Review

Impacts of Contaminants from Different Sources on Geotechnical Properties of Soils

Shan Zhao [1,2,*]**, Baoju Zhang** [1,3]**, Wenbing Zhang** [1]**, Xinjia Su** [1] **and Botao Sun** [1]

[1] College of Ocean Science and Engineering, Shanghai Maritime University, Shanghai 201306, China
[2] College of Civil Engineering, Tongji University, Shanghai 200092, China
[3] College of Harbour, Coastal and Offshore Engineering, Hohai University, Nanjing 210098, China
[*] Correspondence: szhao@shmtu.edu.cn

Abstract: Within sites affected by industrial, domestic, and agricultural contaminants, the geotechnical characteristics of soils are susceptible to a certain degree of deterioration. The resultant corrosion of concrete exacerbates the vulnerability of underground structures, posing a potential hazard to the stability of superstructures. However, the current lack of comprehensive understanding regarding the precise influence of contaminants from different sources on the geotechnical properties of soils underscores the critical need for further research in this field. This review aims to elucidate the underlying mechanisms of various impacts, revealing that the permeability, shear strength, and compressibility of soils can either increase or decrease depending on the specific contaminants present. Notably, even though these impacts may not manifest prominently in the short term, their persistence can endure over an extended duration. The primary objective of this comprehensive review is to draw the attention of the scientific community and policy makers to this issue, emphasizing the need to mitigate potential hazards and safeguard a habitable environment for present and future generations.

**Keywords:** contaminants; different sources; geotechnical properties; soils

1. Introduction

Soil contamination represents a prevalent and consequential issue in numerous countries, particularly those characterized by high population densities and intensive land utilization. A case in point is China, where, between 2005 and 2013, 16.1% of soil samples surpassed the prescribed environmental quality standards, with heavy metals and organic contaminants constituting the primary sources of contamination [1]. Similarly, the soils in the capital city of India exhibited significant contamination with metals such as aluminum (Al), copper (Cu), cadmium (Cd), lead (Pb), and zinc (Zn) due to the crude recycling activities associated with electronic waste [2]. Soil contamination primarily occurs in proximity to industrial/commercial plants, waste landfills, petrol stations, military camps, and nuclear power plants [3]. These contaminated sites assume critical roles as pollution sources, initially posing ecotoxicological risks to the surrounding terrestrial and groundwater ecosystems and subsequently impacting human health [4,5]. It is crucial to recognize that the impact of soil contamination is further amplified when considering the distinct environmental dynamics of tropical, arid, and semi-arid regions. In these varying contexts, the process of leaching takes center stage as a critical factor shaping geotechnical properties. Within tropical areas characterized by abundant rainfall and rapid vegetation growth, leaching significantly influences soil permeability, shear strength, and compressibility. Similarly, in arid and semi-arid conditions where water scarcity and high evaporation rates prevail, leaching plays a substantial role in modulating these geotechnical characteristics [6,7].

The origins of contaminants encompass a broad spectrum and include, but are not limited to, the following sources: (i) industrial facilities and petrol stations, which contribute to pollution through the release of acidic and alkaline contaminants, as well as

aliphatic and aromatic hydrocarbons resulting from small spills or petrol leakage; (ii) residential waste disposal sites, which have the potential to disperse hazardous substances into the environment and leach them into groundwater; and (iii) agricultural soils contaminated by the residues of fertilizers, pesticides, and herbicides, owing to the persistent and heavy application of these compounds. Different contaminants exhibit diverse impacts on the environment and human health, which are contingent upon their properties, such as bioavailability, solubility, potential for dispersion, carcinogenicity, and more [3]. Human health is directly influenced by soil contamination through various routes, including skin contact, ingestion, inhalation, and dermal absorption. For instance, the cadmium concentrations found in animals residing near an abandoned iron mine in Morocco surpassed the acceptable upper limit, posing health risks to individuals who consume meat from these livestock [8]. Additionally, a methane gas explosion that transpired in a house built over a former landfill site in Derbyshire resulted in severe injuries to three occupants [9]. Consequently, contaminated sites cannot be simply abandoned but necessitate remediation prior to redevelopment.

From an engineering perspective, the influence of contaminants from diverse sources on soil is of paramount importance. Geotechnical properties of foundation soils serve as crucial indicators for assessing foundation stability. Contaminants originating from various sources can easily infiltrate soil pores through intentional or unintentional leakage, leading to alterations not only in the visual appearance of soil particles but also in their geotechnical properties [10–13]. Under seismic loading, a tiny change in the geotechnical properties of the underlying soil can lead to intricate energy dissipation mechanisms, affecting the transmission of forces and deformations through the foundation and ultimately influencing the structural performance [14,15]. Furthermore, underground concrete foundations are highly susceptible to severe corrosion caused by the intrusion of contaminants, thereby resulting in a compromised bearing capacity and structural durability [16,17]. Consequently, the type, duration of exposure, and associated processes of transport and transformation of contaminants significantly impact the geotechnical properties of soils and the stability of concrete foundations, particularly within the soil-bearing layer. More alarmingly, the reduction in bearing capacity of contaminated foundations can potentially lead to engineering structural failures [18,19]. Therefore, elucidating the impacts of contaminants from distinct sources on the geotechnical properties of soil holds immense value in mitigating economic losses and preventing human casualties arising from foundation failures (Figure 1).
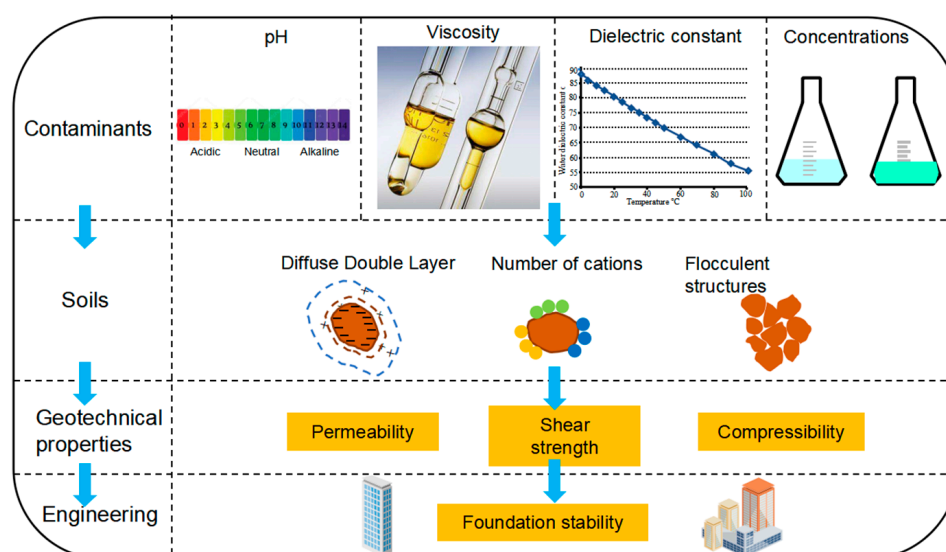

Figure 1. Mechanisms of the impacts of contaminants on the geotechnical properties of soils.

It is evident that the impact of various contaminants on the geotechnical properties of site soils lacks a comprehensive and systematic review. The existing literature primarily

focuses on the impacts of individual contaminants or a specific type of contaminant on soils [20,21]. Shayler et al. offered foundational insights into soil contaminants and their implications for human health and the environment; however, mechanistic exploration was lacking [22]. In a recent study, Al-Khyat et al. examined the repercussions of soil contamination arising from inadequate petroleum and industrial product management on soil quality, yet the consideration of agricultural pollutants was omitted [23]. Consequently, this review aims to address this research gap by elucidating the transport processes of contaminants in both unsaturated and saturated zones, firstly, and examining the impacts of contaminants from diverse sources on soil permeability, shear strength, and compressibility. The ultimate objective is to draw the attention of the scientific community to the remediation of contaminated sites while providing a theoretical foundation and technical support for effective remediation strategies.

2. Transport of Contaminants

The migration of contaminants significantly influences the geotechnical properties of soil and concrete foundations, making it imperative to comprehend the contaminant transport process. Contaminants are discharged from their sources and subsequently migrate to the soil surface, initiating a downward infiltration process through the unsaturated zone and capillary fringe, ultimately reaching the saturated zone. This intricate transport mechanism involves various phenomena, such as adsorption, volatilization, and biodegradation, as well as chemical reactions, including acid–base reactions and redox reactions. Additionally, the process encompasses advection, mechanical dispersion, and diffusion, which occur concurrently with groundwater movement [24–26]. A graphical representation of this transport process is illustrated in Figure 2.
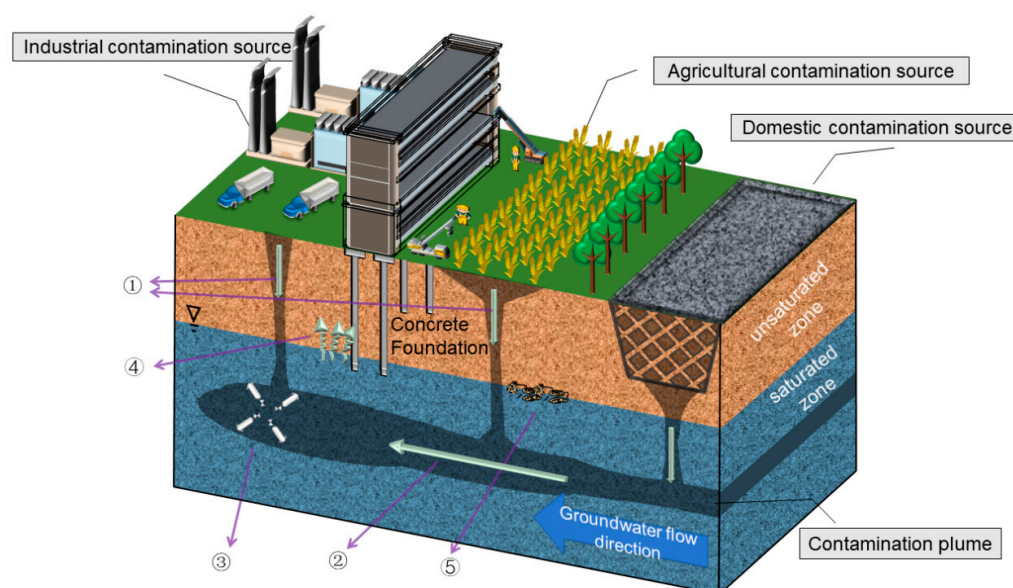
Figure 2. Transport processes of contaminants: ① infiltration, ② advection, ③ mechanical dispersion and diffusion, ④ volatilization, and ⑤ biodegradation.

The unsaturated zone serves as a temporary storage medium for contaminants, thereby delaying their entry into the saturated zones [27]. In a study conducted by Guo et al. [28], an analysis of nonconservative solute benzene and conservative solute bromine transport in the unsaturated zone revealed that the content of contaminants in the silty clay layer was notably higher compared to that in the sand. This led to the conclusion that the presence of a silty clay layer prolonged the penetration time of both solutes. Typically, a higher proportion of fine particles exerts a greater hindrance on contaminant migration. Consequently, it is crucial to monitor the water quality of the unsaturated zone and employ appropriate technical measures to prevent it from acting as a conduit for contaminants to

enter the saturated zone [29]. In a review conducted by Singh et al. [30], various types of lysimeters were examined for their application in monitoring solute transport within the unsaturated zone, offering valuable insights and experiences in this field.

The capillary fringe, situated between the unsaturated zone and the saturated zone, acts as a transitional zone with close hydraulic connectivity [31,32]. Lateral water flow within the capillary fringe is a significant characteristic, observable even with a small difference in hydraulic head [33]. Ronen et al. [34] further divided the capillary fringe into two regions: the upper stagnation region and the lower flow region. Lateral flow occurs in the flow region, while contaminants with a lower density than water, such as light non-aqueous phase liquids (LNAPLs), may accumulate in the stagnation region. Bacteria, similar to contaminants, can migrate between the capillary fringe and the saturated zone under advection [35]. Bacteria possess various functional groups on their cell walls and rely on electrostatic interactions and hydrogen bonds to adsorb cations and organic matter [36]. The upper part of the capillary fringe generally exhibits relatively abundant water and oxygen, while the lower part is saturated and anoxic. As a result, the capillary fringe serves as a site for natural aerobic and anaerobic biodegradation processes, playing a pivotal role in the contaminant dynamics within the subsurface [37–39]. In a soil column experiment, Kurt et al. [40] observed significant biodegradation of nonvolatile compounds such as aniline and diphenylamine near the capillary fringe. Additionally, due to the lower density of LNAPLs compared to water, they tend to accumulate in the capillary fringe, forming a thin layer that is more susceptible to biodegradation processes [41].

Upon entering the saturated zone, contaminants not only form plumes of contamination within the aquifer but also diffuse towards low permeable layers along the concentration gradient, which have traditionally acted as sinks for storing contaminants [42]. These low permeable layers can subsequently become sources of contaminants once the primary sources are eliminated. In a groundwater monitoring study conducted at a trichloroethylene-contaminated industrial site in Connecticut, Chapman and Parker [43] observed that trichloroethylene concentrations persisted for an extended period, even after reductions to certain levels, due to plume tailing behavior. The persistence of contamination plumes is believed to arise from both the back diffusion of the low permeable layers and the dissolution of contaminants in highly contaminated areas of the aquifer [44,45]. Seyedabbasi et al. [46] demonstrated that both mechanisms contribute to the prolonged lifespan of contamination plumes, with the back diffusion of low permeable layers being of greater significance. Consequently, once groundwater becomes contaminated, remediation efforts become exceedingly complex.

The successful restoration of contaminated sites requires a nuanced understanding of the diverse contaminant conditions and environmental settings. As detailed in the above paragraph, various contaminant sources encompass industrial/commercial plants, waste landfills, petrol stations, military camps, and nuclear power plants, each demanding a tailored solution. In response to these challenges, a spectrum of probable remediation techniques emerges. Industrial or commercial contamination in urban areas might find mitigation through in situ chemical oxidation [47] or enhanced bioremediation, such as a superfund site in Libby, Montana [48]. Waste landfill sites may benefit from phytoremediation or permeable reactive barriers. The distinct conditions of arid and semi-arid regions call for innovative approaches like electrokinetic remediation [49] or phytostabilization. Similarly, tropical regions characterized by high rainfall could leverage constructed wetlands or soil vapor extraction [50]. Incorporating these diverse remediation strategies into contaminated site restoration not only acknowledges the intricate interplay of contaminants and environments but also emphasizes the necessity of tailoring approaches for effective, sustainable, and region-specific solutions.

3. Impacts of Contaminants on Geotechnical Properties of Soil

The foundation soil consists of both coarse and fine particles. Coarse-grained soil typically exhibits a single-grained structure, with varying void ratios and dry densities

across different gradations [51]. In the case of fine-grained soils, the interactions between clay particles result in either net attraction or net repulsion forces, leading to the formation of a flocculent structure with larger pores or a dispersed structure with smaller pores, respectively. The thickness of the double layer formed by clay particles is microscopically influenced by the permeating fluid, while changes in the clay structure impact the permeability, shear strength, and compressibility of the clay [52]. Consequently, the proportion of fine-grained and coarse-grained components plays a crucial role in determining the magnitude of the physical and mechanical properties of the soil [53].
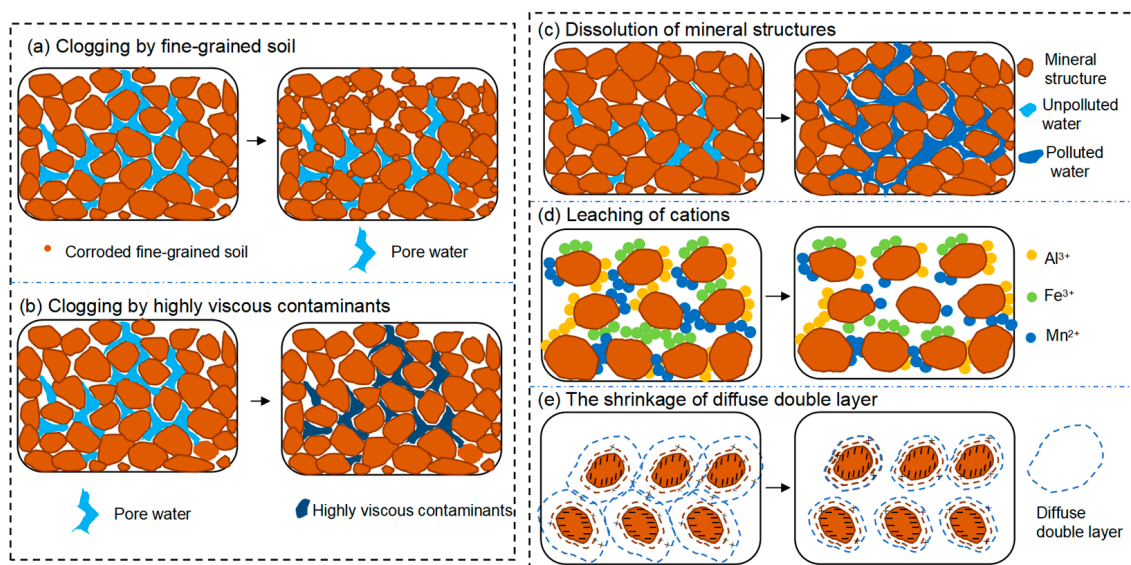
3.1. Permeability

Permeability, which refers to the capacity of a soil to transmit specific fluids, is a significant indicator of soil settlement. Various factors influence permeability, including soil types, soil structure, and the characteristics of permeating fluids [54,55]. In terms of the soil itself, gradation plays a crucial role in determining the magnitude of the permeability coefficient. In the context of contaminated soil and groundwater environments, the variability in permeability primarily stems from changes in the permeating fluids, which can consist of one or more combinations of acidic, alkaline, neutral, polar, and nonpolar fluids. The density, viscosity, and dielectric constant of the permeating fluid are vital factors that influence soil permeability [56]. The impacts of different contaminants on soil permeability are summarized in Table 1.

Table 1. Impacts and mechanisms of different contaminants on the permeability coefficient of soil.

Soil Type	Permeability Test	Contaminant	Permeability Coefficient k(m/s)		Variations	Mechanisms	References
			Natural Soil	Contaminated Soil			
Well-graded sand (SW)	Constant head test	Crude oil	$1.85\ (10^{-7})$	$1.28\ (10^{-7})$	↓	The high viscosity of the permeable fluid and the blockage of the pores.	[57]
Sandy loam	Falling head test	Engine oil	$3.74\ (10^{-7})$	$\sim 0.22\ (10^{-7})$	↓	Engine oil occupied the pores of the soil.	[58]
Silty loam			$2.65\ (10^{-7})$	$\sim 0.22\ (10^{-7})$	↓		
High plastic clay (CH)	—	Lead nitrate	$3.22\ (10^{-10})$	$1.86\ (10^{-10})$	↓	The deposition of salt in the pores of the soil.	[59]
Lateritic soil	Falling head test	Benzene	$1.44\ (10^{-8})$	$2.9\ (10^{-5})$	↑	The shrinkage of the double layer of clay particles.	[60]
		Ethanol		$9.7\ (10^{-6})$	↑		
		Kerosene		$9.5\ (10^{-6})$	↑		
Compacted tailing	Constant head test	Copper sulfate	$4.47\ (10^{-6})$	$4.67\ (10^{-6})$	↑	The shrinkage of the double layer of clay particles and increase of effective pore volume.	[61]
Compacted bentonite			$1.0\ (10^{-13})$	$2.0\ (10^{-13})$	↑		
High plastic clay (CH)	Falling head test	Alkaline leachate	$\sim 2.72\ (10^{-10})$	$\sim 0.59\ (10^{-10})$	↓	Alkaline leachate makes soil structure became dispersed and clay particles clogged pores of the soil.	[62]
Low plastic clay (CL)	Constant head test	Landfill leachate	$\sim 7.27\ (10^{-7})$	$\sim 5.81\ (10^{-7})$	↓	The addition of fine grains and microorganisms clogged soil pores.	[63]
Silt–bentonite mixture	Falling head test	Landfill leachate	$\sim 3.36\ (10^{-7})$	$\sim 1.12\ (10^{-8})$	↓	The growth of bacteria clogged the pores of the soil.	[64]
Coarse sand	Falling head test	Di-ammonium phosphate	$1.80\ (10^{-4})$	$0.51\ (10^{-4})$	↓	Soil particles become finer owing to the effect of alkaline solutions, the decreasing the effective pore space, and the hydraulic conductivity.	[65]
Fine to medium sand			$3.00\ (10^{-5})$	$0.12\ (10^{-5})$	↓		
Silty clay			$1.16\ (10^{-8})$	$8.17\ (10^{-8})$	↑	The alkaline solution dissolves the clay minerals, resulting in a larger permeability coefficient.	

3.1.1. Impact of Industrial Wastewater

The permeability of soils contaminated by industrial wastewater can exhibit both increases and decreases (Figure 3). Decreases in the permeability coefficient can be attributed to the following reasons: (i) the erosion of coarse-grained soil leading to the generation of fine-grained soil that clogs the pores (Figure 3a). For example, Karkush and Ali [59] introduced lead nitrate solutions with concentrations of 10,000, 20,000, and 30,000 mg/L to high plastic clay. The permeability decreased from an initial value of 3.22×10^{-10} m/s to 2.60×10^{-10}, 1.98×10^{-10}, and 1.86×10^{-10} m/s, respectively, and (ii) contaminants causing pore clogging (Figure 3b). For instance, Oyediran and Enya [57] added a crude oil equivalent of 10% of the soil volume to well-graded sand (SW) in Southern Nigeria. One group was exposed outdoors, while the other group underwent constant head permeability tests in the laboratory. The results indicated that the permeability of both contaminated soils decreased, which was attributed to the high viscosity of the permeating fluid and pore clogging. A recent study also demonstrated that the addition of gas oil and benzene resulted in reduced sand permeability, highlighting the influence of the permeating fluid's viscosity [66]. In the study conducted by Rahman et al. [58], different levels of engine oil, specifically 2%, 4%, 8%, 12%, and 16% based on the dry weight of the soil, were added to sandy loam and silty loam soils. The results indicated that the permeability of both soils decreased as the engine oil content increased. Similarly, both Nazir [67] and Salimnezhad et al. [68] observed a decrease in the permeability of high plastic clay soils due to engine oil contamination. The scanning electron microscope (SEM) images of natural soil and oil-contaminated soil clearly illustrated the presence of crude oil coatings and a reduction in the total pore volume and specific surface area.

Figure 3. Possible mechanisms of the decrease and increase in permeability by contaminants.

The mechanisms underlying the increase in permeability encompass the following factors: (i) the severe dissolution of mineral structures (Figure 3c). For instance, Izdebska-Mucha et al. [69] conducted a study on diesel-contaminated low plastic clay in Poland. The SEM analysis revealed a flocculent structure and larger pores in the contaminated clay, indicative of significant mineral structure dissolution compared to uncontaminated clay; (ii) the leaching of cations (Figure 3d). He et al. [61] observed an increase in permeability in both compacted tailings and bentonite following copper sulfate contamination. The leaching of cations, such as iron and aluminum, from the residual soil was identified as the primary cause. Bakhshipour et al. [70] simulated the impact of acid rain on the geotechnical properties of high plastic silty soil and low plastic clay. The results demonstrated an increase in permeability coefficients for both soils due to the leaching of iron and aluminum;

and (iii) the shrinkage of the double layer (Figure 3e). Amadi and Eberemu [60] found that the permeability of lateritic soil contaminated by benzene, ethanol, and kerosene increased with the increasing contaminant content. This increase was attributed to the shrinkage of the double layer and overall enlargement of the soil pores. These mechanisms contribute to the understanding of the processes leading to increased permeability in contaminated soils, highlighting the importance of mineral dissolution, cation leaching, and double-layer shrinkage as influential factors.

3.1.2. Impact of Landfill Leachate

Landfill leachate, containing a variety of organic and inorganic contaminants, exhibits different effects on soil permeability. Nayak et al. [71] conducted a study in India where they mixed acidic landfill leachate, rich in Cl^-, Mg^{2+}, Ca^{2+}, and NH_4^+ ions, with compacted lateritic soil at various levels (0%, 5%, 10%, and 20% of the soil dry weight). They observed an increase in permeability of the compacted lateritic soil, which could be attributed to the increased effective pore volume resulting from the reaction between acidic contaminants and clay minerals. Similarly, George and Beena [72] obtained similar conclusions in their study on lateritic soil.

In contrast to acidic leachate, alkaline landfill leachate tends to reduce soil permeability. For example, Khodary et al. [62] investigated the influence of alkaline leachate on the geotechnical properties of Egyptian high plastic clay. In this particular landfill, the leachate was characterized by high salinity, heavy metals, and hydrocarbons. Through falling head permeability tests, the permeability coefficient decreased from 2.72×10^{-10} m/s to 0.59×10^{-10} m/s. This reduction was attributed to the dispersed soil structure and significantly decreased porosity caused by the alkaline leachate.

Shariatmadari et al. [63] conducted field sampling and laboratory leachate treatment to measure the permeability of soil in a landfill. They found that the permeability coefficient increased as the distance from the landfill site increased. The SEM images revealed that leachate interacted with soil particles, leading to a significant decrease in particle size. The effects of landfill leachate-containing microorganisms on the permeability of compacted silt–bentonite mixtures were investigated by Francisca and Glatstein [64]. Through falling head tests and SEM images, they observed that bacterial growth resulted in pore blockage and a subsequent reduction in the permeability coefficient by one to two orders of magnitude over a 15-month experimental period.

3.1.3. Impact of Agricultural and Aquacultural Activity

Chemical fertilizers, herbicides, and pesticides commonly utilized in agricultural practices can have an impact on soil permeability. Eltarabily et al. [65] conducted a study to simulate the short-term effects of phosphate fertilizer on the geotechnical properties of coarse sand, fine-to-medium sand, and silty clay using a di-ammonium phosphate solution. The results indicated that the permeability responses of the three soils varied as the concentration of di-ammonium phosphate increased from 0% to 20%. Specifically, the permeability of coarse sand decreased from 1.802×10^{-4} m/s to 0.511×10^{-4} m/s, and the permeability of fine-to-medium sand decreased from 3.001×10^{-5} m/s to 0.117×10^{-5} m/s, while the permeability of silty clay increased from 1.161×10^{-8} m/s to 8.169×10^{-4} m/s. These findings can be explained by the alkaline solution causing the coarse portion of the soil to transform into fine particles, resulting in a decrease in the permeability coefficient for coarse and fine-to-medium sand. Conversely, in the case of silty clay, the alkaline solution dissolves clay minerals, leading to a larger permeability coefficient (Figure 4). Moreover, the unregulated expansion of aquaculture has been found to potentially compromise soil permeability due to interactions between aquaculture leachate and subsoil, suggesting a negative impact on the overall hydraulic conductivity of the soil [73,74].
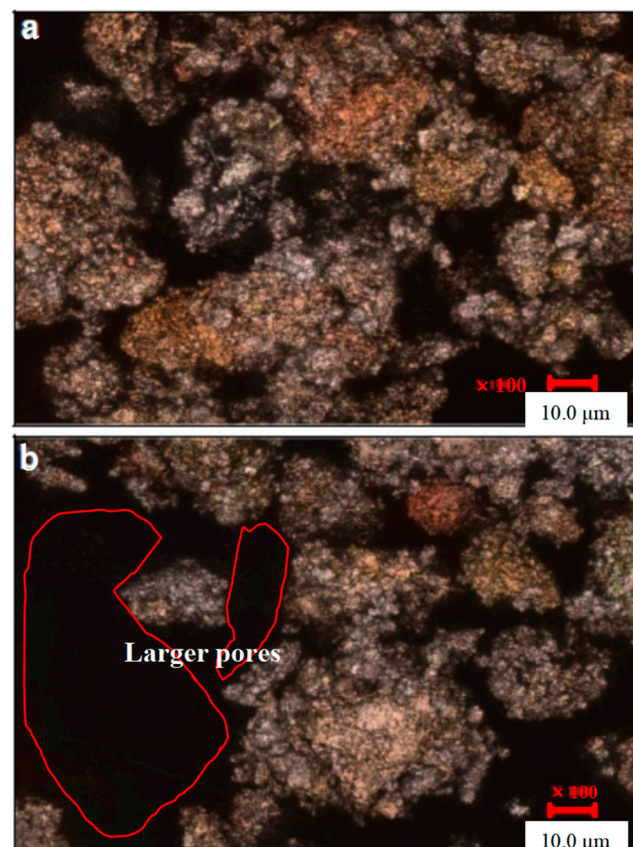
Figure 4. Laser optical scanning micrographs: (**a**) uncontaminated silty clay and (**b**) contaminated with 20% phosphate. Reprinted with permission from Ref. [65].

3.2. Shear Strength

The shear strength of soil refers to its maximum resistance against shearing stress at the failure plane. According to the Mohr–Coulomb strength theory, soil shear strength comprises cohesion strength and friction strength, as shown in Equation (1):

$$\tau_f = c + \sigma tan\varphi \tag{1}$$

Cohesion is the combined result of attractive and repulsive forces between soil particles, while internal friction is the resistance between individual soil particles at their contact points due to friction. It is worth noting that the internal friction angle is typically greater in coarse-grained soil compared to fine-grained soil. Numerous studies have investigated the factors influencing soil shear strength, including soil bulk density, water content, organic carbon content, and permeable fluids [66,75,76]. Both cohesion and the internal friction angle are crucial parameters that affect soil shear strength. Therefore, it is essential to explore the variations in soil cohesion and the internal friction angle resulting from contamination. Table 2 provides a summary of the changes in soil cohesion and the internal friction angle before and after soil contamination.

Table 2. Summary of the impacts of different contaminants on cohesion and the internal friction angle of soil.

Soil Type	Test Method	Contaminant	Cohesion c (MPa)		Variations	Internal Friction Angle φ (°)		Variations	Mechanisms	References
			Natural Soil	Contaminated Soil		Natural Soil	Contaminated Soil			
SP	Direct shear test	Gas oil	~7.30	~12.20	↑	~20.15	~14.34	↓	The increase of cohesion is owing to the low dielectric constant of gas oil, and the decrease of the internal friction angle is caused by the lubrication effect.	[76]
ML			~10.00	~12.40	↑	~19.80	~10.88	↓		
CL			~12.00	~14.68	↑	~18.58	~6.17	↓		
SP	Direct shear test	Benzene	0	~7.30	↑	~38.00	~30.00	↓	The viscosity of gas oil is higher than benzene.	[66]
		Gas oil		~8.90	↑		~28.00	↓		
SP		Benzene	0	~7.10	↑	~30.00	~24.00	↓		
		Gas oil		~8.40	↑		~20.00	↓		
90% kaolinite and 10% sand	Direct shear test	Lead nitrate	~36.00	~21.00	↓	~32.48	~32.93	↑	The invasion of heavy metal cations leads to the double layer contraction, which leads to the flocculent structure of the clay and the decrease of the shear strength.	[77]
		Zinc nitrate		~28.67	↓		~33.45	↑		
60% kaolinite and 40% sand		Lead nitrate	~31.00	~15.00	↓	~36.17	~37.47	↑		
		Zinc nitrate		~23.74	↓		~37.88	↑		
Kaolinite	Triaxial consolidated undrained test	Copper chloride	~24.00	~19.68	↓	~ 14.10	~ 12.40	↓	The double layer contraction and the clay particles become relatively free.	[78]
Silty clay	Direct shear test	Landfill leachate	~21.95	~19.92	↓	~18.06	~23.73	↑	The mineral content of clay decreases, which leads to the decrease in soil cohesion. Changes in the geometric arrangement of soil particles may increase the internal friction angle.	[79]
10% bentonite, 20% sand and 70% clay	Direct shear test	Landfill leachate	35.25	51.50	↑	29.70	28.46	↓	The content and specific surface area of fine grains increased.	[80]

Table 2. *Cont.*

Soil Type	Test Method	Contaminant	Cohesion *c* (MPa)		Variations	Internal Friction Angle *φ* (°)		Variations	Mechanisms	References
			Natural Soil	Contaminated Soil		Natural Soil	Contaminated Soil			
Lateritic soil	Triaxial consolidated undrained test	Landfill leachate	18.20	20.00	↑	30.00	25.00	↓	The landfill leachate liberates the clay particles in the soil mass and increases the clay content in the lateritic soil.	[81]
Clay loam	Direct shear test	Agricultural contamination	21.39	22.46	↓	36.90	41.05	↑	The increase of organic carbon content enhanced the cohesion of soil.	[82]
Clay loam	Direct shear test	Rice straw	~40.70	~91.66	↑	~7.12	~15.98	↑	The content of soil organic carbon was improved.	[83]
		Wheat straw		~82.69	↑		~17.73	↑		
Amber clay	Ring shear test	Atrazine	6.40	9.50	↑	27.32	21.70	↓	The increase of pore fluid viscosity promotes particle sliding and reduces the internal friction angle of soil.	[84]
Black clay			8.60	12.60	↑	28.80	23.40	↓		
Kaolinite clay			4.70	7.20	↑	26.80	22.40	↓		

Note: SP: poorly graded sand; ML: low plasticity silt; CL: low plasticity clay.

3.2.1. Impact of Industrial Wastewater

Nasehi et al. [76] conducted an investigation into the changes in geotechnical properties of poorly graded sand, low plastic silty soil, and low plastic clay contaminated with gas oil. Through direct shear tests, they observed that the cohesion of all three soil samples increased while the internal friction angle decreased under the influence of oil lubrication. This can be attributed to the lower dielectric constant and higher viscosity of gas oil compared to water. Similarly, Hanaei et al. [66] mixed two types of poorly graded sand with gas oil and benzene at a ratio of 15% of the sand's dry weight. The direct shear test results indicated that the cohesion increased from 0 to approximately 7.3 kPa and 7.1 kPa, respectively, after contamination with benzene, while the internal friction angle decreased from around 38° and 30° to about 30° and 24°, respectively. When contaminated with gas oil, the cohesion increased from 0 to approximately 8.9 kPa and 8.4 kPa, with corresponding reductions in the internal friction angles to around 28° and 20°, respectively. Furthermore, an increase in the content of gas oil and benzene led to a larger variation range in cohesion and the internal friction angle. Additionally, gas oil exhibited a more pronounced effect compared to benzene.

Negahdar and Nikghalbpour [77] conducted a study on the impact of different concentrations of lead nitrate and zinc nitrate on the geotechnical properties of kaolinite–sand mixtures with varying mixing ratios. Their findings revealed that the cohesion of the kaolinite–sand mixtures decreased as a result of lead and zinc contamination, with a positive correlation observed between the concentration of heavy metal contaminants and the decrease in cohesion. However, the internal friction angle exhibited only slight changes. According to the double-layer theory, the presence of heavy metal cations led to a reduction in the thickness of the double layer, resulting in the formation of a flocculent structure in the clay particles and a decrease in shear strength. The more pronounced effect of lead compared to zinc may be attributed to certain minerals in the soil exhibiting stronger adsorption properties towards lead. Another study by Zhang et al. [78] investigated the contamination of kaolinite by copper chloride and found that both the cohesion and internal friction angle of kaolinite decreased as the concentration of copper chloride increased. This can be explained by the decrease in the double-layer thickness, allowing for the greater movement of clay particles. Similarly, marl soil possesses a stratified configuration due to the prevalence of clay minerals. Upon exposure to a 25 cmol/kg soil lead contaminant, the soil structure exhibited progressive tangling and limited flocculation, leading to expanded interstitial spaces. This is because, with Pb carbonate deposits coating the clays, the repulsive forces among the particles weakened, causing a reduction in the thickness of the diffused double layer [85].

Additionally, it has been observed that low concentrations of gas oil, fuel oil, and crude oil can enhance the shear strength of sand, clay, and lateritic soil. Notably, the shear strength of sand and lateritic soil exhibited significant improvement at an oil content of 2%, while the shear strength of clay increased at a 4% oil content [18].

3.2.2. Impact of Landfill Leachate

Due to the varying compositions of landfill leachate, the impacts on soil shear strength can differ significantly. Li et al. [78] observed a decrease in cohesion of Wuhan silty clay contaminated by landfill leachate, ranging from approximately 21.95 kPa to 19.92 kPa, while the internal friction angle increased from about 18.06° to around 23.73°. X-ray diffraction tests on the silty clay indicated that the decrease in clay mineral content post-contamination contributed to the reduction in soil cohesion, while the alteration in soil arrangement may explain the increase in the internal friction angle. Similarly, Demdoum et al. [79] demonstrated an increase in cohesion of compacted mixed soil from 35.25 kPa to 51.50 kPa, accompanied by a slight decrease in the internal friction angle from 29.70° to 28.46°. This can be attributed to the higher content of fine particles within the mixture due to the presence of leachate. Sunil et al. [80] conducted a study involving the mixing of landfill

leachate with lateritic soil at a ratio of 20% of the soil weight. The effective cohesion of the lateritic soil increased from 18 kPa to 20 kPa, while the effective internal friction angle decreased from 30° to 25°. The authors indicated that this phenomenon was a result of the leachate's ability to release clay particles within the soil aggregates, consequently increasing the clay content in the lateritic soil.

3.2.3. Impact of Agricultural Activity

Agricultural activities have a significant impact on the shear strength of soil. In the Abarkooh Plain of Iran, the transformation of desert soil into farmland resulted in an increase in the cohesion of wheat planting soil from 21.39 kPa to 22.46 kPa and an increase in the internal friction angle from 36.9° to 41.05° due to crop planting and fertilization [82]. This can be attributed to the initial low organic carbon content of the soil, which is enhanced through agricultural activities, thereby strengthening the cementation between soil particles and increasing the cohesion. Fang et al. [83] also reported similar findings on the shear strength of clay loam under the influence of natural fertilizers. In another study by Keramatikerman et al. [84], amber clay, black clay, and kaolinite clay samples were collected and contaminated with 6% herbicide atrazine. The results from ring shear tests indicated a positive correlation between the cohesion of clay and atrazine content. The cohesion of amber clay, black clay, and kaolinite clay increased from 6.4 kPa, 8.6 kPa, and 4.7 kPa to 9.5 kPa, 12.6 kPa, and 7.2 kPa, respectively. However, the internal friction angle exhibited a negative correlation with the atrazine content, decreasing from 27.32°, 28.80°, and 26.80° to 21.70°, 23.40°, and 22.40°, respectively. This can be attributed to the increase in pore fluid viscosity and the promotion of particle sliding after atrazine contamination.

3.3. Compressibility

Soil compressibility is influenced by various factors, including the soil itself and environmental conditions such as density, organic content, and soil structure [68,86]. Numerous studies have demonstrated that the contamination of industrial wastewater, landfill leachate, and agricultural sewage can lead to changes in soil compressibility. Chen et al. [87] highlighted the differences in compressibility of kaolinite based on the dielectric constant of the pore fluid, whether it was greater than or less than 24. Furthermore, for landfills with a well-impermeable layer, the waste load often remains below the pre-consolidation stress of the foundation soil (OCR > 1). However, when the accumulation of leachate increases the effective stress of the waste load beyond the pre-consolidation stress, it results in an increase in settlement of the foundation soil [88]. The compression index is an important parameter that reflects soil compressibility and can be utilized to estimate the consolidation settlement of the foundation soil [89,90]. Table 3 provides an overview of the effects of different contaminants on soil compressibility.

Table 3. Impacts of different contaminants on soil compressibility.

Soil Type	Contaminant	Compression Index C_c		Variations	Mechanisms	Reference
		Natural Soil	Contaminated Soil			
CH	Acidic industrial wastewater	0.226	0.316	↑	Industrial waste water destroys soil structure and makes the contaminated soil have greater consolidation potential than the undisturbed natural soil. Therefore, the compression index of soil increases.	[91]
	Basic industrial wastewater		0.282	↑		
CL	Acidic industrial wastewater	0.169	0.245	↑		
	Basic industrial wastewater		0.235	↑		

Table 3. *Cont.*

Soil Type	Contaminant	Compression Index C_c		Variations	Mechanisms	Reference
		Natural Soil	Contaminated Soil			
Osaka Bay clay	Sulphuric acid	0.474	0.722	↑	The corrosion of sulfuric acid weakens the cementation between clay particles and reacts with clay minerals, which loosens the soil structure and increases the compression index. The opposite performance of Kawasaki mud may be caused by the decrease in the diffuse double-layer thickness.	[92]
Ariake clay		~1.220	~1.469	↑		
Kawasaki mud		~0.400	~0.315	↓		
CH	Motor oil	0.150	~0.300	↑	The structural stability of clay contaminated with motor oil has been damaged, and the clay particles are loosely stacked together. Compared with natural soil, it has a larger compression index and may cause extra settlement when under new loads.	[67]
CH	Crude oil	~0.300	~0.380	↑	Since crude oils are nonpolar fluids, they do not react with soil components and occupy pores in the soil. Crude oil is more easily drained from the soil when subjected to loading. Therefore, crude oil-contaminated soil has a higher compression index than natural soil.	[68]
10% bentonite, 45% sand and 45% clay	Landfill leachate	0.127	0.106	↓	Mineralogical degradation and microorganisms play an important role. Compared with water, landfill leachate-contaminated soil has a higher pre-consolidation pressure. Therefore, it has less compressibility and a smaller compression index.	[80]
10% bentonite, 45% sand and 45% clay		0.120	0.097	↓		

Note: CH: high plastic clay; CL: low plastic clay.

3.3.1. Impact of Industrial Wastewater

Industrial wastewater is known to typically increase the compressibility of contaminated soil. In a study conducted by Irfan et al. [91], the effects of different concentrations of acidic and alkaline industrial wastewater on the geotechnical properties of high plastic clay and low plastic clay were investigated. The findings revealed that both acidic and alkaline wastewater contamination increased the compressibility of the soil. Specifically, when contaminated with 20% of the soil dry weight, the compression index of high plastic clay increased from 0.226 to 0.316 and 0.282 under the influence of acidic and alkaline wastewater, respectively. Similarly, for low plastic clay, the compression index increased from 0.169 to 0.245 and 0.235 under the same contamination conditions. Gratchev and Towhata [92] explained the impact of sulfuric acid on the compressibility of Osaka Bay clay, Ariake clay, and Kawasaki mud using the double-layer theory. Shehzad et al. [93] investigated the changes in the compression index and compressive strength of low plastic clay in Pakistan when contaminated with paper textile and rubber industrial wastewater. The results indicated that the compression index of low plastic clay increased from 0.075 to a range of 0.110–0.170 with mixing ratios of wastewater and soil at 5%, 10%, and 20%. This increase in compressibility is believed to be associated with a reduction in interparticle

friction caused by the presence of contaminants. Nazir [67] studied the variations in the geotechnical properties of high plastic clay contaminated with oil and found that the compression index increased from 0.150 to approximately 0.300 after a 25-month contamination cycle. This increase in compressibility was attributed to the loose arrangement of clay particles resulting from the structural rearrangement of the contaminated soil. The study on high plastic clay contaminated with crude oil also revealed an increase in the compression index with a higher crude oil content, indicating the easy discharge of crude oil without significant clay adsorption [68].

3.3.2. Impact of Landfill Leachate

Different components of landfill leachate have varying effects on soil compressibility. In the study conducted by Li et al. [79], it was observed that the compression index and compressibility of silty clay increased when treated with landfill leachate, with the compression index rising from approximately 0.08 to 0.10. Demdoum et al. [80] investigated the compressibility of a compacted mixture of bentonite, sand, and clay used as landfill cushion after leachate contamination. They found that, when the sand content exceeded 45%, the compression index of the contaminated bentonite–sand–clay mixture was lower compared to the unpolluted group. The authors highlighted the role of microbial degradation and mineral dissolution in explaining this phenomenon. In a simulation study by Ray et al. [94], the contamination of bentonite with heavy metals (Cu^{2+} and Zn^{2+}) was examined. The results showed that, as the concentration of heavy metals increased, the consolidation coefficient of bentonite increased, and the compression index decreased from 0.64 to 0.58 and 0.54, respectively. The authors attributed this effect to the decrease in the thickness of the double layer of clay particles under the influence of heavy metal cations, leading to a reduction in the compressibility of bentonite.

3.3.3. Impact of Agricultural Activity

In recent times, the expansion of infrastructure projects such as bridges, tunnels, and roads in developing countries has led to the conversion of agricultural lands, necessitating research into the impacts of fertilizers and pesticides on soil properties, especially in countries with limited land availability. Although studies on the effects of agricultural contaminants on soil compressibility are limited, it has been demonstrated that prolonged fertilizer use can result in a decrease in the soil-bearing capacity and an increase in foundation settlement, leading to structural damage [95]. Furthermore, the application of farmyard manure and mulch has been found to enhance the capillary water-holding capacity and saturated water content in the soil, as observed in the research conducted by Zhang et al. [96] and Agbede et al. [97]. These studies have also confirmed that farmyard manure contributes to a reduction in the soil bulk density and temperature, while increasing the total porosity and moisture content, thereby potentially influencing soil compressibility. Moreover, farmyard manure contains a significant number of solid substances that can occupy soil pores, consequently affecting the compressibility of agricultural soil. Additionally, in a study investigating the geotechnical properties of clay contaminated with ammonium chloride and ammonium phosphate, Cyrus et al. [98] observed that the compression index of the soil decreased as the curing period progressed, indicating that the development of soil chemical bonds played a role in mitigating compressibility.

4. Conclusions

The geotechnical properties of soils play a crucial role in ensuring the stability of structures built on contaminated sites. Contaminants from various sources have an impact on these properties to varying degrees. This comprehensive study focused on the effects of contaminants originating from industrial, domestic, and agricultural sources on the permeability, shear strength, and compressibility of foundation soils. In culmination, the significance of our study extends beyond theoretical exploration, reaching into the realm of practical implications for both engineering professionals and environmental stewards.

The intricate interplay between contaminants from diverse sources and soil geotechnical properties underscores the importance of proactive intervention. Recognizing the long-lasting consequences of these interactions, our research serves as a vital blueprint for informed decision-making in the face of soil contamination challenges.

In conclusion, the impacts of contaminants from various sources on soil geotechnical properties is a gradual process that demands careful consideration due to their long-lasting nature. It is crucial to address this issue proactively to prevent a "frog in boiling water" scenario, whereby problems go unnoticed until they reach critical levels. By taking immediate action, we can mitigate potential hazards and secure a sustainable environment for both present and future generations.

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