technical transactions

No. 2025/023

civil engineering and transport

Paradigm

Practical implications of hydrocarbon pollution in the assessment of geotechnical behaviour of cohesive soils

Dorota Izdebska-Mucha
dizdebsk@uw.edu.pl | https://orcid.org/0000-0002-3602-5352
Kamil Kiełbasiński
k.kielbasinski@uw.edu.pl | https://orcid.org/0000-0003-2655-5031
Paweł Dobak
p.dobak@uw.edu.pl | https://orcid.org/0000-0001-7096-0515
Emilia Wójcik
wojcike@edu.pl | https://orcid.org/0000-0001-6872-1734
Department of Engineering Geology and Geomechanics, Faculty of Geology, University of Warsaw
Gintaras Žaržojus
gintaras.zarzojus@gf.vu.lt | https://orcid.org/0000-0003-2079-4680
The Faculty of Chemistry and Geosciences, Vilnius University

Scientific Editor: Andrzej Winnicki, Cracow University of Technology
Technical Editor: Aleksandra Urzędowska, Cracow University of Technology Press
Typesetting: Anna Pawlik, Cracow University of Technology Press

Received: October 23, 2025
Accepted: December 4, 2025

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing interests: The authors have declared that no competing interests exist.

Citation: Izdebska-Mucha, D., Kiełbasiński, K., Dobak, P., Wójcik, E., Žaržojus, G. (2025). Practical implications of hydrocarbon pollution in the assessment of geotechnical behaviour of cohesive soils. *Technical Transactions, e2025023*. https://doi.org/10.37705/TechTrans/e2025023

Abstract

The paper presents the results of experimental laboratory investigation of cohesive soils from the Warsaw area, polluted with diesel fuel. The study revealed adverse changes in key physical parameters, sorption capacity and mechanical properties. The results were analysed in relation to pollution degree as well as structural modifications. The obtained findings were further used in numerical analyses to evaluate bearing capacity, foundation settlement, and slope stability, as well as to assess the overall behaviour of contaminated soils serving as building foundations.

Keywords: glacial till, diesel fuel contamination, shear strength, compressibility, settlement, slope stability, microstructure

1. Introduction

The pollution of soils by petroleum products is one of the most pervasive environmental problems associated with industrialization, urban development, and energy production. Leakage from underground storage tanks, accidental oil spills, and improper waste disposal have led to widespread pollution of soils and groundwater systems worldwide. Petroleum pollution not only poses risks to ecosystems and human health but also alters the engineering performance of soils. Presence of petroleum hydrocarbons in the soil-water system modifies its biological, physicochemical and geotechnical conditions (Zadroga and Olańczuk--Neyman, 2001; Chmielewski et al., 2020).

When hydrocarbons replace or partially displace pore water, they change the surface properties and interactions between soil particles and grains (Kaya and Fang, 2000; Anandarajah, 2003; Kaya and Fang, 2005, Izdebska-Mucha et al., 2011). This effect is more pronounced in cohesive soils, leading to changes in granulometric composition, consistency limits, microstructure, permeability and mechanical properties, thereby affecting the overall engineering behaviour of the soil (e.g. Korzeniowska-Rejmer, 2001; Rajabi and Sharifipour, 2019; Saeed et al., 2024). The extent of these changes depends on the type and viscosity of the pollutant, the degree of pollution, the lithological composition of the soil, and the duration of pollution.

Previous studies have reported that hydrocarbon pollution adversely influences shear strength, bearing capacity, and compressibility of the soil (Puri et al., 1994; Al-Sanad et al., 1995; Aiban, 1998; Puri, 2000; Shin et al., 1999; Czado et. al., 2010; Kermani and Ebadi, 2012; Khosravi et al., 2013; Ling and Yong, 2013; Siang et al., 2014; Onyelowe. 2015; Karkush and Jihad, 2020; Salimnezhad et al., 2021). Such alterations can compromise the performance and safety of geotechnical structures, including foundations, slopes, and embankments. However, despite numerous experimental investigations, there remains a lack of integrated approaches that link laboratory-derived soil property changes with their macroscopic geotechnical implications. Bridging this gap is crucial for developing predictive tools that can simulate the response of contaminated soils under changing field conditions.

The present study aims to investigate the effect of diesel fuel on the physical--chemical, strength, and deformation parameters of a typical cohesive soil and to assess its implications for geotechnical performance through numerical analysis. Laboratory testing program was carried out on model soil samples with a controlled degree of pollution and included granulometric composition, consistency limits, sorption capacity, direct shear strength, compressibility, and microstructural analysis. The obtained parameters were implemented in numerical simulations to assess how the observed changes influence settlement behaviour, bearing capacity, and slope stability. The findings of this study contribute to a better understanding of the micro-scale mechanisms and macro-scale engineering responses in oil-contaminated cohesive soils and provide a scientific basis for evaluating the geotechnical risks associated with hydrocarbon pollution.

https://doi.org/10.37705/TechTrans/e2025023

2. Materials and methods

2.1. Soil

In this study soil samples were collected from the construction site in Warsaw area. The soil represents glacial till of the Odra glaciation, which is one of the most common type of Quaternary deposits in Poland. According to the macroscopic description (PN-EN ISO 14688–1:2018–05) the soil was classified as a clay with silt and sand, brown, with stiff consistency. The X-ray diffraction (XRD) analysis was performed using PANalytical B.V. X'Pert PRO MPD, Bragg-Brentano method, and the results were analysed using X'Pert HighScore Plus software (ver.2.2e). As shown in Fig. 1, the XRD results revealed the polimineral composition of the clay fraction and the high quartz content in the tested soil, which is typical of glacial clayey deposits.

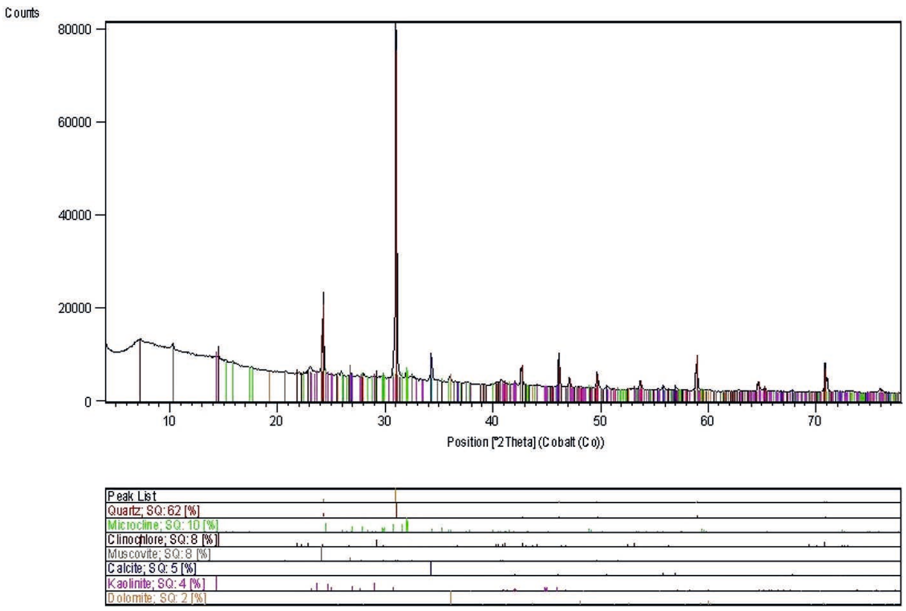


Fig. 1. Mineralogical composition of the tested soil according to XRD analysis (own elaboration)

2.2. Pollutant

The natural soil samples were homogenised and polluted with commercially purchased diesel fuel (ON). Diesel fuel, composed of hydrocarbons $C_9 – C_{25}$, has lower density (0.82–0.84 g/cm^3), greater viscosity (2–4.5 mm^2/s), and much lower dielectric constant ($\varepsilon \sim 2$) in comparison to water.

2.3. Sample preparation

Comparative laboratory analyses were performed on remoulded soil samples containing 0, 4, 12% ON. The procedure of sample pollution was adopted after previous studies (Dobak et al., 2022) and it is shown in Fig. 2. The applied procedure simulates long-term pollution and allowed to obtain homogeneous soil mixtures with a controlled degree of pollution. For the oedometer and direct shear tests, the soil–ON–water pastes were compacted at the mould to achieve a bulk density as close as possible to natural conditions, while avoiding the extrusion of ON from the sample, thereby maintaining the intended ON content.

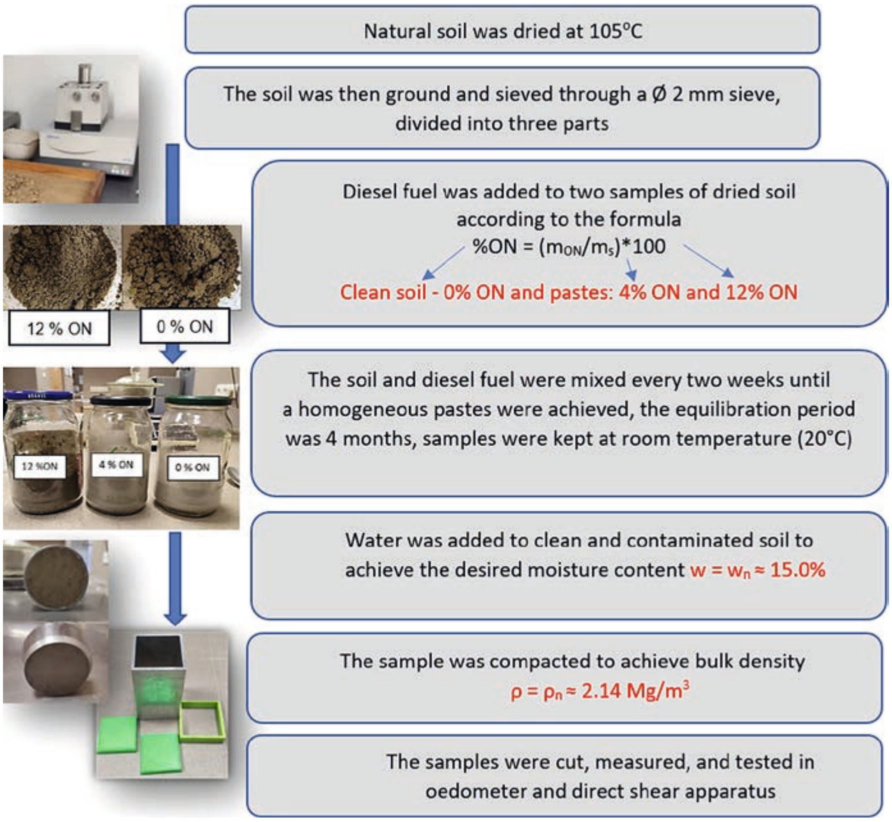


Fig. 2. Sample preparation method of diesel fuel polluted soil (own elaboration)

3. Methods

3.1. Physical-chemical properties

Particle size distribution was determined according to PKN-CEN ISO/TS 17892-4:2009 using the pipette method. In the test procedure the dispersing agent was not applied, such as the results revealed an actual microaggregate composition of the soil.

Liquid limit and plastic limit were tested according to PN-EN ISO 17892--12:2018-08. The cone penetrometer method was used for the liquid limit measurements. The Atterberg limits were calculated in terms of the water content in the ON-polluted soil samples following the recommendations proposed by Khamehchiyan et al. (2007).

The methylene blue capacity (MBC) and cation exchange capacity (CEC) were determined following PN-B-04481 (1988).

3.2. Mechanical properties

Oedometer consolidation tests were carried out according to PN-EN ISO 17892--5:2017-06. The sample consolidation at each stage of loading was carried out until the deformation sensors indicated no further changes. To prevent pore fluids loss due to evaporation, all specimens were covered with plastic film.

The shear strength was tested in a standard direct shear test apparatus following ASTM D3080-04. The tests were performed with a rate of shear equal to 0.1 mm/min at normal loads of 50, 100, 150 and 200 kPa.

3.3. Microstructure

Scanning electron microscope (SEM), model ZEISS SIGMA VP (Carl Zeiss Microscopy, Cambridge, UK) was used to study the fabric of the clean and polluted soil. Prior to the analysis the specimens were freeze-dried and dusted with gold, following the procedure described by Trzciński (1998).

3.4. Numerical analyses

Numerical calculations were performed using FEM modelling in ZSOIL software. The soil medium was modelled using the Mohr-Coulomb (M–C) constitutive model (Table 1). Within the experimental framework, a soil foundation interaction model was created to determine soil bearing capacity, embankment construction to determine settlement, wide-scale excavation works to assess slope stability assessment, and narrow-space excavation in steel sheet pile wall to evaluate structural loading of the wall construction.

The aim of the simulation was to obtain an answer to the question whether soil ON contamination significantly affects the bearing capacity and deformability of the subgrade under typical conditions with different structures.

3.5. Numerical prediction of bearing capacity

Foundation bearing capacity modelling was determined through simulation of a footing with dimensions L = B = 2 m using two approaches. Analytical calculations were performed using Eurocode 7 guidelines (PN-EN 1997--1-2008) for bearing capacity assessment under undrained conditions, and FEM simulation to determine the maximum foundation load. Due to the need to compare the bearing capacity obtained from Eurocode calculations with FEM calculation results, the footing model was simulated as a 3D model. To avoid the necessity of using contact elements at the foundation-soil medium interface, foundation placement at a depth of 1 meter below ground surface was simulated by applying load to the model surface simulating stress conditions at the foundation level.

Table 1. Parameters used for numerical modelling (own elaboration)

Layer	E	n	ϕ	c	ψ	γ	Formulation
	[MPa]	[–]	[deg]	[kPa]	[deg]	[kN/m^3]	
Foundation	27000	0.2	–	–	–	0	Elastic
Pavement	27000	0.2	–	–	–	22	Elastic
Embankment	150	0.25	40	1	5	16.7	M–C
Sheet pile wall	200000	0.3	–	–	–	78.5	Elastic
Soil 0% ON	6.4	0.35	23.3	63	0	18.8	M–C
Contaminated soil 4% ON	5.5	0.35	22.8	52	0	18.6	
Contaminated soil 12% ON	5.4	0.35	19.9	44	0	18.4	
Subsoil	120	0.25	35	1	5	16.7	

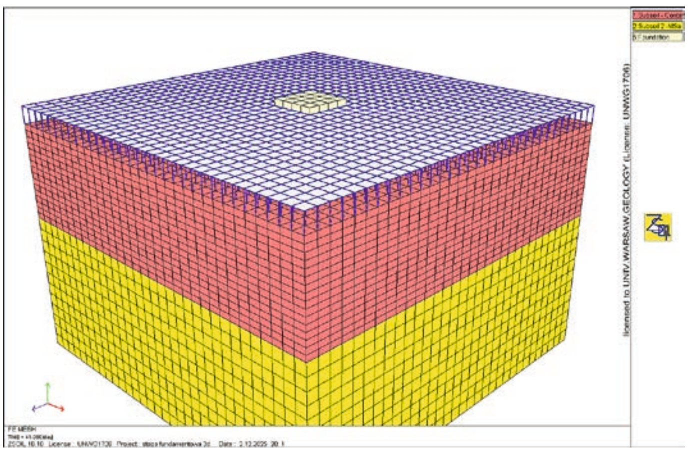


Fig. 3. 3D FEM model for bearing capacity assessment (own elaboration)

3.6. Numerical prediction of settlement

In order to assess the influence of contamination on the settlement an 10 meter high embankment was modelled. The construction stage was divided into 10 steps. In stages 1–9, the height of the embankment structure was increased and the construction of pavement layers was simulated, while in stage 10, loading from road traffic was applied. Due to the simulation of loading under plane strain conditions, a uniformly distributed load of 15 kPa increased by an additional 5 kPa to account for dynamic loading effects. The parameters of the embankment layers are given in Table 1.

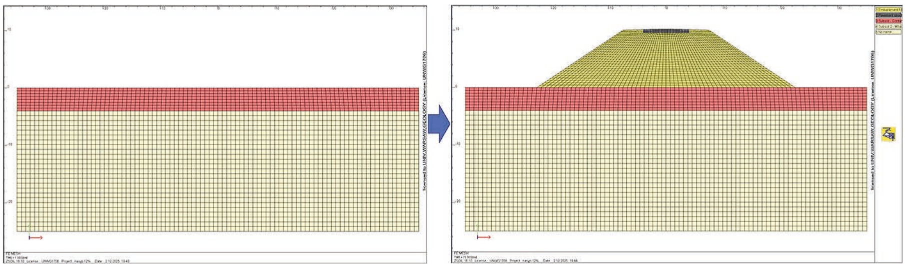


Fig. 4. 2D FEM model for settlement assessment (own elaboration)

3.7. Numerical prediction of slope stability

In order to assess the impact of contamination on the stability of excavation slopes, a model of a sloping excavation was created in two variants with slopes ratio of 1:1 and 2:1. The initial stage covered the subgrade loaded with construction work loading at a level of 10 kPa. Excavation implementation was carried out in 4 stages, simulating soil extraction with a thickness of 1 meter in each phase. After achieving the target excavation depth, slope stability assessment was conducted. Calculations were performed using the $c - \varphi$ reduction method (SRM-strength reduction method) to determine the safety factor (SF). A detailed description of the method was described by Griffiths and Lane (1999) and Sanecki et al. (1999). The strength reduction calculations excluded the subsoil layer just below the contaminated layer.

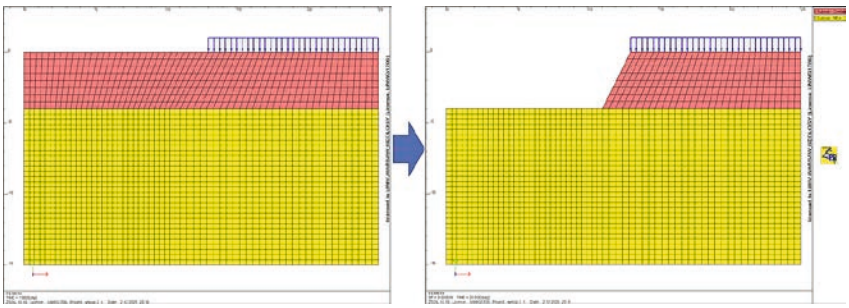


Fig. 5. 2D FEM sloping excavation model (own elaboration)

3.8. Numerical prediction of retaining wall load

In order to assess the impact of contamination on the degradation of soil parameters and, consequently, the increased impact (pressure) on the retaining structure, a 4-meter-deep excavation protected by a sheet pile wall was modelled. Firstly, the initial stage covering earthwork loading of 10 kPa was simulated. The wall elements were simulated as elastic elements in the form of a beam with steel sheet pile characteristics. Contact interface conditions were implemented on both sides of the beam, simulating friction between soil and wall surface at a level of 60% of the internal friction angle of the soil in contact with the wall. Excavation to the final depth was simulated in 2 stages (Fig. 6).

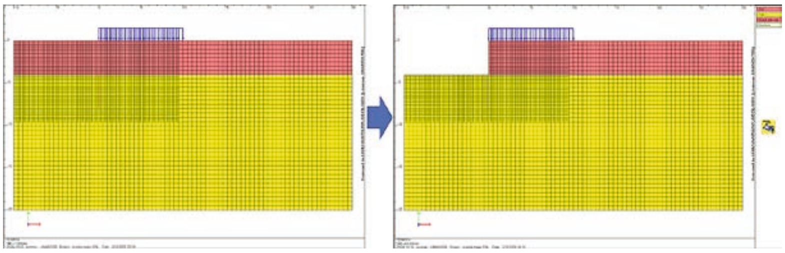


Fig. 6. 2D FEM retaining wall excavation model (own elaboration)

4. Results

4.1. Effect of diesel fuel on physical-chemical and mechanical properties

Table 2 presents the effect of diesel fuel contamination on the key physical-chemical and the mechanical properties of the tested soil. The results show that the clay and the sand content decreased by 3% and 4% points, respectively, for the soil containing 12% ON, while the silt content increased with increasing degree of pollution. The changes observed can be attributed to the aggregation effect of clay particles coated with hydrocarbons, resulting in a decrease in clay content and an increase in the silt content. On the other hand, the presence of hydrocarbons may cause the weakening of structural bonds occurring in the clean soil and the disintegration of larger aggregates within the sand fraction, which caused a reduction in the sand content. Similar effects have been reported in previous studies, though the magnitude of the changes varied significantly with soil type, pollutant characteristics, and testing method (e.g. Korzeniowska-Rejmer and Izdebska-Mucha, 2006; Izdebska-Mucha and Korzeniowska-Rejmer, 2010; Karkush and Kareem, 2017; Izdebska-Mucha et al., 2021).

The plastic limit and the liquid limit of the polluted soil decreased by a maximum of 7.4% points and 8.5% points, respectively, compared to the clean soil. Accordingly, the plasticity index decreased by about 1%. However, these changes did not affect the classification of the studied soil, and all the samples represented lean clay CL according to USCS system.

The obtained results indicated reduction in the sorption capacity with the increasing ON content. This change can be attributed to effect of hydrocarbons surrounding the clay particles which in turn reduces the ability of attraction of other molecules, such as the methylene blue or water molecules. As a result a reduction in cation exchange capacity, specific surface area, and plasticity was obtained.

Importantly, low changes in the key physical properties of polluted soil are not indicative of a relatively greater effect of pollution on the shear strength parameters, i.e. cohesion and angle of internal friction, which decreased by a maximum of 30% and 17%, respectively, for the soil containing 12% ON.

Generally it can be observed, that the tested soil showed rather small changes in the considered parameters when polluted with 4% ON, whereas for the pollution of 12% ON the changes became significantly higher.

Table 2. Changes in physical-chemical and mechanical properties of tested soil (own elaboration)

Diesel fuel content	Soil parameters										
	psychical-chemical									mechanical	
	Clay Cl (%)	Silt Si (%)	Sand Sa (%)	Plastic limit w_p (%)	Liquid limit w_L (%)	Plasticity index Ip (%)	Activity A = Ip/Cl (–)	Methylene blue capacity MBC (g/100 g)	Cation exchange capacity CEC (meq/100 g)	Cohesion c (kPa)	Angle of internal friction Φ (°)
0% ON	23	37	40	15.1	35.0	19.9	1.11	3.35	8.96	63	23.3
4% ON	23	38	39	14.2	33.0	19.3	1.07	3.18	8.51	52	22.8
12% ON	20	44	36	7.7	26.5	18.8	1.25	2.23	5.96	44	19.4

4.2. Effect of diesel fuel on compressibility

The one-dimensional compression tests were carried out in order to assess the impact of diesel fuel pollution on changes in compressibility and consolidation parameters of the studied cohesive soil. These characteristics generally depend on the soil lithology, the external loading to which the soil is subjected, as well as the type and duration of pollution. Due to the glacial origin, the granulometric composition of the tested soil may exhibit significant spatial variability. Parts of the soil material with a significant clay content (20% and more) demonstrate insulating properties that hinder the rapid penetration of petroleum-derived pollutants. In contrast, spatially variable silty and sandy interlayers are preferred pathways for the filtration of the liquid phase, i.e. water and petroleum pollutants.

In this context, to quantitatively assess this process in soils with a typical composition of glacial till, it is reasonable to conduct tests on reconstituted samples. This approach is acceptable according to the applied standard for oedometric testing (PN-EN ISO 17892-5:2017-06, section 6.2.4.1). By applying remoulded samples, it is possible to prepare material with approximately uniform spatial pollution, whereas in the case of diesel fuel penetration into an undisturbed sample, this process would require an unacceptably long time without any guarantee of uniform pollution.

The experimental study of the soil polluted with diesel fuel (4% and 12%) is an extension of typical standard application. This non-standard approach reflected in the variation of the initial characteristics of the soil material, i.e. the bulk density and dry density, the values of which decreased with increasing contamination (Table 3). This effect may result from lower density of ON in comparison to water and the controlled slighter compaction such as to prevent squeezing out the fuel from the soil.

Table 3. Changes in compressibility of tested soil (own elaboration)

Diesel fuel content	Initial bulk density ρ	Initial dry density ρ_d	Oedometric modulus E_{oed}			
			0–0.05	0.05–0.1	0.1–0.2	0.2–0.4
(% dry weight)	(g/cm³)	(g/cm³)	MPa	MPa	MPa	MPa
0% ON	1.88	1.66	2.5	1.2	3.1	6.8
4% ON	1.85	1.59	2.3	1.8	3.0	5.5
12% ON	1.84	1.54	0.8	1.2	2.4	5.4

Based on the results presented in Table 3 it can be observed that for samples containing 0% and 4% ON, the minimum value of the oedometric modulus (E_{oed}) was found under the second step of loading (0.05–1.0 MPa). This behaviour indicates a collapse of the artificially formed soil structure under a load of approximately 100 kPa. In contrast, the 12% ON pollution revealed the effects likely associated with a significant reduction in friction between soil particles and grains. This resulted in approximately four times higher compressibility of the soil material, already at the initial loading stage of 0.05 MPa. At subsequent loading stages, an increase in the E_{oed} was observed; however, on average, it remained lower in comparison to the samples 0% and 4% ON. The tendency towards diminishing differences in compressibility became apparent under higher loading conditions (400 kPa).

The effect of diesel fuel has also clearly reflected in the consolidation behaviour of the soil. The model proposed by Casagrande ($\log t$ vs. h), due to its characteristic S-shaped curve (Fig. 7), provides a useful reference for comparison with experimental results, enabling the identification of distinct features in the behaviour of the tested soil. The interpretation of differences between the model and the experimental results may be related both to the artificially formed soil structure and to pollution with diesel fuel.

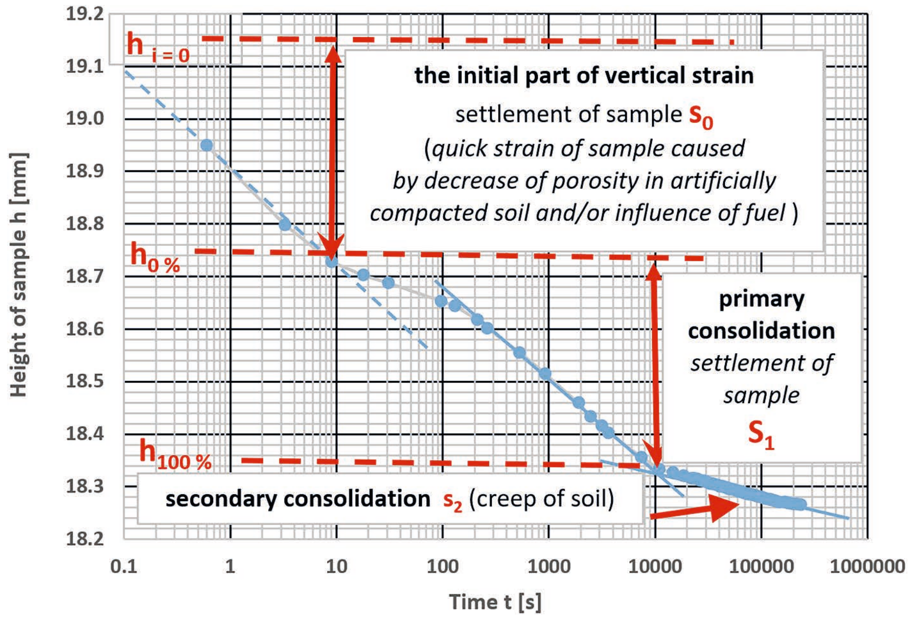


Fig. 7. Phases of consolidation (own elaboration)

The primary characteristic of the obtained consolidation curves is the scattered data of the initial settlement stage, theoretically defined as phase s_0 – the immediate settlement. In most of the analysed cases, instead of a very rapid deformation, a delayed response was observed. The immediate settlement typically occurs within the first several to several dozen seconds after the application of the load. On the ($\log t$ vs. h) plot, it is usually represented by a straight line with a steeper slope than that corresponding to the subsequent deformations associated with phase s_1 (primary consolidation).

The completion of the primary consolidation stage ($h_{100\%}$) can generally be determined by the intersection of the linear approximations representing the middle portion of the s_1 phase and the part of consolidation curve corresponding to creep settlement (s_2). It should also be noted that in some tests, a highly variable or non-classical shape of the ($\log t$ vs. h) relationship is observed, or a nearly constant slope is maintained throughout the test, which prevents reliable determination of the coefficient of consolidation (c_v). Its validity should therefore be verified through quantitative analyses, such as c_v optimization methods (Dobak, 1999; Dobak and Gaszyński, 2015).

When the shape of the ($\log t$ vs. h) plot allowed the identification of the s_1 phase, a decrease in the coefficient of consolidation (c_v) was observed with increasing stress levels and higher pollution (Table 4). The coefficient of secondary compression (C_α, creep) showed higher values with increasing ON content. These results indicate the effect of reduced interparticle friction resulting from the presence of hydrocarbons at the liquid–solid interface.

Table 4. Changes in parameters of primary and secondary consolidation of tested soil (own elaboration)

Diesel fuel content	Coefficient of consolidation c_v			Coefficient of secondary compression (creep) C_α
	0.05–0.1 MPa	0.1–0.2 MPa	0.2–0.4 MPa	
(% dry weight)	*10^{-8} (m²/s)			(–)
0% ON	–	8	2	0.00117
4% ON	–	4	2	0.00173
12% ON	5	2	1	0.00301

4.3. Effect of diesel fuel on microstructure

SEM analysis of clean and polluted soil samples revealed a significant influence of diesel fuel on soil microstructure. In the 0% ON sample (Fig. 8A) the clay material was densely packed with structural elements tightly arranged, forming a relatively uniform clayey matrix. The polluted soil showed a clear transformation of microstructural features, which became more pronounced as the degree of pollution increased (Fig. 8b, c). In the 12% ON sample, the clay matrix consists of smaller structural elements (microaggregates) that appear to be arranged more loosely. This leads to a redistribution of pore space and suggests an increase in inter-microaggregate porosity. The grains are either loosely coated with a clay film or have exposed surfaces. On the surface of clay particles, a thin layer of a substance, probably hydrocarbons, can be observed (Fig. 8d).

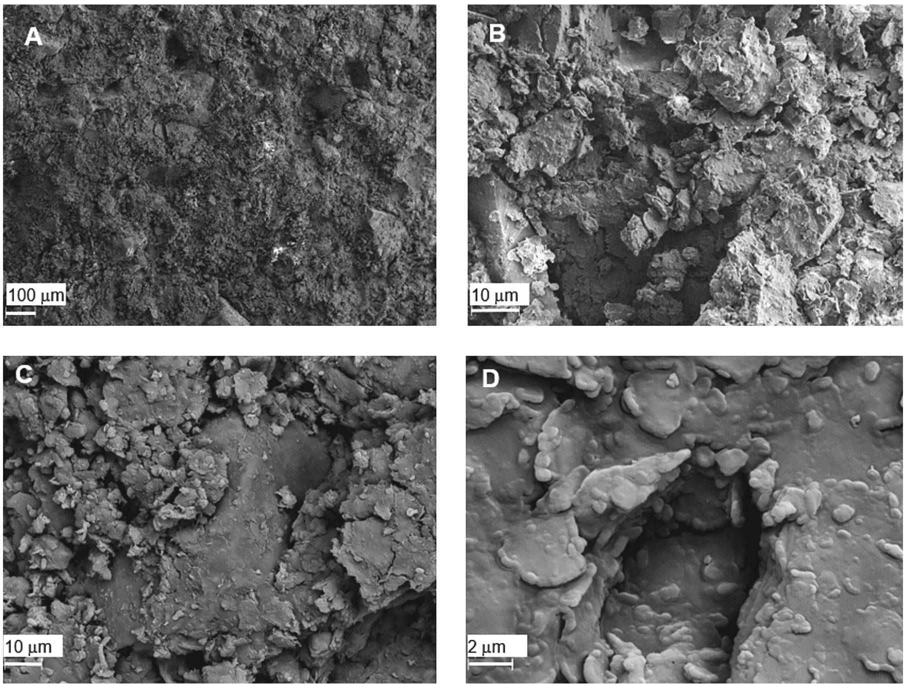


Fig. 8. Soil microstructure in Scanning Electron Microscope. a) 0% ON, ×200; b) 4% ON, ×3300;c)12% ON, ×2500; d) 12% ON, ×15000 (own elaboration)

The microstructural analysis revealed that the polluted soil had a less cohesive structure, which explains the reduction in cohesion and friction angle. Additionally, the presence of hydrocarbons on soil particles increases lubrication at particle contact, contributing to lower shear resistance and greater compressibility.

5. Polluted soil behaviour and practical implications

5.1. Expansiveness

Preliminary identification of potentially expansive soils typically relies on empirical correlations, which apply the basic soil properties. The most commonly used parameters for assessing soil expansiveness include index properties such as the Atterberg limits and particle size distribution, as well as sorption and swelling parameters, which are indicative of the soil mineralogical composition (Izdebska-Mucha and Wójcik, 2014).

In the present study, the physical-chemical parameters listed in Table 2 were used to evaluate the effect of diesel fuel pollution on the potential expansiveness of the examined soil. The results of the analysis, based on widely adopted

https://doi.org/10.37705/TechTrans/e2025023

systems (IS 1498, 1970; Chen, 1975; van der Merwe, 1964; Casagrande acc. Head, 1992) as well as more recent classifications for soil expansiveness (Yilmaz, 2006; Yukselen and Kaya, 2008), are summarized in Table 5.

According to most of the classifications considered, a 0% diesel fuel sample is characterized by medium or low/medium expansiveness. Despite relatively small changes in physicochemical parameters values, the category of samples contaminated with diesel fuel shifted toward low expansiveness, according to four out of six classifications. The observed changes in soil expansiveness classification are the result of the presence of hydrocarbons on the surface of the soil skeleton, as observed in the SEM analysis. Covering the clay particle surface of the soil with hydrocarbons reduces its availability and interaction with water, which is the essence of the soil ability to volume changes, i.e. its expansiveness. The application of hydrocarbon polluted soils as construction materials is one of the alternative methods of disposing polluted soil (Oluremi and Osuolale, 2014). In this light, reduced expansiveness is a beneficial effect in the polluted soil behaviour.

Table 5. Changes in expansiveness of tested soil by various classification systems. Soil expansiveness: L – low, M – medium, soil plasticity: I – intermediate (medium) (own elaboration)

Diesel fuel content	Classifications					
	Chen (1975)	IS 1498 (1970)	van der Merwe (1964)	Yukselen and Kaya (2008)	Yilmaz (2006)	Casagrande acc. Head (1992)
0% ON	M	L/M	M	L	M	L/I
4% ON	M	L	M	L	M	L
12% ON	L	L	M	L	L/M	L

5.2. Numerical prediction of bearing capacity

Bearing capacity results estimated on 3D FEM modelling are approximately 20% higher than those calculated based on the PN-EN 1997-1-2008 standard for all degrees of diesel oil pollution. Obviously, it should be kept in mind that this is the ultimate bearing capacity, which in reality cannot be utilized in practice due to significant soil deformations. The loss of bearing capacity relative to the uncontaminated soil was 18% at 4% diesel oil pollution and 44% at 12% pollution for both the analytical and numerical modelling. The impact on soil bearing capacity is noteworthy, especially since the factor that strongly influences soil bearing capacity is the angle of internal friction, which changes by several degrees as a result of pollution. All results were presented in Fig. 9.

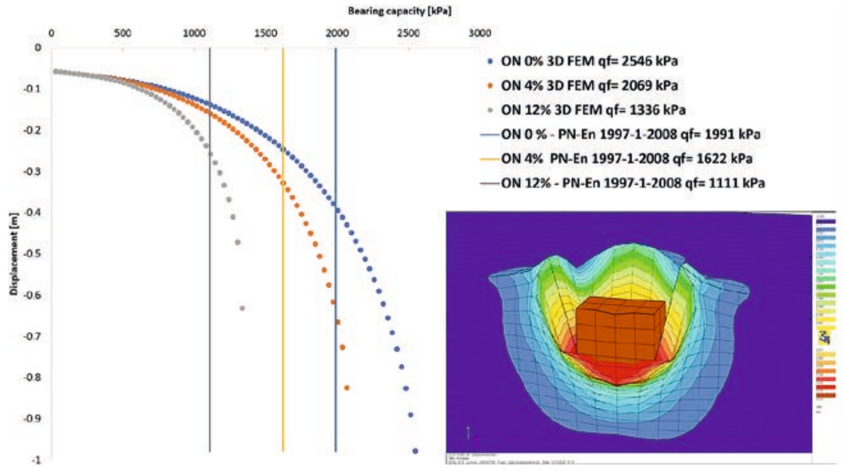
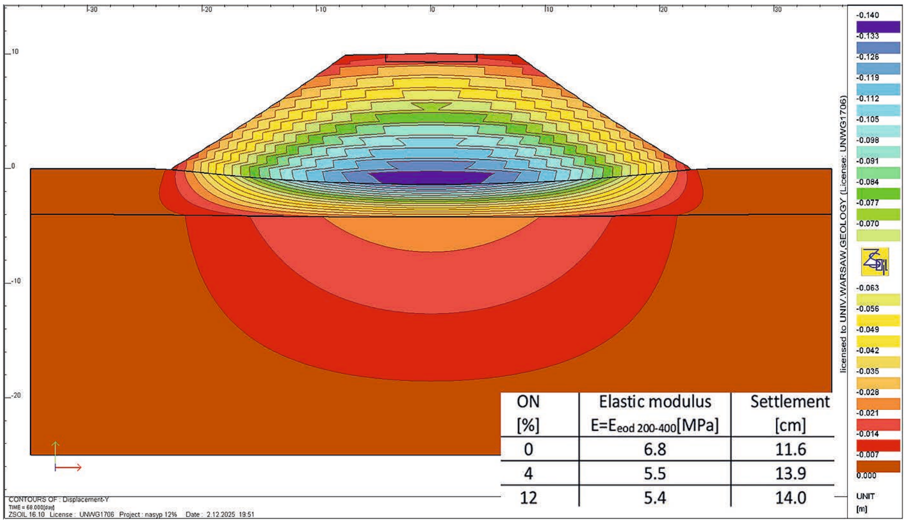


Fig. 9. PN-EN 1997-1-2008 and 3D FEM bearing capacity assessment results (own elaboration)

5.3. Numerical prediction of settlement

The elastic modulus E value of the layer contaminated with diesel oil was determined based on oedometer test results E_{eod}. Usually, both parameters are not comparable, but in the case of subgrade loaded by a wide embankment, estimation of maximum settlement at the embankment centre axis, where horizontal soil deformability is significantly constrained, this approach gives acceptable results. Due to the significant embankment height (10 m), the constrained modulus was selected according to stress increment for the stress range of 200–400 kPa.



ON [%]	Elastic modulus $E=E_{eod\ 200\text{-}400}$ [MPa]	Settlement [cm]
0	6.8	11.6
4	5.5	13.9
12	5.4	14.0

Fig. 10. 2D FEM settlement results (own elaboration)

The results of oedometer tests indicate that the greatest decrease in constrained modulus occurs after adding 4% diesel oil, while further changes are so small that they have no significant effect on the settlement. For the presented model adding 4% ON increases settlement in the model by 2.3 cm and it is worth mentioning that approx. 20% of the additional settlement is achieved only due to the increase in compressibility caused by pollution. A further increase in pollution has a slight effect on the increase in settlement due to mentioned earlier influence on constrained modulus. It should be noted that the differences in settlement will be greater in the case of thicker layers, but a situation in which a thick layer of clay is evenly contaminated can be considered implausible.

5.4. Numerical prediction of slope stability

The stability calculation for an sloped excavation with a slope of 1:1 and 2:1 proved slope stability for both clean and contaminated soil parameters. In both cases, the safety margin is maintained even at the highest level of pollution, and the lowest SF values do not exceed the threshold of SF = 2.9. Considering the fact that the stability is ensured at SF = 1, this is a large safety margin. Nevertheless pollution with 12% diesel fuel causes a significant decrease in SF compared to the SF of a slope made of uncontaminated soil, amounting to approx. 30%. It is well-known that the height of a slope has a direct impact on its stability. Therefore, a slope twice as high, with a 2:1 gradient build of a contaminated layer with 12% diesel oil, was also modelled. The calculation results also confirmed the stability of such a slope at SF = 1.8. However, the occurrence of such a thick layer of contaminated cohesive soil is not very probable, unless it concerns the surface layer of a slope.

https://doi.org/10.37705/TechTrans/e2025023

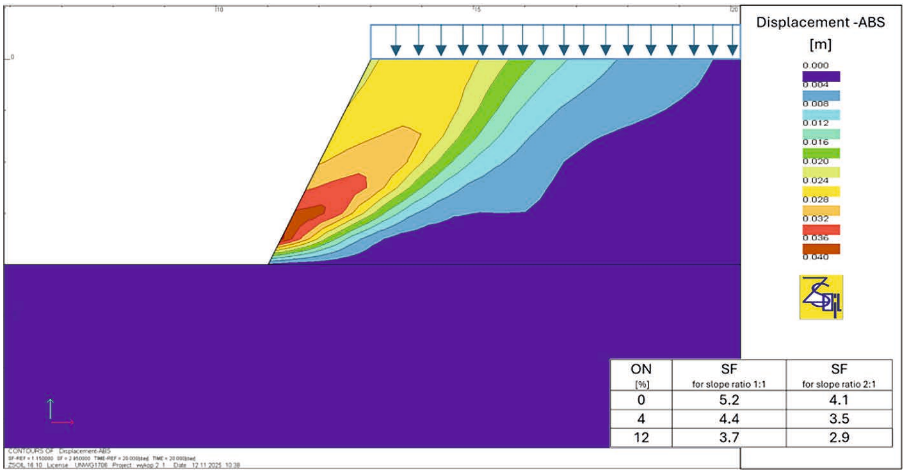


Fig. 11. 2D FEM sloping excavation stability results (own elaboration)

5.5. Numerical prediction of retaining wall load

Wall loading results for subgrade with different degrees of diesel oil pollution of the cohesive layer do not differ significantly. The maximum bending moment in the wall at 12% pollution is 100.8 kNm. Meanwhile, the minimum moment for uncontaminated soil is 94.7 kNm. Small changes are conditioned by the high cohesion of the soil, which significantly limits structural loading at the small modelled depth. The influence of pollution on sectional forces and moments does not exceed 5% even at the highest degree of pollution. Wall loading results and selected displacement map in the modelled computational cross-section are presented in Figure 12.

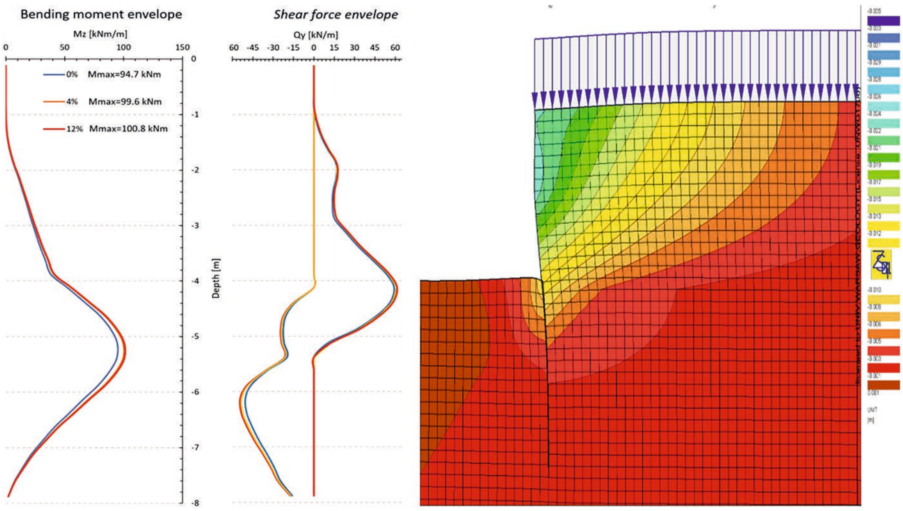


Fig. 12. 2D FEM retaining wall load results (own elaboration)

6. Conclusions

The paper describes the results of experimental and numerical investigations of the effect of diesel fuel on geotechnical behaviour of a model cohesive soil. The laboratory testing program included granulometric analysis, Atterberg limits, sorption capacity, oedometric and direct shear tests, microstructural analysis. The obtained results were used for further analysis of the soil in terms of geotechnical classifications and expansiveness, as well as for assessing the geotechnical implications of pollution through numerical modelling. The following conclusions can be drawn:

1. Diesel fuel pollution caused a modification of soil granulometric composition and sorption properties. An increase in silt content and a decrease in clay content were observed, indicating aggregation of clay particles coated by hydrocarbons. The reduction of the liquid and plastic limits and the cation exchange capacity reflects the decline in the soil ability to adsorb water molecules.
2. The presence of hydrocarbons significantly reduced the shear strength parameters. Cohesion decreased by approximately 30%, and the internal friction angle dropped by about 17% at the highest degree of pollution (12% ON). These changes result from the lubrication effect and reduced bonding between mineral particles caused by hydrocarbon films identified in SEM analysis.
3. The degree of pollution affects both the pattern and the extent of changes in soil compressibility. Increasing load reduces the significance of contamination, which is reflected in the similarity of the oedometric modulus values for the 12% ON samples. Potentially, diesel fuel content larger than 4% has a significant impact on increasing soil compressibility. This may be the basis for predicting the activation of settlement under existing structures when pollution of the subsoil has occurred, e.g., due to failures in petroleum products transmission infrastructure or traffic accidents.
4. In soils polluted with diesel fuel and artificially structured, deformation behaviour differs notably from that observed in the model consolidation process. Soil creep plays an important role: not only in the final phase of settlement, but also after applying subsequent load increments. Creep also modifies the process of primary consolidation (liquid seepage), which in many cases makes it impossible to determine reliable c_v values.
5. When interpreting the test results for soil material that was both remoulded and contaminated, it is essential to critically analyse the vertical deformation of the soil as a function of time. The recommended graph for such analysis is $(\log t \text{ vs. } h)$. The assessment of divergences between experimental and theoretical consolidation models allows for a critical distinction between settlement phases. Optimization methods provide a means to improve the quantitative reliability assessment of the c_v determination.
6. Analysis of the numerical modelling results indicates that the obtained decrease in strength parameters caused by pollution does not significantly affect the stability of slopes or loads on sheet pile walls. It should be remembered that in the presence of a landslide or excessive deformation of the wall with the development of a slip zone, the behaviour of the soil may be subject to residual strength. In that case the effect of cohesion will be ignored, and the lubricating effect of pollution may contribute to a significant reduction in the angle of internal friction and stability.
7. When modelling the impact of pollution on the bearing capacity of the ground and its settlement under load, the impact of pollution is clearly visible. In terms of bearing capacity, there is a 44% reduction at the highest level of pollution, and a 4% ON content causes a 20% increase in settlement.
8. Scanning electron microscope analysis revealed rearrangement of structural elements and pore space distribution, and coating of mineral grains by hydrocarbon films. These structural alterations explain the macroscopic decrease in strength and increase in deformability of the polluted soil.

The obtained results provide a quantitative and qualitative basis for predicting deformation and stability in hydrocarbon-affected cohesive soils and may support the development of risk assessment procedures in geotechnical practice.

The authors would like to thank the reviewers for their valuable comments, M.Sc. Eng. Weronika Marciniak for her assistance in the laboratory work and data analysis, and M.Sc. Grzegorz Kaproń for performing XRD analysis.

References

Anandarajah, A. (2003). Mechanism controlling permeability change in clays due to changes in pore fluids. *Journal of Geotechnical and Geoenvironmental Engineering 129*(2), 163–172. https://doi.org/10.1061/(ASCE)1090-0241(2003)129:2(163)

Aiban, S.A. (1998). The long-term environmental effects of the Gulf War. The effect of temperature on the engineering properties of oil-contaminated sands. *Environmental International 24*, 153–161. https://doi.org/10.1016/S0160-4120(97)00131-1

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. https://doi.org/10.1061/(ASCE)0733-9410(1995)121:5(407)

ASTM D3080-04. (2004). *Standard test method for direct shear test of soils under consolidated drained conditions*. ASTM International.

Chen, F.H. (1975). *Foundations on expansive soils*. Elsevier.

Chmielewski, J., Żeber-Dzikowska, I., Pawlas, K., Nowak-Starz, G., Chojnowska-Ćwiąkała, I., Dębska, A., Szpringer, M., Gworek, B., & Czarny-Działak, M. (2020). Substancje ropopochodne – zagrożenie dla środowiska i zdrowia w kontekście edukacji ekologicznej. *Przemysł Chemiczny 99*(6), 837–843. https://doi.org/10.15199/62.2020.6.1

Czado, B., Korzeniowska-Rejmer, E., & Pietras, J.S. (2010). Analiza zmian nośności podłoża budowlanego w wyniku jego zanieczyszczenia substancjami ropopochodnymi na przykładzie gruntów piaszczystych. *Górnictwo i Geoinżynieria 34*(2), 165–171.

Dobak, P. (1999). *The role of the filtration factor in uniaxial consolidation tests of soils* (in Polish). Kraków: Wydawnictwo IGSMiE.

Dobak, P., & Gaszyński, J. (2015). Aspects of permeability and rheology in uniaxial consolidation, considering analysis of soil deformation progress and pore pressure dissipation. *Architecture Civil Engineering Environment 7*(4), 47–55.

Dobak, P., Izdebska-Mucha, D., Stajszczak, P., Wójcik, E., Kiełbasiński, K., Gawriuczenkow, I., Szczepański, T., Zawrzykraj, P., & Bąkowska, A. (2022). Effects of hydrocarbon contamination on the engineering geological properties of Neogene clays and Pleistocene glacial tills from Central Poland. *Acta Geologica Polonica 72*(4), 529–555. https://doi.org/10.24425/agp.2022.142647

Griffiths, D.V., & Lane, P.A. (1999). Slope stability analysis by finite elements. *Geotechnique 49*, 387–403.

Head, K.H. (1992). *Manual of soil laboratory testing. Vol. 1: Soil classification and compaction tests*. London.

IS 1498. (1970). *Indian standard classification and identification of soils for general engineering purposes*. New Delhi: BIS.

Izdebska-Mucha, D., & Korzeniowska-Rejmer, E. (2010). Selected characteristics of clay soils polluted by petroleum substances in the context of their barrier properties. In: M. Datta, R.K. Srivastava, G.V. Ramana, & J.T. Shahu (Eds.), *Proceedings of the 6th International Congress on Environmental Geotechnics*, Vol. 1 (pp. 705–710). New Delhi:Tata McGraw-Hill Education.

Izdebska-Mucha, D., Trzciński, J., & Klein, M. (2021). The effect of diesel fuel contamination on the particle size distribution and plasticity of muds from the area of Warsaw-Siekierki. *Przegląd Geologiczny 69*(12), 800–810.

Izdebska-Mucha, D., Trzciński, J., Żbik, M., & Frost, R.L. (2011). Influence of hydrocarbon contamination on clay soil microstructure. *Clay Mineral*, *46*, 47–58. https://doi.org/10.1180/claymin.2011.046.1.04

Izdebska-Mucha, D., & Wójcik, E. (2014). Expansivity of Neogene clays and glacial tills from central Poland. *Geological Quarterly 58*(2), 281–290. https://doi.org/10.7306/gq.1151

Karkush, M.O., & Jihad, A.G. (2020). Studying the geotechnical properties of clayey soil contaminated by kerosene. *Key Engineering Materials 857*, 383–393. https://doi.org/10.4028/www.scientific.net/KEM.857.383
Karkush, M.O., & Kareem, Z.A. (2017). Investigation of the impacts of fuel oil on the geotechnical properties of cohesive soil. *Engineering Journal 21*, 127–137. https://doi.org/10.4186/ej.2017.21.4.127
Kaya, A., & Fang, H.-Y. (2000). The effects of organic fluids on physicochemical parameters of fine-grained soils. Canadian *Geotechnical Journal 37*(4), 943–950. https://doi.org/10.1139/t00-033
Kaya, A., & Fang, H. (2005). Experimental evidence of reduction in attractive and repulsive forces between clay particles permeated with organic liquids. *Canadian Geotechnical Journal 42*, 632–640. https://doi.org/10.1139/t04-112
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*, 655–671. https://doi.org/10.1080/15320383.2012.672486
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. https://doi.org/10.1016/j.enggeo.2006.10.009
Khosravi, E., Ghasemzadeh, H., Sabour, M. R., & Yazdani, H. (2013). Geotechnical properties of gas oil-contaminated kaolinite. *Engineering Geology 166*, 11–16. https://doi.org/10.1016/j.enggeo.2013.08.004
Korzeniowska-Rejmer, E. (2001). Wpływ zanieczyszczeń ropopochodnych na charakterystykę geotechniczną gruntów stanowiących podłoże budowlane. *Inżynieria Morska i Geotechnika 2*, 83–86.
Korzeniowska-Rejmer, E., & Izdebska-Mucha, D. (2006). Ocena wpływu zanieczyszczeń ropopochodnych na uziarnienie i plastyczność gruntów spoistych. *Inżynieria i Ochrona Środowiska 9*(1), 89–103.
Ling, S.Y., & Yong, L.C. (2013). Behavior of piles in palm biodiesel contaminated mining sand. *International Journal of Environmental Science 3*, 1822––1830.
Merwe, D. H. van der. (1964). The prediction of heave from the plasticity index and percentage clay fraction of soils. *Civil Engineer in South Africa 6*, 103–106.
Oluremi, J. R., & Osuolale, O. M. (2014). Oil contaminated soil as potential applicable material in civil engineering construction. *Journal of Environment and Earth Science 4*, 87–99.
Onyelowe, K. C. (2015). Pure crude oil contamination on Amaoba lateritic soil. *Electronic Journal of Geotechnical Engineering 20*, 1129–1142.
PKN-CEN ISO/TS 17892-4:2009. (2009). Badania geotechniczne – Badania laboratoryjne gruntów – Część 4: Oznaczanie składu granulometrycznego.
PN-B-04481. (1988). Grunty budowlane. Badania próbek gruntu.
PN-EN 1997-1:2008 (2008) Eurokod 7: Projektowanie geotechniczne – Część 1: Zasady ogólne.
PN-EN ISO 14688-1:2018-05. (2018). Rozpoznanie i badania geotechniczne – Oznaczanie i klasyfikowanie gruntów – Część 1: Oznaczanie i opis.
PN-EN ISO 17892-5:2017-06. (2017). Rozpoznanie i badania geotechniczne – Badania laboratoryjne gruntów – Część 5: Badanie edometryczne gruntów.
PN-EN ISO 17892-12:2018-08. (2018). Rozpoznanie i badania geotechniczne – Badania laboratoryjne gruntów – Część 12: Oznaczanie granic płynności i plastyczności.
Puri, V.K. (2000). Geotechnical aspects of oil-contaminated sands. *Journal of Soil Contamination 9*, 359–374. https://doi.org/10.1080/10588330091134301

Puri, V.K., Das, B.M., Cook, E.E., & Shin, E.C. (1994). Geotechnical properties of crude oil contaminated sand. *ASTM Special Technical Publication 1265*, 58–66. https://doi.org/10.1520/STP12658S

Rajabi, H., & Sharifipour, M. (2019). Geotechnical properties of hydrocarbon contaminated soils: A comprehensive review. *Bulletin of Engineering Geology and the Environment 78*, 3685–3717. https://doi.org/10.1007/s10064-018-1377-7

Saeed, H., Nalbantoglu, Z., & Uygar, E. (2024). A comprehensive review of hydrocarbon contaminated soil behavior, geotechnical properties and potential remediation. *Soil and Sediment Contamination: An International Journal 34*(6), 1023–1067. https://doi.org/10.1080/15320383.2024.2395952

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. https://doi.org/10.1016/j.jrmge.2020.11.011

Sanecki, L., Truty, A., & Urbański, A. (1999). O możliwościach modelowania komputerowego stateczności złożonych układów geotechnicznych. *Materiały XLV Konferencji Nauk KILiW PAN, Krynica–Wrocław*.

Shin, E.C., Lee, J.B., & Das, B.M. (1999). Bearing capacity of a model scale footing on crude oil-contaminated sand. *Geotechnical and Geological Engineering 17*, 123–132. https://doi.org/10.1023/A:1016078420298

Siang, A.J.L.M., Wijeyesekera, D.C., Yahya, S.M.A.S., & Ramlan, M. (2014). Innovative testing investigations on the influence of particle morphology and oil contamination on the geotechnical properties of sand. *International Journal of Integrated Engineering 6*, 60–66.

Trzciński, J. (1998). Ilościowa analiza mikrostrukturalna w skaningowym mikroskopie elektronowym (SEM) gruntów poddanych oddziaływaniu wody. In: B. Grabowska-Olszewska (Ed.), *Geologia stosowana. Właściwości gruntów nienasyconych* (pp. 113–150). Warszawa: Wydawnictwo Naukowe PWN.

Yilmaz, I. (2006). Indirect estimation of the swelling percent and a new classification of soils depending on liquid limit and cation exchange capacity. *Engineering Geology 85*, 295–301. https://doi.org/10.1016/j.enggeo.2006.02.011

Yukselen, Y., & Kaya, A. (2008). Suitability of the methylene blue test for surface area, cation exchange capacity and swell potential determination of clayey soils. *Engineering Geology 102*, 38–45. https://doi.org/10.1016/j.enggeo.2008.08.001

Zadroga, B., & Olańczuk-Neyman, K. (2001). *Ochrona i rekultywacja podłoża gruntowego. Aspekty geotechniczno-budowlane*. Gdańsk: Wydawnictwo Politechniki Gdańskiej.