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Numerical Analysis of Load-Bearing Capacity in Contaminated and Uncontaminated Soils Treated with Nanomaterials

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Abstract

Construction of load-bearing structures requires both a strong foundation and stable soil. For projects located on weak or contaminated soils, stabilization techniques are a prerequisite. Nanotechnology holds promise for improving soil strength and stability, offering innovative solutions for enhancing site conditions in geotechnical engineering. This numerical study explores the potential application of nano-clay (NC) and nano-silica (NS) in improving the overall load-bearing performance of a strip footing resting on clean and kerosene-contaminated soils. The objectives are to assess the impact of varying nanoparticle contents and curing durations on soil performance. Results suggested that adding NC and NS substantially enhances the bearing capacity ratio (BCR) up to a maximum of 4.76 and 4.33 at 1% NC and 1.5% NS, respectively, compared to untreated soil. Overdosing, however, resulted in reduced effectiveness, emphasizing the significance of optimal contents. Conversely, the BCR improvement was less noticeable in kerosene-contaminated soils until it peaked at 2.5% NS and 2% NC. However, results of both clean and contaminated soils revealed that nanomaterials negatively impact settlement behavior. Curing age was found to be a major factor affecting BCR, in which treated soils showed a consistent increase in BCR over time. These findings endorse the potential of nanomaterials for stabilizing soil used in geotechnical engineering. Careful selection of dosages and consideration of soil contamination are critical to optimizing performance in complex geotechnical conditions.

Keywords: Kerosene-Contaminated Soil; Nanoclay; Nanosilica; Soil Stabilization.

1. Introduction

The incorporation of nanotechnology into geotechnical engineering has recently attracted much attention, owing to its potential to enhance soil properties, including strength and compressibility. Progressive solutions such as nanomaterials provide an advanced technique to address demanding situations, such as low bearing capability and excessive settlement in both uncontaminated and contaminated soils [1, 2]. Nanomaterials, especially nano-clay and nano-silica, have shown great potential as soil components, offering improved average performance as compared to conventional stabilizing techniques [3, 4]. Soil contamination has been evidenced to adversely affect the engineering performance of soils, leading to their unsuitability for construction projects [5]. Research on the effects of kerosene on soil properties revealed significant negative impacts. These include changes in permeability and consistency index, as well as decreases in soil strength, compaction, and bearing capacity. A numerical study indicated that the increase in the content and depth of kerosene contamination resulted in a decline in the bearing capability of circular foundations [6]. Traditional stabilizing techniques, such as mechanical compaction and chemical additives, usually prove inadequate when dealing with the contaminated soils and are considered expensive, intrusive, and harmful to the environment [7]. Nanomaterials offer a sustainable and advanced alternative for soil stabilization. By filling up voids, strengthening particle bonds, and improving soil conduct at the microstructural level, these nanoparticles interact with soil particles. This leads to increased strength, reduced permeability, and improved load-bearing capacity [8, 9].

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Nano-silica can be found in nature or manufactured from various materials [10]. It has been used for strengthening the mechanical and microstructural properties of soils. The addition of nano-silica alters soil microstructure and forms the calcium-silicate-hydrate (CSH) gel, leading to decreased porosity, and binds soil particles [11]. Scanning Electron Microscopy (SEM) studies revealed that nano-silica improves compaction and particle bonding, resulting in a denser soil matrix with fewer voids [12]. It also demonstrated exceptional effectiveness in raising unconfined compressive strength (UCS). Selvakumar et al. [13] found that incorporating 6% nano-silica led to a 422% increase in UCS, boosting its bearing capacity by up to 620%. A small amount of nano-silica significantly alters the soil engineering behavior due to its strong reactivity and greater specific surface area [11]. Nano-silica significantly increased soil strength at optimal percentages. However, exceeding the optimal dosage results in a reduction of compressive strength due to the uneven distribution of nano-silica and the establishment of weak connections between the cementitious compounds and soil particles [14-16]. A review study by Barbhuiya & Hasan [17] concluded that adding 0.7% to 5% nano-silica into clayey soil enhances the unconfined compressive strength by a factor of 1.38 to 6.65, achieving a peak value at the optimal dosage, after which the strength diminishes. Additionally, nano-silica is particularly helpful in stabilizing polluted soils since it reduces pollutant leachability and strengthens soil structure by employing producing cementitious chemicals [18]. Nevertheless, the primary disadvantage of nano-silica is inadequate dispersion during soil mixing [19].

Comparably, nano-clay as a multifunctional additive characterized by its high specific surface area and cation exchange has proven to be a versatile soil stabilizer that strengthens particle interactions and improves soil compaction. At the optimum dosages, nano-clay can increase soil strength and durability by up to 400% [1]. Similar observations have been reported by Mir & Hariprasad Reddy [20] and Khalid et al. [21], in which at an ideal level of nanoclay soil strength and bearing capacity significantly increased, while after that particle clustering and decreased homogeneity caused performance to drop. Nano-clay can also stabilize contaminated soils by adsorbing organic and heavy metal contaminants and reducing their movement [22].

The effectiveness of the nanomaterials is strongly influenced by the curing age, since it controls particle interactions, bonding, and strength development that occurs over time. Due to the ongoing development of cementitious products and enhanced soil-nanomaterial integration, studies have demonstrated that extended curing times can result in a more significant improvement in unconfined compressive strength and shear strength [23]. Al-Sanad & Ismael [24] examined the effects of the curing period on Kuwaiti sand, both clean and oil-contaminated. They found that as sand ages and the oil content decreases as a result of volatile compound evaporation, its strength and stiffness increase with time. The rate of UCS gain for clean and kerosene-contaminated CL soil–nanomaterial mixes seemed to rise and drop, respectively, across the 28 days of curing [25].

The major objectives are to assess the enhancements in bearing capacity and to evaluate settlement under varying nanoparticle concentrations in different soil conditions. Thus, this work promotes the development of effective and sustainable methods for improving soil for geotechnical engineering. The findings offer useful data for the potential application of nanomaterials in geotechnical engineering and are intended to develop practical soil stabilization techniques for both contaminated and uncontaminated areas.

2. Materials and Methods

The materials and experimental results used in this investigation, which served as the basis for the numerical and parametric analyses in this work, were initially published by Ali Zomorodian et al. [25]. The materials include kerosene, nano-clay, and nano-silica as well as natural soil classified as sandy lean clay (CL). A summary of the material properties is provided in Table 1.

Table 1. Material properties [25]

Materials	Property	Value
Clean soil	LL (%)	36.5
	PL (%)	17
	% Clay (%)	61
Nano-clay	Material	Montmorillonite
	Form	Powder
	Particle Density (Mg/m^3)	3-3.7
	Size (nm)	1-2
	Specific Surface Area (m^2/g)	220-270
Nano-silica	Form	Powder
	Particle Density (Mg/m^3)	2.4
	Size (nm)	11-13
	Specific Surface Area (m^2/g)	200

According to Ali Zomorodian et al., [25], the experimental program evaluated the effects of kerosene, nano-clay, and nano-silica on the unconfined compressive strength (UCS) of sandy lean clay (CL) soil. UCS testing was performed on specimens of uncontaminated and kerosene-contaminated soils (0, 2, 4, 8, and 12 weight percent kerosene) with a diameter of 38 mm and a duration of 76 mm in the preparatory section (ASTM, 2016). The second stage investigated UCS for clean and 12 wt% kerosene-contaminated soils mixed with varying amounts (0 – 3 wt%) of nano-silica or nano-clay. Results of UCS are summarized in Table 2.

Table 2. Unconfined Compressive Strength of clean and contaminated soils with nanomaterials [25]

Kerosene content (wt%)	NS (%)	NC (%)	Curing age (days) 1	7	14	28
			UCS (kPa)			
0	0	0	40.9	89.4	135.2	232.4
0	0.5	0	52.8			
0	0	0.5	126.9			
0	1.0	0	70.1			
0	0	1.0	194.3	231.9	288.1	448.6
0	1.5	0	176.3	223.5	276.5	437.4
0	0	1.5	109.4			
0	2.0	0	157.3			
0	0	2.0	122.4			
0	1.5	1.0	278.5	316.4	368.3	527.6
2	0	0	40.1			
4	0	0	38.9			
8	0	0	27.5			
12	0	0	15.8			
12	1.0	0	16.2			
12	0	1.0	24.6			
12	1.5	0	18.1			
12	0	1.5	26.4			
12	2.0	0	24.7			
12	0	2.0	26.8	57.7	76.1	106.4
12	2.5	0	35.8	40.5	55.5	60.9
12	0	2.5	16.1			
12	3.0	0	26.0			

Soil samples were prepared by oven-drying the CL soil (450 g per batch) at 110 °C for 24 hours. Kerosene-contaminated samples were mixed manually, covered, and left for 48 hours to achieve ionic equilibrium before being compacted into specimens using standard Proctor effort. Nanomaterial-soil blends were prepared by mixing nano-silica or nano-clay with water at the optimum water content, and then combining the suspension with oven-dried soil.

Specimens were compacted at constant dry density and cured for 1, 7, 14, or 28 days at ambient temperature and constant water content. The study analyzed the effects of kerosene content, nanomaterial additives, and curing duration on mobilized strength, using a total of 41 different CL soil mixtures with three specimens per mix.

2.1. Finite Element Analysis

In engineering materials, the strength of soils can serve as a critical measure for failure analysis. Various failure criteria are used to characterize material behavior under stress. Conical failure criteria, such as the renowned Mohr-Coulomb criterion, are suitable for soils that exhibit both frictional and cohesive components of shear strength. In contrast, cylindrical failure criteria are typically applied to materials like metals or undrained clays, which exhibit "frictionless" behavior (where $\varphi_u \approx 0$).

The Von Mises criterion, represented geometrically as a right circular cylinder aligned along the space diagonal, as shown in Figure 1, is a widely used approach for assessing whether a stress state has exceeded the elastic limit. This criterion considers only one of the three stress invariants, t or $\bar{\sigma}$, as relevant for yield determination. Unlike conical criteria, the Von Mises criterion is symmetric in the π-plane and does not depend on the invariants. s or θ. This symmetry limits its direct applicability to traditional soil mechanics strength theories. Since the Von Mises criterion assigns equal weight to all three principal stresses, the intermediate principal stress σ_2, must be accounted for after failure to accurately describe the behavior of undrained clays.

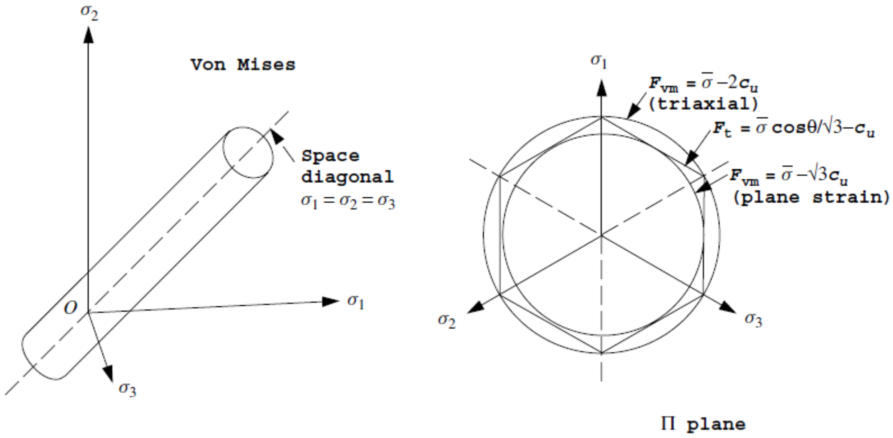

Figure 1. Failure criteria for Von Mises & Tresca

In plane strain applications, it can be shown that no plastic volume change occurs at the point of failure. The intermediate principal stress is given by Equation 1:

$$\sigma_2 = \frac{\sigma_1 - \sigma_3}{2} \tag{1}$$

Thus, the Von Mises failure criterion is expressed in Equation 2 as:

$$F_{vm} = \bar{\sigma} - \sqrt{3}\, c_u \tag{2}$$

where c_u represents the undrained "cohesion" or shear strength of the soil. Conversely, in triaxial conditions given in Equation 3, where:

$$\sigma_2 = \sigma_3 \tag{3}$$

The appropriate Von Mises failure criterion as provided in Equation 4 is:

$$F_{vm} = \bar{\sigma} - 2c_u \tag{4}$$

Failure occurs when the correct stress condition is applied to either case, satisfying the expression given in Equation 5:

$$\left|\frac{\sigma_1 - \sigma_3}{2}\right| = c_u \tag{5}$$

To further explore these principles, stabilized clean and contaminated soil samples by nanomaterials were analyzed using a finite element parametric study focused on bearing capacity problems. As shown in Figure 2, the study involved a strip footing resting on homogeneous, isotropic, undrained clay soil. The footing was subjected to a uniform stress (q), incrementally increased until failure. The behavior of the undrained clay was modeled using the Von Mises failure criterion. A nonlinear finite element program developed by Smith et al. [26] was employed in this analysis. Figure 2 also illustrates the boundary conditions and finite element mesh used to simulate a typical bearing capacity problem.

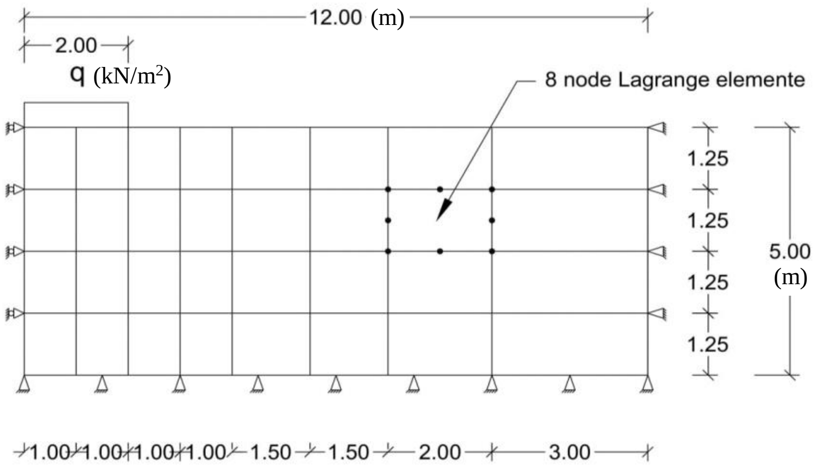

Figure 2. Finite element mesh and boundary condition of the problem investigated

The numerical simulation's finite element mesh, which consists of 8-node Lagrange, where the element sizes varied. Near the centerline, elements were 1 m, gradually increasing towards the vertical boundaries to a size of 3 m, as shown in the mesh configuration. This mesh is covered a soil area measuring 12 m in length and 5 m in depth. In order to simulate no displacement, the boundary conditions incorporate rollers along the vertical boundaries to allow horizontal movement and fixed supports along the bottom edge. This arrangement guarantees a precise representation of the soil's response under loading conditions. The utilization of 8-node elements enhances precision in depicting stress and displacement distributions, especially under non-linear loading circumstances

Figure 3 presents a flowchart detailing the step-by-step methodology adopted in this study. The process begins with the preparation of soil samples, followed by the incorporation of nanomaterials at varying dosages, numerical modeling, and analysis of the results. This structured approach ensures a comprehensive evaluation of the effects of nanomaterials on the soil's mechanical properties.

Define Objective

- Assess improvements in soil bearing capacity and settlement using nanomaterial.
- Identify types of soils: clean and kerosene-contaminated.

↓

Material Selection and Preparation

- Select soil type: Sandy lean clay (CL) as were initially published by Zomorodian et al. [25].
- Choose stabilizer: Nano clay (NC) and Nano silica (NS).
- Prepare soil samples: clean and contaminated conditions.

↓

Numerical Modelling Setup

- Use a nonlinear finite element proposed by Smith and Griffiths [26].
- Define parameters: Soil properties, nanomaterial content, curing durations and boundary conditions.
- Simulate strip footing on homogeneous soil Von Mises failure criterion.

↓

Parametric Analysis

- Evaluate effects of NC and NS dosages.
- Investigate curing duration on BCR and settlement.

↓

Result Analysis

- Compare clean vs. contaminated soils.
- Assess trade-offs: strength improvements vs. settlement behavior.

Figure 3. Flow chart of the process of the methodology

3. Results and Discussion

3.1. Bearing Capacity and Settlement Performance

3.1.1. Clean soil with Nanomaterials

Pressure-settlement curves of the non-stabilized and stabilized sandy lean clay with different percentages of nano-clay (NC) and nano-silica (NS) are shown in Figures 4-a and 4-b, respectively. The nanomaterials were added individually to the soil in the percentage range of 0.5%, 1.0%, 1.5%, and 2.0% by dry weight of soil. The stress-strain behavior of soil treated with nanoparticles showed an increase in the load bearing capacity. The improvement is analyzed with respect to the bearing capacity ratio (BCR). The BCR is defined as the ratio of the ultimate bearing capacity of stabilized soils to that of the non-stabilized soil (control soil). The ultimate bearing capacity is characterized by the maximum pressure observed at the point where the slope of the pressure-settlement curve initially reaches zero or a consistent minimum value [27].

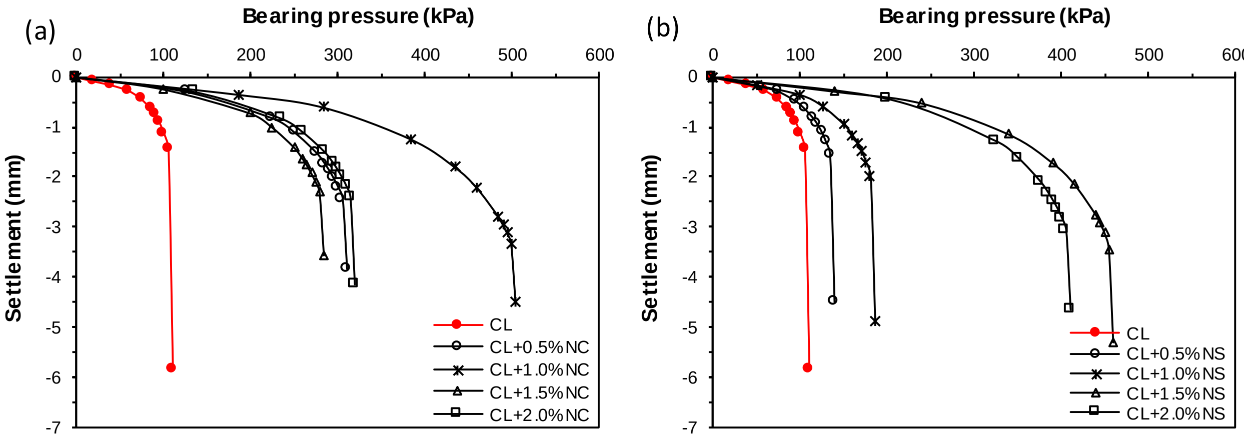

Figure 4. Pressure-settlement curves of clean soil with varied percentages of (a) Nano-clay and (b) Nano-silica

Figures 5-a and 5-b illustrate the BCR and settlement at ultimate bearing pressure (s_{ult}) of clean soil stabilized with clay and silica nano-particles at varying percentages. The results showed that the BCR initially increased and then declined as the nanomaterial content increased. Adding just 1% 1% nano-clay notably improved the BCR by approximately 4.76 times higher than untreated soil. Similarly, 1.5% nano-SiO2 was identified as the optimal content, enhancing the bearing capacity by 4.33 times compared to untreated soil. The observed behavior trend can be justified by understanding the interplay between the dosage of nanomaterial and its effect on the soil matrix. Initially, the addition of nanomaterial enhances soil strength and the corresponding bearing capacity due to its high specific surface area, promoting faster pozzolanic reactions and forming strong cementitious bonds between soil particles and the hydration products. However, beyond an optimal dosage (i.e., 1% NC and 1.5% NS), the excessive nano-sized additives lead to the accumulation of nanoparticles, which form weak bonds within the matrix rather than contributing to structural cohesion. Overdosed nanoparticles typically agglomerate owing to their high surface energy and van der Waals forces, leading to inadequate dispersion and less surface area for reaction. It exhibits a more like coarse-particle behavior, which lessens strength gains and stabilizing efficacy. It may also disrupt the soil fabric, by filling up voids or disrupting the normal arrangement of particles. This can lead to brittle behavior, loss of ductility, and in some situations, increased porosity due to incomplete pozzolanic reactions. Similar trends observed in previous studies regarding the impact of nanomaterial content on soil stabilization and corroborate that maintaining an optimal nanomaterials dosage is critical for balancing strength and stability of the soil matrix [13, 16, 21].

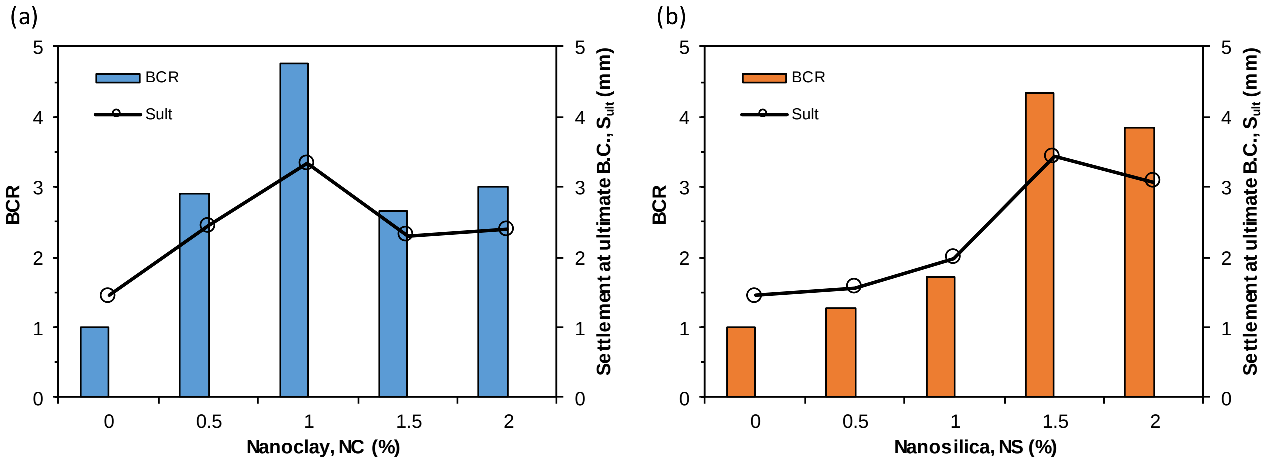

Figure 5. Bearing Capacity Ratio (BCR) and Settlement at ultimate bearing capacity of clean soil stabilized with (a) Nano-clay and (b) Nano-silica at varied percentages

In Figures 5-a and 5-b, the settlement at ultimate bearing capacity increased with the incorporation of nanomaterials, reaching its peak, approximately 2.3 times higher than the control soil, at the optimal dosages of nano-clay and nano-silica. (i.e., 1% NC and 1.5% NS). Such undesired increase in settlement at the ultimate bearing capacity with higher nanomaterial content, particularly at the optimal dosage, is often linked to insufficient stiffness gains, microstructural changes, time-dependent deformation mechanisms and reduced plasticity. Lower stiffness due to overdosing of additives can result in larger deformations under service loads [28, 29]. According to Choobbasti & Kutanaei [30], agglomeration of overdosed nanoparticles produces microstructural discontinuities that promote compressibility under stress by creating weak zones and larger pores. Over time, structural alterations brought on by hydration reactions, particularly those involving nano-SiO_2, cause settlement [31]. Nanomaterials produce a decrease in the plasticity index of clayey soil, rendering it brittle and more susceptible to sudden deformation [1]. Thus, nanomaterials can change the soil's compressibility properties, which might lead to unfavourable settlement behavior under heavy loads, even while increasing soil strength.

As shown in Figures 6-a to 6-d, the effects of the optimum dosage of nano clay, nano silica, and their mixture were also investigated across curing times ranging from 1 to 28 days. After a day of curing, soil treated with 1% nano clay (NC) demonstrated a 505 kPa bearing capability, while soil treated with 1.5% nano silica (NS) showed a 460 kPa bearing capability. The two materials produced a much higher bearing capability of 725 kPa when combined (1%CNC), demonstrating the beneficial effects of their interaction. The 1% nano-clay (NC) aggregate and 1.5% nano-silica (NS) consistently surpassed their contributions, exhibiting a synergistic boost in bearing ability during all curing durations. A similar pattern was seen at different curing intervals.

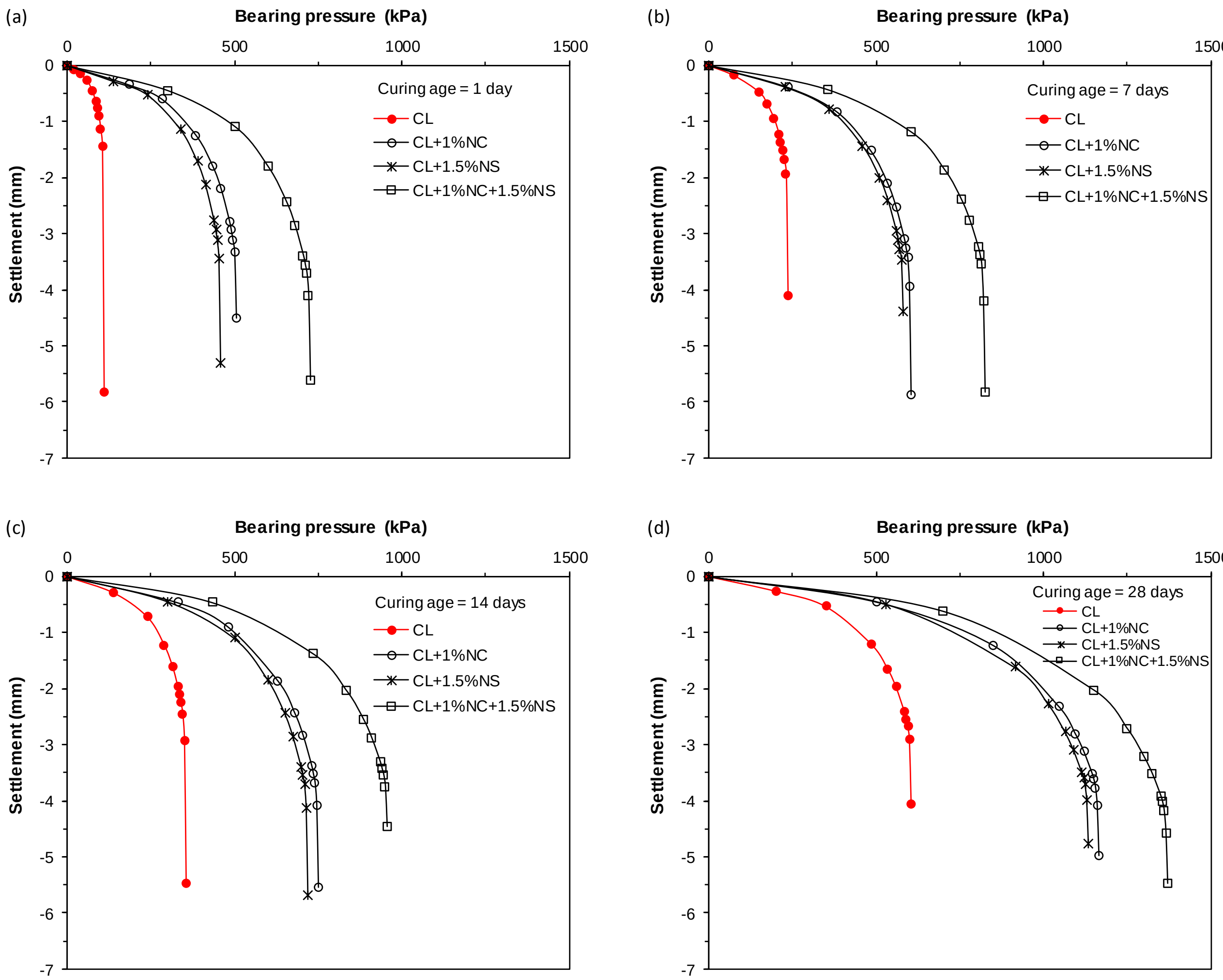

Figure 6. Pressure-settlement curves of clean soil with the optimal percentage of nanomaterials at curing age of (a) 1 day, (b) 7 days, (c) 14 days, and (d) 28 days

The variation in BCR with curing age for untreated soil, soil treated with 1% nano-clay, 1.5% nano-silica, and their combination is shown in Figure 7. The untreated soil had the lowest BCR, increasing linearly from 1 at 1 day to 5.7 at 28 days. Soil treated with 1% NC improved from 4.7 to 11, while 1.5% NS increased from 4.3 to 10.7 over the same period, showing 132% and 148% improvements, respectively. The combination of 1% NC and 1.5% NS achieved the highest BCR, rising from 6.8 at 1 day to 13 at 28 days. These results indicate that while both clay and silica nano-particles individually enhance soil strength, their combined application provides the highest improvement, emphasizing a synergistic effect that is particularly evident after 14 days of curing.

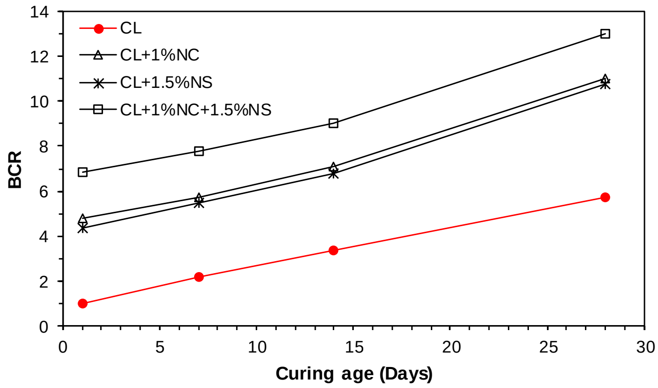

Figure 7. Bearing capacity ratio with curing time of soil treated with the optimal dosage of nanomaterials

In contrast, the addition of nanomaterials negatively impacts the compression behavior over time, as shown in Figure 8. The results indicated that settlement varied within 1 mm across all curing ages for soils treated with nanomaterial additives, yet it consistently remained approximately 1.5 to 2.5 times higher than that of the untreated soil. The observed increase in settlement for nanomaterial-treated soils compared to untreated soil can be attributed to several factors. The introduction of nano-sized additives, such as nano-clay and nano-silica, enhances bonding potential but creates a more compressible matrix due to particle rearrangement under load [17, 32]. Hydration and pozzolanic reactions contribute to strength but also lead to delayed densification, influencing early settlement behavior. Optimal dosages improve soil properties; however, excessive amounts can cause agglomeration and heterogeneity, resulting in increased settlement [14-16].

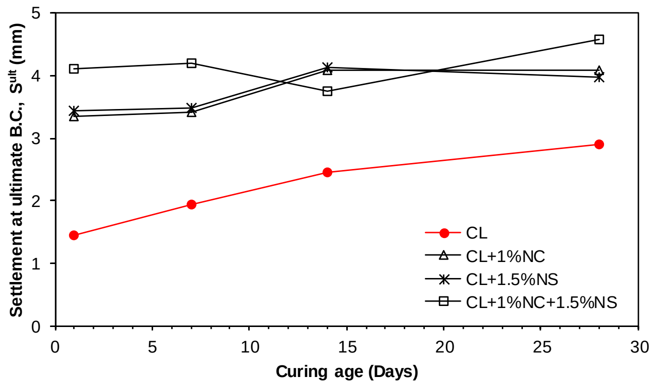

Figure 8. Settlement reduction percentage with a curing time of soil treated with the optimal dosage of nanomaterials

The result of bearing stress versus vertical displacement under the centreline where shown in Figure 9. The number of iterations to achieve convergence where also shown. Convergence happens in comparatively few rounds at load levels below failure, however the method requires more iterations to obtain convergence close to failure. In accordance with theoretical expectations, bearing failure was noted at a value that was quite near to the Prandtl load of 514 kN/m² [25].

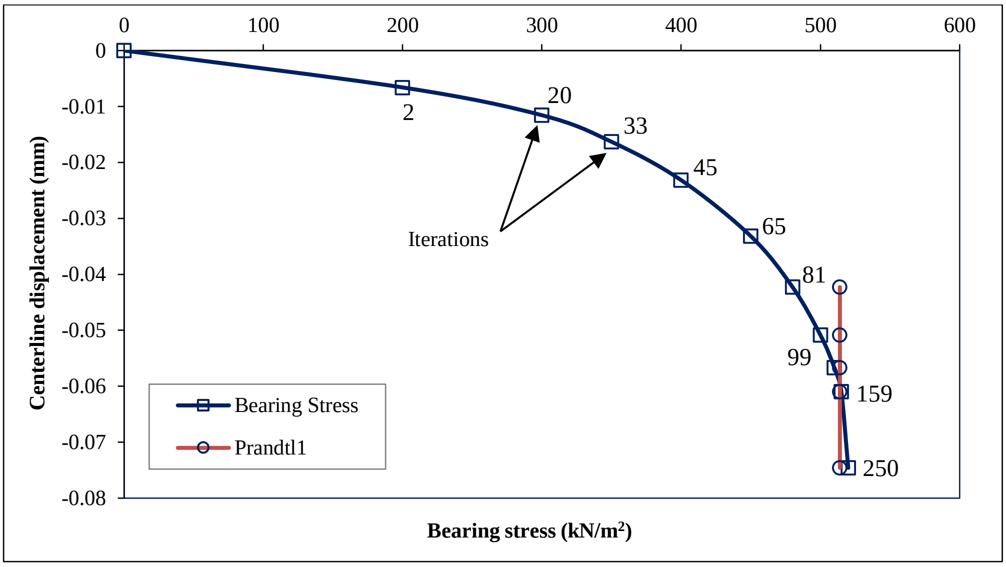

Figure 9. Verification of the model with previous study

The same data set used by Smith et al. [26], who created and validated the algorithm initially, was used to validate the numerical model. This validation validates the program's accuracy and dependability in forecasting soil behavior under several loading scenarios.

3.1.2. Kerosene-Contaminated Soil

Figure 10-a presents the pressure-settlement curves for both clean soil and kerosene-contaminated soil at varying percentages of dry weight. Correspondingly, Figure 8-b depicts the load-bearing capacity for different levels of kerosene contamination. The presence of kerosene (K%) led to a reduction in the bearing capacity, with the lowest value of 41 kPa observed at a contamination level of 12% K. Such reduction occurs as kerosene alters the physical and chemical properties of the soil. It reduces soil cohesion by weakening capillary and electrostatic forces, disrupts the soil structure by displacing water in the pores, and increases pore fluid pressure, which reduces particle friction. These effects are more pronounced at higher contamination levels, as seen in the observed bearing capacity drop to 41 kPa at 12% kerosene contamination. Studies by Al-Khyat et al., [5] and Saeed et al. [33] confirmed that hydrocarbon contamination reduces soil strength by altering its cohesion, density, and structural integrity.

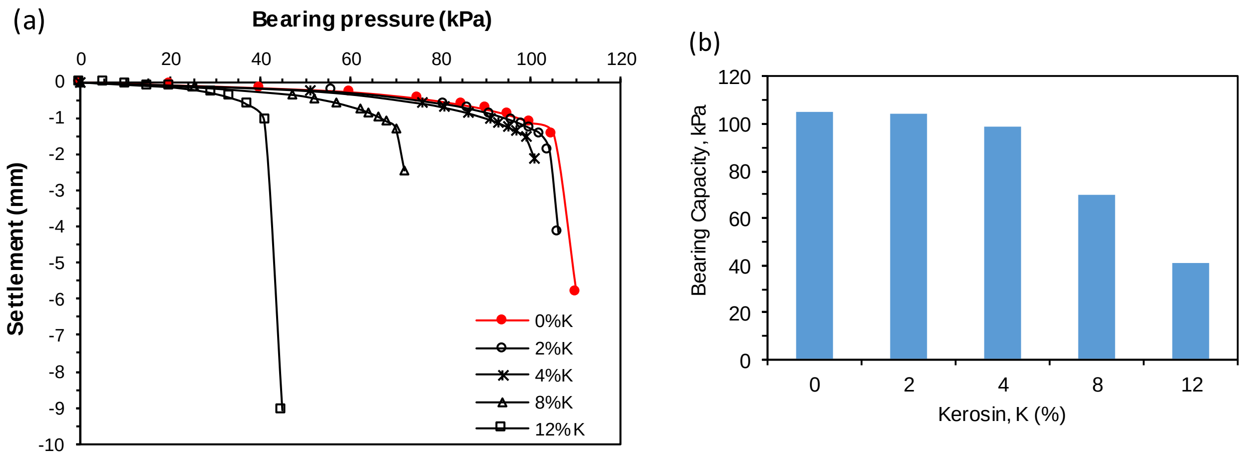

Figure 10. (a) Pressure-settlement curves of kerosene-contaminated soil and (b) the corresponding bearing pressure with kerosene contents

3.1.3. Kerosene-Contaminated Soil with Nanomaterials

Figures 11-a and 11-b illustrate the pressure-settlement curves for 12% wt kerosene-contaminated soil stabilized with varying amounts of nano-clay (NC) and nano-silica (NS), respectively. The stress-strain response of the contaminated soil enhanced with nanoparticles demonstrated an improvement in load-bearing capacity,

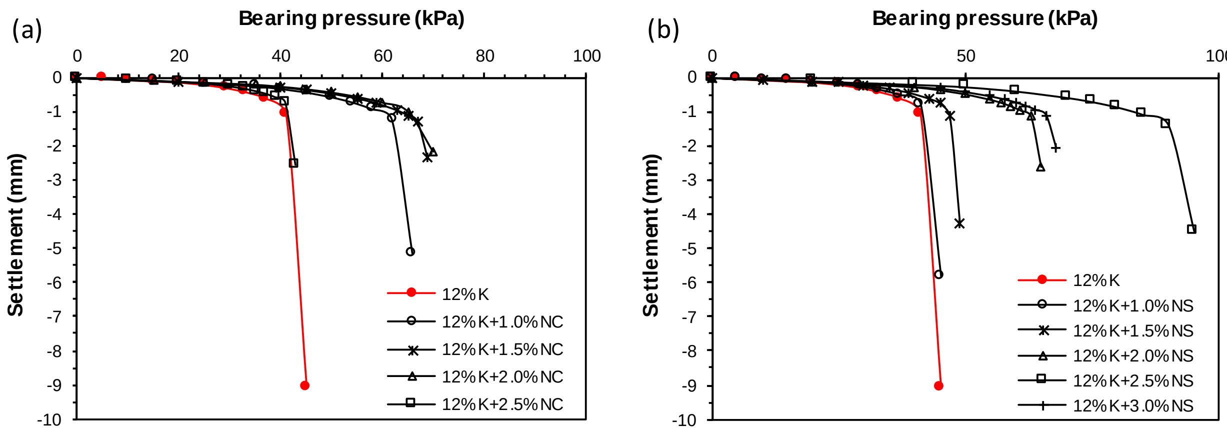

Figure 11. Pressure-settlement curves of 12% kerosene-contaminated soil with varied percentages of (a) Nano-clay and (b) Nano-silica

The corresponding Bearing Capacity Ratio, BCR, and settlement at the ultimate bearing pressure are presented in Figures 12-a and 12-b. For kerosene-contaminated soil, the results indicated that the BCR increased significantly with the addition of NC and NS, reaching its peak at 2%NC and 2.5% NS. This demonstrates that incorporating nanoparticles effectively improves the load-bearing capacity of contaminated soil, likely due to enhanced particle bonding and stabilization of the soil structure. However, the settlement at ultimate bearing pressure (S_{ult}) also increased with nanomaterial content, peaking at the optimal nanomaterial dosage of 2%NC and 2.5% NS. While this may indicate improved ductility and stress redistribution, excessive settlement harms soil behavior, as it can lead to structural instability and reduced serviceability. After the optimal dosage, S_{ult} decreased slightly, which may reflect a trade-off between strength and stiffness as nanomaterial content increases.

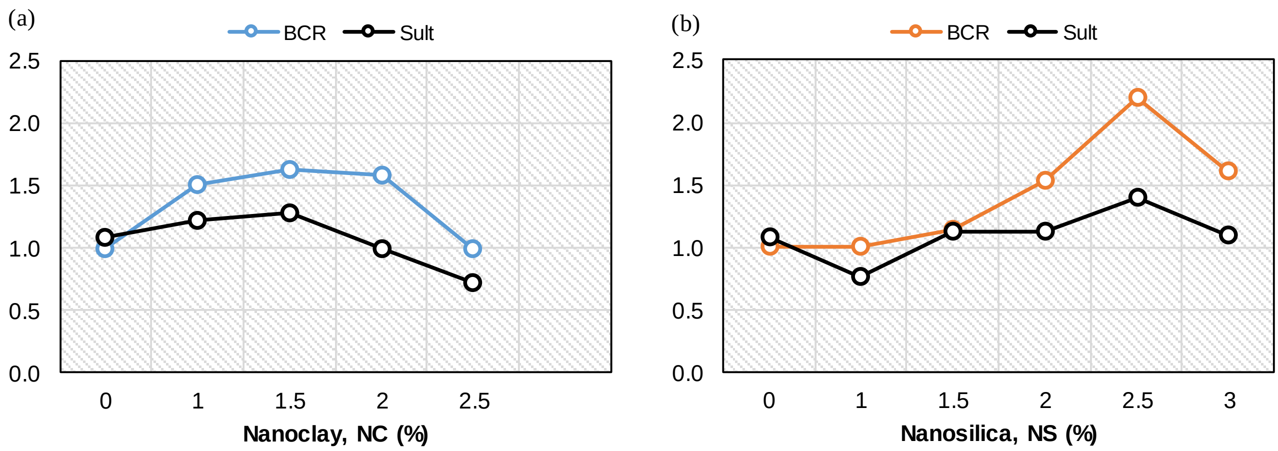

Figure 12. Bearing Capacity Ratio (BCR) and Settlement at the ultimate bearing capacity of 12% kerosene-contaminated soil stabilized with (a) Nano-clay and (b) Nano-silica at varied percentages

Figure 13 demonstrates the influence of the optimal amounts of clay and silica nano-particles on the bearing capacity and settlement behavior of contaminated soil over curing durations from 1 to 28 days. The BCR and settlement at the ultimate bearing capacity are given in Figure 14. The results revealed that the bearing capacity ratio of kerosene-contaminated soil treated with 2.0% NC and 2.5% NS increased consistently with curing time, reaching a peak at 28 days. The BCR improvement is more pronounced with 2.0% NC compared to 2.5% NS throughout the curing period. In contrast, the settlement at ultimate bearing capacity initially increased slightly with curing time but remained higher for nano-SiO2 treated soil compared to nano-clay-treated soil. This trend highlights the effectiveness of nano-clay in enhancing soil strength while exhibiting comparatively lower settlement than nano-silica over the curing period.

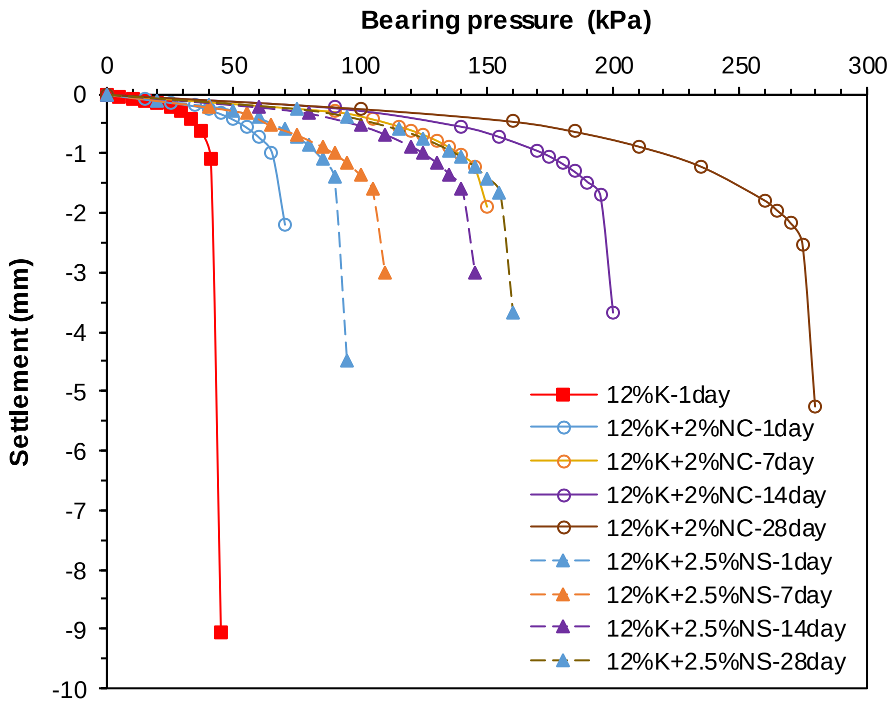

Figure 13. Pressure-settlement curves of 12% kerosene-contaminated soil with the optimal percentage of nanomaterials at varied curing ages

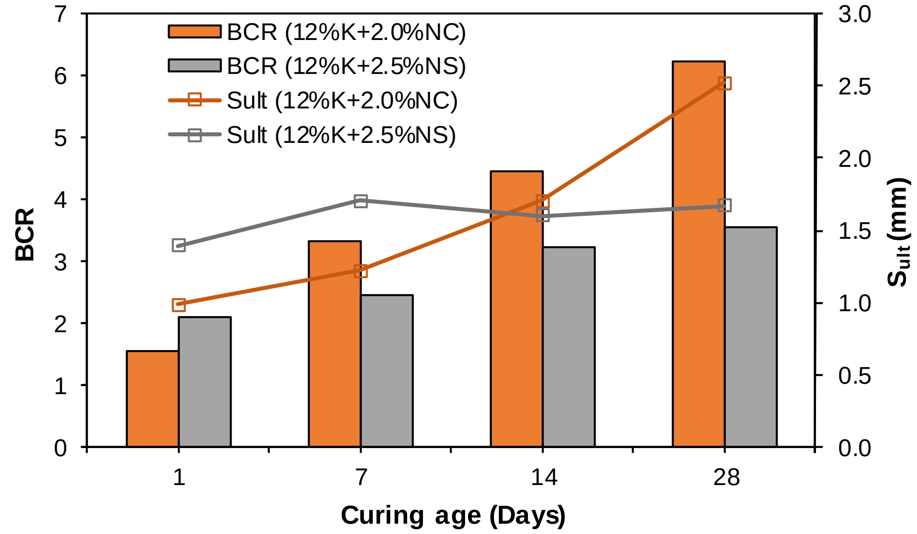

Figure 14. Bearing capacity ratio and settlement at the ultimate bearing capacity with curing time of 12% kerosene-contaminated soil treated with the optimal dosage of nanomaterials

Figure 15 presents a comparison between clean and contaminated soil in terms of the bearing capacity ratio with increasing contents of nanomaterials. The results indicate a clear difference in the Bearing Capacity Ratio behavior between clean clay (CL) and kerosene-contaminated soil (12% K) with varying nanomaterial content. For clean clay, the BCR shows a sharp increase, achieving maximum improvement at 1% nano-clay (NC) and 1.5% nano-silica (NS), demonstrating the significant effectiveness of nano-sized additives in enhancing the bearing capacity of uncontaminated soil. However, for contaminated soil, the improvement in BCR is less pronounced, with lower peak values at 2%NC and 2.5%NS. This reduced efficiency in contaminated soil is likely due to the kerosene's interference with the bonding and stabilization mechanisms of nanomaterials. This comparison highlights the adverse impact of contamination on soil behavior and the relative effectiveness of nanomaterials in mitigating this effect. It can be concluded that while nanomaterials can enhance the bearing capacity, the degree of improvement depends on the type of nanomaterial, its dosage, and the soil's contamination condition.

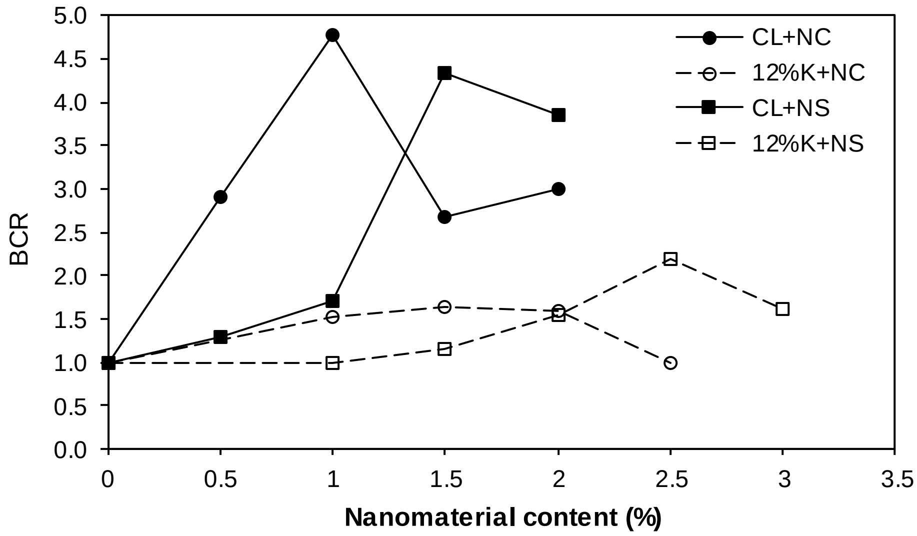

Figure 15. Bearing capacity ratio of clean and kerosene-contaminated soil treated with different dosages of nanomaterials

The settlement at ultimate bearing capacity (S_{ult}) exhibits contrasting behaviors between clean and kerosene-contaminated soil when stabilized with varying nanomaterial contents as shown in Figure 16. For clean clay, s_{ult} increases significantly with the addition of nano-clay and nano-SiO2, peaking at 1% NC and 1.5% NS. This indicates that while the nanomaterials enhance bearing capacity, they also lead to increased deformability. In contrast, the contaminated soil shows a much smaller increase in s_{ult}, remaining relatively consistent across the nanomaterial contents. This reduced settlement in contaminated soil could be attributed to the interaction between kerosene and nanomaterials, which may limit their ability to alter soil compressibility significantly. Overall, while clean soil exhibits higher settlement sensitivity to nanomaterials, the contaminated soil shows more stable but lower overall settlement values.

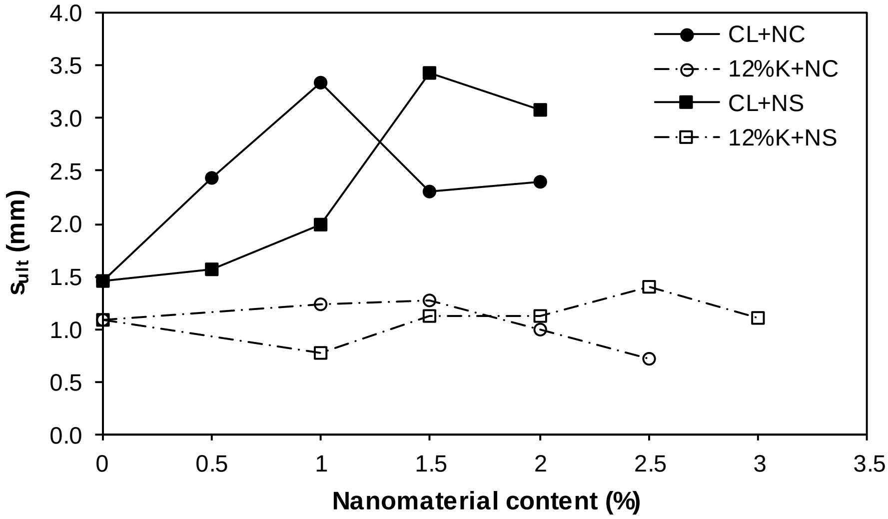

Figure 16. Settlement at the ultimate bearing capacity of clean and kerosene-contaminated soil treated with different dosages of nanomaterials

A promising method to counteract such settlement issues while preserving soil strength is the combined stabilization technique that integrate nanomaterials with cement or lime. This approach has been supported by several studies [34, 35]. The pozzolanic reaction between nano-silica and cement is enhanced, resulting in a denser microstructure and improved particle bonding. This increases compressive and shear strength while decreasing settling as a result of better compaction and load-bearing capability. Similarly, nano-clay improves the interaction between lime and soil by boosting surface area and reactivity, which enhances strength and decreases settlement by providing more long-term stability.

4. Conclusions

The numerical study investigated the effects of nano-clay (NC) and nano-silica (NS) on the bearing capacity and settlement behavior of clean clay (CL) and kerosene-contaminated soil. Key findings are as follows:

- Optimal soil stabilization was achieved with 1% NC and 1.5% NS for clean clay, improving the bearing capacity ratio (BCR) by 4.76 and 4.33 times, respectively, compared to untreated. Overall performance was dropped by the excessive amount of nanomaterial, highlighting the significance of employing the optimal dosages.
- The addition of nanomaterials increased settlement at the ultimate bearing capacity (S_{ult}) by 2.3 times compared to untreated soil at the optimal content, emphasizing the need to balance between the desired soil strength and allowable deformability.
- Curing age significantly influenced BCR, with treated soils showing substantial improvement over time. The combination of 1% NC and 1.5% NS exhibited the highest BCR, rising from 6.8 to 13 over 28 days, indicating the most effective enhancement in bearing capacity.
- Nano-clay was more effective than nano-silica in improving BCR while causing lower settlement in uncontaminated soils.
- For kerosene-contaminated soil, the optimal dosages of 2% NC and 2.5% NS improved BCR, but settlement at ultimate bearing capacity also increased, peaking at these dosages.
- The BCR improvement in contaminated soil was less pronounced than in clean clay, indicating contamination reduces the effectiveness of nanomaterials in enhancing soil strength. Settlement behavior in contaminated soil remained relatively stable, with nano-clay-treated soil showing less settlement compared to nano-silica-treated soil.

5. Declarations

5.1. Author Contributions

Conceptualization, Z.A.H. and S.A.; methodology, Z.A.H.; software, Z.A.H.; validation, S.A., M.S.S., and H.A.H.; formal analysis, S.A. and M.S.S.; investigation, Z.A.H. and S.A.; resources, S.A., M.S.S., and Z.A.H.; data curation, Z.A.H. and S.A.; writing—original draft preparation S.A.; writing—review and editing, S.A., M.S.S., and Z.A.H.; visualization, H.A.H.; supervision, Z.A.H.; project administration, S.A.; funding acquisition, Z.A.H., S.A., and M.S.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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