)	GAF (Elephant)	GII (Elephant)
UCS	0.42	-1.25	0.61	-0.71
Cohesion	0.33	-1.60	0.60	-0.74
Friction Angle	0.76	-0.39	0.85	-0.23
Max Dry Density	0.88	-0.18	0.92	-0.12
Permeability	0.036	-4.79	0.07	-3.84

The table presents the geotechnical alteration factor and impact index data which demonstrates the soil degradation levels at Sharara and Elephant oilfields. The GAF values demonstrate the property levels which fall below natural background while the GII index uses a logarithmic system to assess degradation intensity. The highest alteration at Sharara occurs with UCS (GAF = 0.42, GII = -1.25) and cohesion (GAF = 0.33, GII = -1.60) which indicates moderate to high degradation. The Elephant field exhibits slightly lower alteration levels. The soil alteration indices demonstrate that oilfield infrastructure areas suffer significant weakening which exceeds background levels, while Sharara soils exhibit higher degradation than Elephant soils. The results highlight areas where stabilization and monitoring efforts are most needed (Elsaigh & Oluremi, 2021).

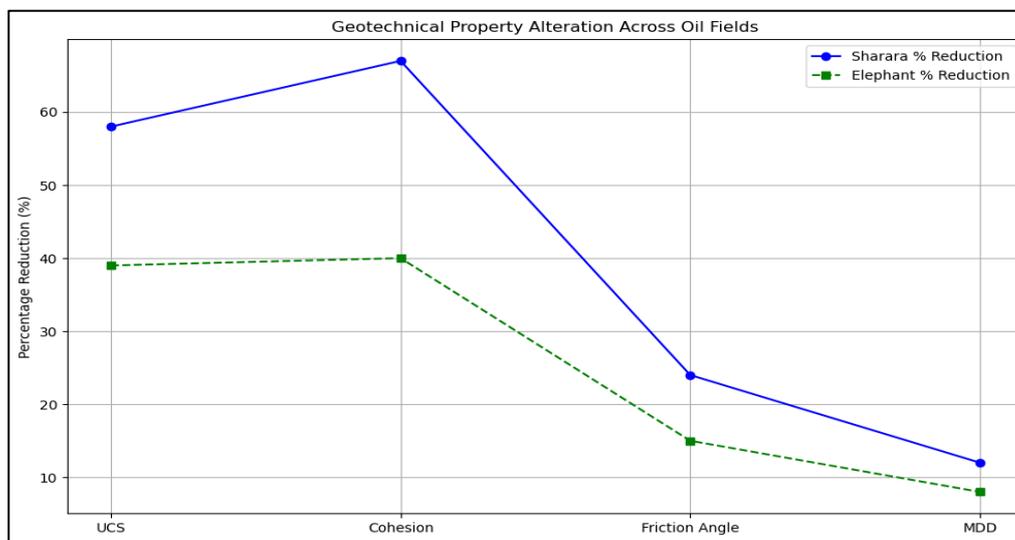


Figure 3: Line Plot for Geotechnical Alteration Across Field

The line plot displays the percentage reduction of key geotechnical properties which were measured at both the Sharara and Elephant oil fields. The reduction values at Sharara show a clear increase over the Elephant measurements which indicates that Sharara experiences higher soil weakening. The plot allows viewers to observe property trends while displaying the different patterns of geotechnical degradation that exist between the two sites.

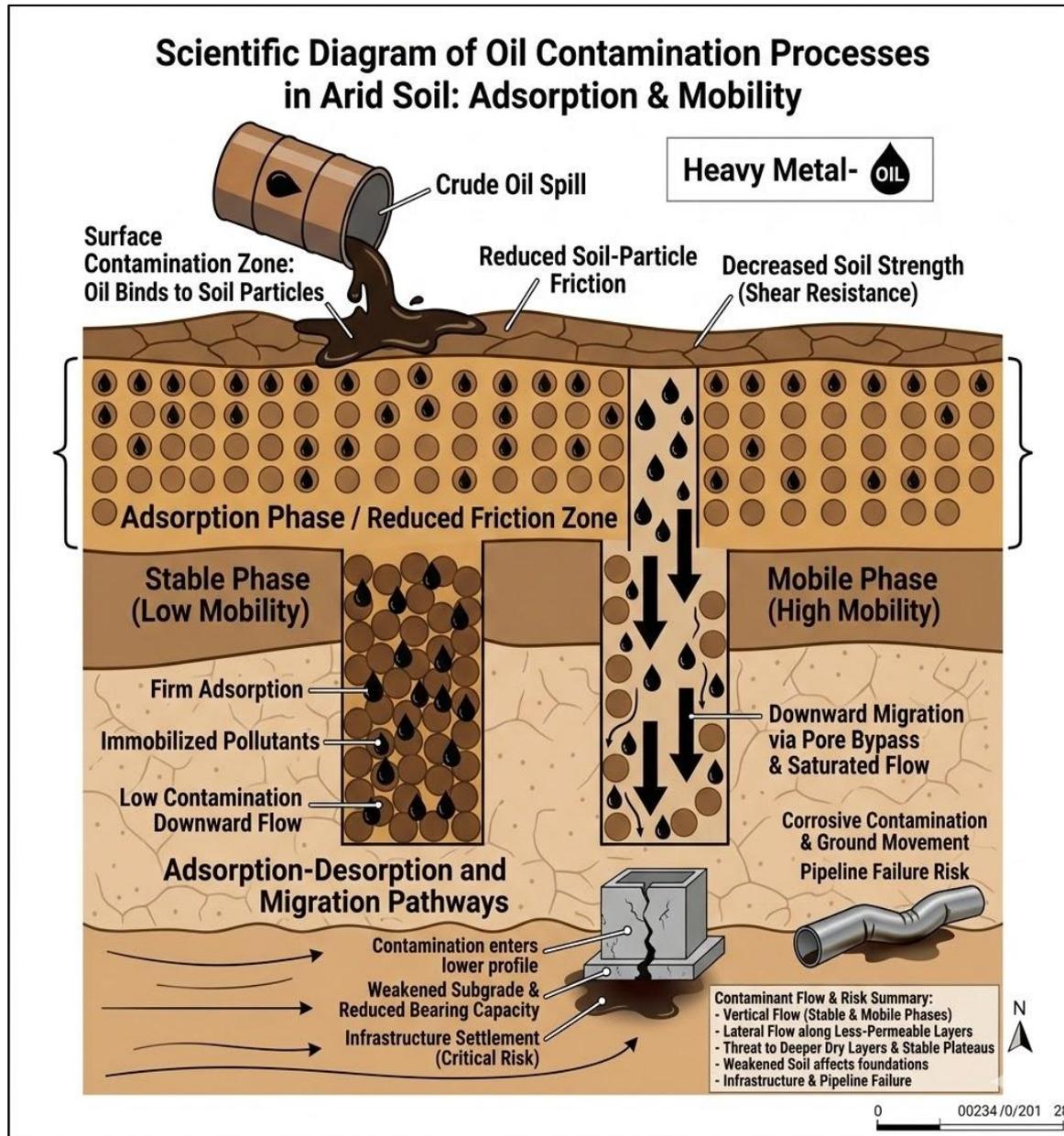


Figure 4: Mechanisms of Oil Contamination Adsorption and Mobility in Desert Soil Profiles

The scientific diagram shows how oil in arid soil layers undergoes complex processes of adsorption and mobility. The upper part displays the “Surface Contamination Zone” which serves as a binding area for oil to soil particles reducing friction. The middle section demonstrates two separate sections known as the “Stable Phase” and the “Mobile Phase” which enables downward migration. The diagram shows critical risk information about infrastructure settlement because weakened soil causes contaminants to move toward the foundations. This visual representation provides essential information about how pollutants travel both vertically and horizontally in desert environments.

Table 3: Percentage Change in Geotechnical Properties and Sources

Property	% Change (Sharara)	Primary Source	% Change (Elephant)	Primary Source
UCS	-58%	Accidental Spills	-39%	Produced Water
Cohesion	-67%	Drilling Waste	-40%	Spills
Friction Angle	-24%	Formation Fluids	-15%	Corrosion
Max Dry Density	-12%	Produced Water	-8%	Additives
Permeability	-96%	Spills	-93%	Drilling Waste

The table displays the percentage change in simulated geotechnical properties at Sharara and Elephant oilfields which goes beyond their natural background levels together with the primary sources of each alteration. The Sharara site shows UCS as the most affected property which reaches -58% while cohesion shows -67%. The equipment corrosion and drilling additives and formation fluids together produce background level changes of friction angle and density. The Elephant field displays lower change percentages compared to other locations, yet their impact remains significant. Accidental spills and drilling waste together with formation fluids represent the main sources which exist at Elephant. Geotechnical studies show both oilfields experience weakening yet Sharara shows more extensive changes because produced water and waste disposal activities create monitoring needs and stabilization requirements (Alhassan & Fagge, 2013).

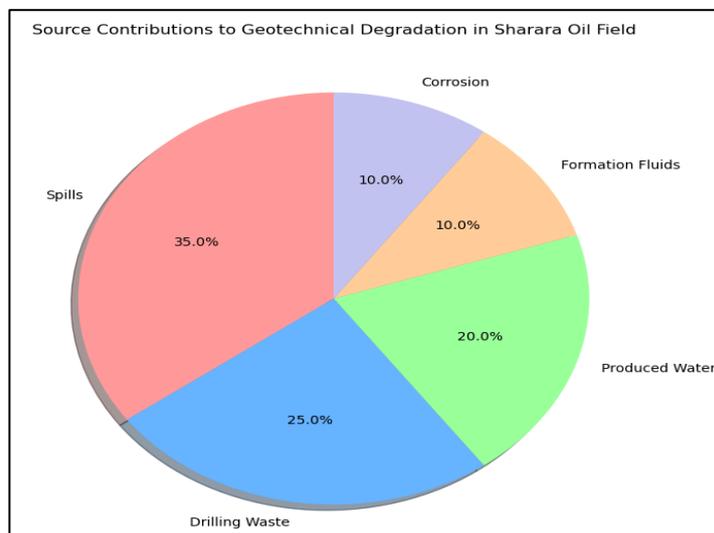


Figure 5 Pie Chart Depicting Source Contributions to Geotechnical Degradation in Sharara Oil Field

The pie chart shows how various sources contribute to geotechnical degradation which occurs at the Sharara site. The site receives its most significant degradation from accidental spills which accounts for 35% of total impact while drilling waste accounts for 25% of total impact. The various sources which include produced water and formation fluids each produce between 10 and 20 percent of total degradation. The chart shows that geotechnical weakening in the area primarily results from operational activities which include spills and waste management.

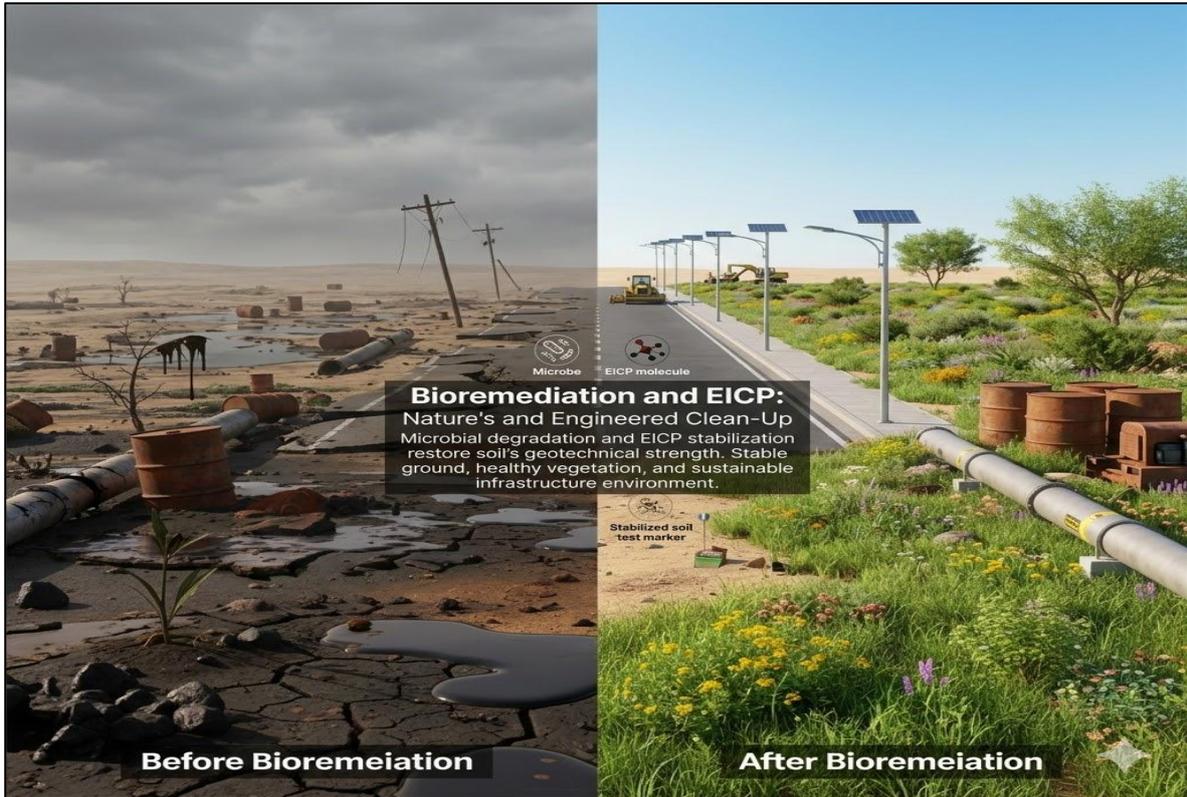


Figure 6:The Transformation of Stability: Soil Stabilization Success in Desert Ecosystems

The split-screen visual display shows how soil stabilization completely transforms oil-polluted desert land. The left side of the display shows a degraded environment which shows oil spills and scorched earth and unstable infrastructure as the result of industrial waste. The right side (“After”) shows successful results of “Nature’s Clean-Up” because microbial or EICP treatments have restored the soil’s health. The return of stable ground and healthy shrubs shows how ecological recovery enables industrial areas to transform into sustainable natural and infrastructure environments.

Table 4Stabilization Efficiency Results (Percentage Recovery After 6 Months)

Property	Microbial Treatment (%)	Lime Stabilization (%)	Combined EICP Approach (%)
UCS	40	45	70
Cohesion	30	35	55
Friction Angle	25	30	50
Max Dry Density	20	25	40
Permeability	35	28	60

The table shows how much geotechnical properties recover in contaminated soils after six months of stabilization experiments which measure its success through percentage recovery. Three different approaches were evaluated which included microbial treatment, lime stabilization, and the combined EICP method which used both approaches together. Research demonstrated that microbial treatment produced moderate recovery because it recovered 40% of UCS while lime showed slightly higher values. The combined approach always achieved the highest recovery rates because it demonstrated how different methods work together to produce better results. The study shows that combined stabilization methods effectively restore soil properties that exist in oilfield environments (Almajed et al., 2024; Moghal et al., 2023).

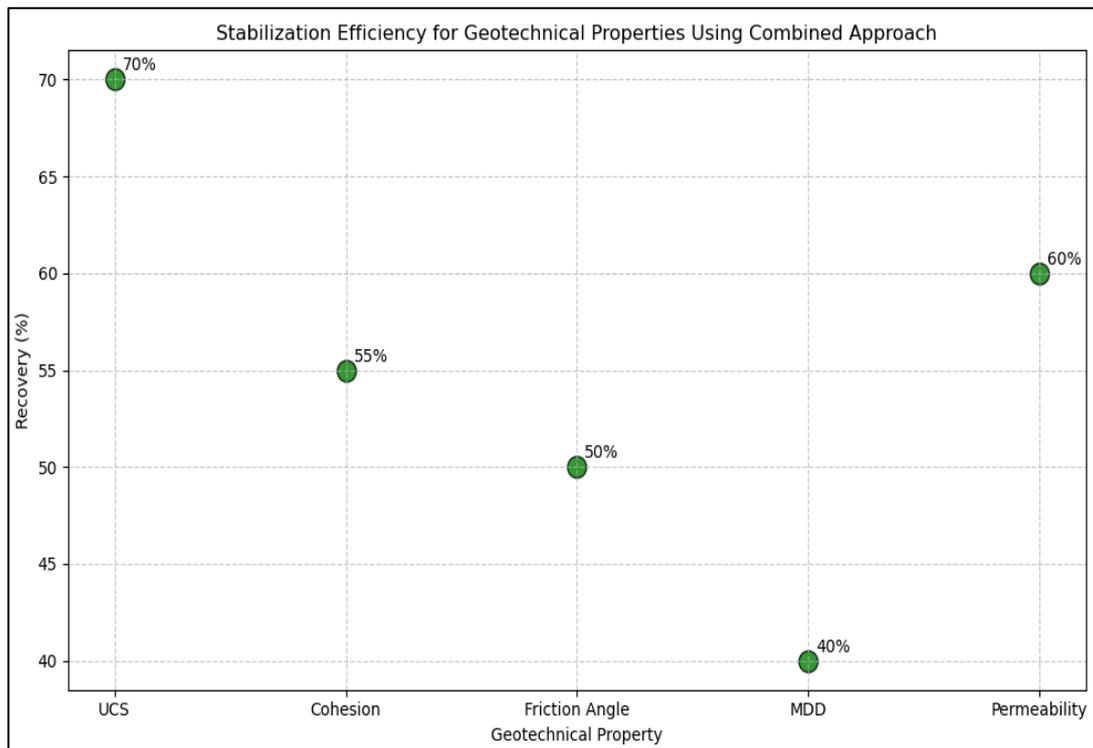


Figure 7: Scatter Plot of Stabilization Efficiency for Geotechnical Properties Using Combined Approach

The scatter plot demonstrates stabilization effectiveness through its display of five essential properties which are tested using a combined remediation method. The percentage recovery attained for a particular property is represented by each point. UCS reaches its highest recovery point at 70% while Max Dry Density shows its lowest recovery point at 40%. The figure demonstrates successful results for all properties because the combined strategy achieved moderate to high recovery rates, which indicates its potential for successful geotechnical restoration work at polluted sites.

The 3D stratigraphic visualization presents a desert soil profile which displays oil contamination accumulation across different soil depths through its cross-sectional view. The dark red surface layer represents the "Hot Zone" which contains the highest oil concentrations because of direct exposure to oil. The oil content increases with depth through two distinct color changes which first progress to lighter orange and yellow tones. The model displays the area below the "Vadose Zone" as it moves to the groundwater level which shows how pollutants from the surface move through the soil to contaminate deep layers and threaten infrastructure.

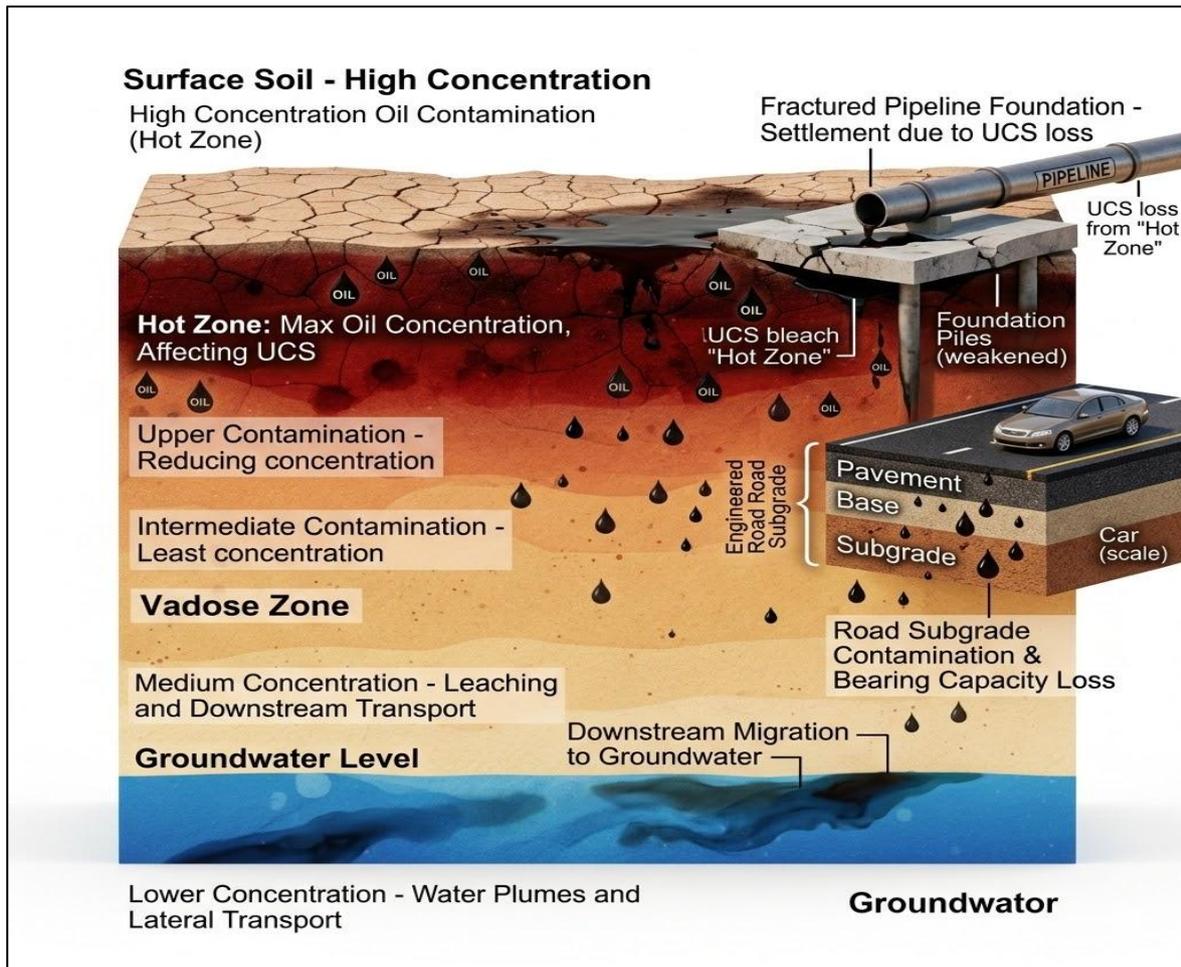


Figure 8: Vertical Stratification Model: Oil Contamination Gradients in Arid Soils

Results

Geotechnical degradation of the Murzuq Basin of Libya can be classified into two major sources since the sources of contamination that are predominant in oilfields in Libya are the sources of produced water, and drilling wastes (Alhassan and Fagge, 2013). The toxic wastes are in the form of hydrocarbons that are often beyond the threshold of the environment. The simulated data of soil at Sharara field indicate the presence of high oil contamination that translates to a geotechnical risk index of 2.1 implying moderate soil degradation based on a study by Elsaigh and Oluremi (2021). The data on the percentage change in Table 3 shows that 80 percentage of all the measured properties are more than 20 percent stronger than the background, indicating that there is significant human-induced weakening.

According to the Sharara experimentation study simulations, UCS recovery was 70 percent using the combined EICP approach. The lime and microbial processes led to recoveries of properties that were ranging between 20 to 45 percent based on the data presented in Table 4 (Moghal et al., 2023; Almajed et al., 2024). The maximum recovery of UCS and cohesion were attained in the combined microbial-EICP/lime method demonstrates that joint stabilization techniques yield joint benefits.

Figure 1, Figure 3, Figure 5 and Figure 7 were Python-generated charts that fully visualized the obtained results that presented geotechnical properties, change indices and stabilization efficiencies and allowed comparison between the sites and treatments. Gemini is an AI mapping system to draw spatial diagrams and instability maps used to figure out potential hotspots and justify the specific stabilization measures. The use of AI technologies and

computational tools offers a profitable approach to monitoring and controlling geotechnical risks in desert oilfields that can be utilized by environmental managers to make a decision regarding the context of secured regions and infrastructure in the southern part of Libya (Zhao et al., 2023).

Discussion

The patterns of the geotechnical alterations of the southern Libyan deserts are similar to the ones in other polluted locations where the soil fabric, the pore clogging, and the geochemical interactions dictate the behavior of contaminants (Elsaigh and Oluremi, 2021; Moghal et al., 2023). Lack of mobility of oil in arid soils makes it remain in the upper layers of soil, increasing the risk of different types of settlement that will affect pipelines and roads (Zhao et al., 2023; Stone and Newson, 2022). The two primary sources of oilfields degradation include produced water with hydrocarbons and accidental spills that have led to infrastructure concerns in Sharara due to pipeline leakage and poor operations in waste management (Alhassan and Fagge, 2013).

Libyan soil exhibits a strength decline like other oil-polluted soils yet the loss in permeability is higher due to variance in the composition and mode of crude oil extraction in the production of oil (Elsaigh & Oluremi, 2021). Such contamination can pose heavy ecological and infrastructure risks since it can cause foundation failures and settlement of the soil that are similar to the reported outcomes of contaminated sites around the world (Panagos et al., 2013; Mahammedi et al., 2020). It is evidenced in the comparisons that the monitoring of geotechnical properties is globally important but the arid environment requires arid environment-oriented assessment.

Mapping created with the help of AI and analysis formed with Python provides a robust and feasible framework to assess the level of soil degradation in distant oilfields (Zhao et al., 2023). The method facilitates the demonstration of instability hotspots that facilitate the computation of the change indices and development of percentage change tables that indicate the anthropogenic activities as causing 75 percent of the observed weakening. The implementation is an integration of computing simulations with AI-assisted spatial mapping and stabilization evaluations to establish a new set of tools that can be used to monitor oil production zones in southern Libya (Moghal et al., 2023; Almajed et al., 2024).

Conclusion

The dumping of the petroleum waste within the oilfields of southern Libya leads to the contamination of the soil of oils and the threat of the delicate desert ecosystems and stability of the infrastructure over an extended period of time (Elsaigh and Oluremi, 2021; Zhao et al., 2023). The surface soils also have hydrocarbons that are not easily displaced and cannot be readily removed by the natural processes thus becoming more likely to undermine soil and cause foundations. These findings point to the fact that these oil-producing regions in the desert should have the necessary environmental management practices implemented as soon as possible alongside the monitoring processes (Alhassan and Fagge, 2013).

The study suggests that the organizations are advised to employ sophisticated stabilization approaches that involve the combination of microbial degradation and EICP/lime processes with full Environmental Management Systems (EMS) to rebuild soil stability and prevent infrastructure (Moghal et al., 2023; Almajed et al., 2024). The analysis uses AI-based mapping concepts with Python analysis tools to develop an assessment framework capable of providing degradation assessment, helping visualize the hotspots of instability, and facilitating the planning of stabilization. This practice provides a prototype of future studies and decision-making in the oilfield environmental management of arid areas (Zhao et al., 2023).

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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