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The effect of nano-clay stabilizing treatment on the real excavation wall failure: A case study

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Abstract. The expansion of urbanity and thereby, demand for residential areas have made it necessary to carry out excavation operations in most cases of construction. In this respect, the most significant challenge that geotechnical engineering faces is that many influential factors affect the performance of excavating methods. Hence, selecting a suitable stabilization method for the excavation wall can certainly prevent financial and life-threatening risks. Meanwhile, nano-material as one of the stabilizer materials remains the central part of improving soil characteristics. In the current paper, the wall of a real excavation, which is stabilized with nano-clay injection, is studied to perceive how modern procedures affect soil slope resistance. For this purpose, the samples extracted from different boreholes of the site are prepared for the tests with and without different percentages of nano-clay for assessing its effects on the soil parameters. It was proved that 7% weight concentration for a nano-clay, which was injected through nine different boreholes and controlled by the results of the permeability test and Scanning Electron Microscopy (SEM) imaging, was a sufficient amount. The loading on stabilized and non-stabilized excavation walls demonstrated that the nano-clay addition affected the strength of the excavation wall significantly by as much as about 70%. Ultimately, nano-clay injection and soil nailing were compared economically.

1. Introduction

Greater urbanity and growing demand for residential areas have made it necessary to perform excavation for most constructions. In principle, excavation is a hazardous geotechnical engineering project [1,2]. Therefore, it is required to carefully perform comprehensive and accurate evaluations to monitor and prevent financial and life-threatening risks. Due to the disruption of excavation walls, annual accidents across the world have attracted the attention of geotechnical engineers. Different excavation support systems are available including braced walls, soldier pile, sheet pile, trench wall, retaining walls, cofferdams, caissons, jet-grout, deep mixed walls, top-down construction, and partial excavation or island method [3]. Selection of appropriate ones among the methods mentioned above depends on such criteria as size of excavation, ground conditions, groundwater level, vertical and horizontal displacements of adjacent ground and limitations of various structures, availability of construction, cost, speed of work, and others [4]. The use of nano-particles can be introduced as another stabilization method [5]. The advent of nano-technology science has made it possible to use this technology in many engineering fields [6–8] including geotechnical and geotechnical earthquake engineering based on laboratory investigation.

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Besides, geotechnical engineers have always exhibited interest in improving soil parameters using suitable additives. Given that nano-particles are sized from 1 nm to 100 nm, they are considered as suitable additives. Also, these materials have a high Specific Surface Area (SSA) due to their very fine size. However, even in negligible amounts, they significantly affect the physicochemical and engineering properties of soil. Given that there is no significant scope of research on the stabilization of excavation walls using nano-materials, some other researches that are similar in nature and subject matter are initially presented in the following. Researchers have already had different and particular ends in nano-material studies in different engineering fields [9–11]. Those research studies aim at comprehensive studies, effects on engineering properties, characteristics and behaviors of soil, problematic and soft soil treatments, and soil liquefaction [12].

Ghasabkolaei et al. [13] reviewed the geotechnical properties of the soils modified with nano-materials in the form of a comprehensive review. Wilson et al. [14] investigated the effects of nano-materials in soils and the area of nano-material science relevant to the analysis of soil structure and they recognized composition.

Taha [15] conducted experiments to evaluate the behavior of soil upon mixing with nano-soil. The nano-soil is a product of the milling of a natural soil in which a more significant portion of its particles was pulverized into nano-sized particles (1–100 nm). Taha and Taha [16] presented an experimental study of four types of soils mixed with three types of nano-material of different percentages. Onyejekwe and Ghataora [17] stabilized soil using proprietary liquid chemical stabilizers such as sulfonated oil and a polymer. Changizi and Haddad distinctively investigated the effect of adding nano-SiO_2 (nano-silica) on soil engineering properties using clayey soil with low plasticity (CL) and also, they studied the effects of recycled polyester fibre in combination with nano-SiO_2 separately [18,19].

Choobbasti et al. [20] investigated the mechanical properties of soil stabilized with nano calcium carbonate and reinforced with carpet waste fibers. Sarli et al. [21] investigated the effect of recycled polyester fiber in combination with nano-SiO_2 as a new stabilizer for improving the geotechnical properties of the loess soil and evaluating the effects of adding recycled polyester fiber and nano-SiO_2 on engineering properties of the soil, especially the maximum dry density and shear strength using silty loess with a low liquid limit. Ghobadi et al. [22] presented the results of geotechnical and mineralogical investigations on lime-treated clay soils and the effects of pH variations on their shear strength parameters. Bahmani et al. [23] investigated the effects of nano-SiO_2 size and replacement content on the physical, chemical, and microstructural characteristics of cemented residual soil.

Majeed and Taha [24,25] explored the effect of nano-material treatment on geotechnical properties of a Penang soft soil and stabilization of soils by using nano-materials. Majeed et al. [26] stabilized soft soil using nano-materials and presented their results. Also, Khalid et al. [27] investigated the effect of nano-clay on soft soil stabilization. Iranpour [28] aimed to understand the impact of nano-materials on collapse soil behavior by an experimental study. Tabarsa et al. [29] investigated the potential for effective loess stabilization using nano-clay, both at the laboratory and in the field at a real site. Coo et al. [30] evaluated the effect of two different nanoparticles on the desiccation-induced shrinkage of the clay. Abbasi et al. [31] studied nano-clay effect on the dispersivity potential of two types of clayey soils and found that the addition of nano-clay to dispersive clayey soils could reduce their dispersivity potential considerably.

Gallagher and Mitchell [32] attempted to assess the effects of colloidal silica grout on the liquefaction resistance of loose sands. Gallagher and Lin [33] evaluated colloidal silica transport mechanisms and theoretically discussed the reduction of soil liquefaction in granular soil. Gallagher et al. [34] reported the results of a full-scale field test to assess the performance of dilute colloidal silica stabilizers in reducing the settlement of liquefiable soil. Laboratory investigation of liquefaction mitigation in silty sand using nano-particles was done by Ochoa-Cornejo et al. [35], and the outcome was compared with the selected results obtained by Huang and Wang [36] on the cyclic resistance of sand with sand-laponite. The soil liquefaction mitigation mechanisms were explored based on nano-particles by Huang et al. [37] who presented the results of dynamic centrifuge testing to conduct clean sand models and sand-laponite models.

Some researchers have attempted to prove the importance of the slope stability merely under the impact of different conditions and parameters without any grouting or injecting processes by different methods. Vo and Russell [38] presented charts derived from stability analyses of curvilinear slopes in non-homogeneous unsaturated soils. Landslides induced by tunneling are quite complex and require much attention to treat and investigate the problem. In this regard, Zhang et al. [39] numerically studied the case of a landslide induced by excavating a large-span multi-arch tunnel in terms of tunnel profile, construction deficiencies, stability of surrounding rocks, and landslide situation. Johari and Talebi [40] employed Random Finite Element Method (RFEM) to prove the rainfall effects on slope stability and steady-state seepage flow stochastically. Johari and Gholampour [41] employed a practical approach to reliability analysis of unsaturated slopes via conditional simulation.

Öge [42] employed back analysis using limit equilibrium and Finite Element Methods (FEMs) to investigate three different excavation stages and consecutively occurring slope failures. The FEM was also employed to estimate the optimization of design schemes. Recently, Ou et al. [43] studied the large deformation of a deep excavation supporting system close to a railway with a high embankment.

According to the literature, geotechnical engineering faces the most significant challenge in excavating methods governed by construction budget, availability of construction equipment, adjacent excavation condition, adjacent buildings, type of foundation of the neighboring structure, and construction site area, hence being environmentally friendly. To respond to these challenges, nano-materials as one of the modern and eco-friendly materials have a prominent role in excavation wall stabilization by enhancing soil shear strength characteristics. Moreover, worthy economic analysis has indicated that the use of nano-clay is still preferable due to numerous advantages. Therefore, the current paper aims to employ one of the most common nano-materials called nano-clay to fight off the challenges mentioned above.

To the best of our knowledge, stabilization of the excavation wall using nano-clay has yet to be studied. On top of that, previous studies have not taken measures against a practical approach or case study while being done as experimental tests. Therefore, this issue can be considered the common pitfall of all previous research. The main objective of this study is to assess the effects of nano-clay on stabilized excavation walls and related parameters via inspection of a real site as a case study and in a practical way. To investigate the site, three boreholes of 20 m, 15 m, and 15 m depths were drilled. Field tests (e.g., SPT) and laboratory tests (i.e., grain size distribution, Atterberg limits, water content, direct shear, and permeability) were performed for each borehole. The direct shear and Atterberg limit tests were carried out with and without different ratios of nano-particles, and the effect of the presence of nano-clay particles was investigated. In another part of this research, an excavation of 10.0 m length, 4.0 m width, and 5.5 m depth was considered and its wall was stabilized by injection of nano-clay particles. Following the injection and after one month, excavation walls were loaded and the efficiency of stabilization using nano-clay particles was evaluated.

2. Nano-materials in geotechnical engineering

The advent of modern science such as nanotechnology has made it possible to use nano-particles in many engineering fields [44,45] including geotechnical engineering. The results of geotechnical engineering studies have indicated the significant effect of nano-particles on the soil parameters. The nano-technology approach to soil mechanics adds a new class of soil particles, called nano-cell, to the classic classification, including sand, gravel, clay, and slit. Although this classification has simplified many problems of soil mechanisms, it suffers from two drawbacks:

- The first one is that the properties of particles change as their size is on a nano scale;
- According to the classic definition, the second one is that clay particles include less than 2 μm particles, meaning that the range of clay particles is 1–2 μm. Therefore, the ratio of upper to lower limit is 2000, which is much higher than that of other particles.

To solve these problems, rough guidance on appropriate sample preparation techniques was offered when measuring the index properties of residual soils as a function of how these soils would be used in practice. Meanwhile, they reported that the presence of 9% Fe-oxides results in forming an interconnected network of silt-sized aggregates with Fe-oxide coating and cementation in weathered old alluvium.

Nanoparticles affect the specific properties of soil. Generally, their properties become remarkably different when materials approach the nanoscale. In addition to the contribution to solutions of environmental problems as being environmentally-friendly of these modern stabilizers, other aspects of their utilizations such as the production of materials and products with new properties, improvement of existing technologies and development of new applications, and optimization of primary conditions for practical applications have already been proved in comparison with traditional stabilizers. The following list provides an overview of such changes [46]:

1. On a nano scale, the higher ratio of surface to volume and in turn, a higher cation exchange capacity exist owing to their exceptionally high SSA and reactive surfaces with charges and they, thus, have profound impact on the microstructural, physical, chemical, and engineering properties of soils, even present at a small weight fraction. Therefore, they interact very actively with other particles and solutions such that very minute amounts may lead to considerable effects on the physicochemical behavior and engineering properties of the soil (including the liquid phase, cations, organic matter, and clay minerals);
2. Gravity forces on a nano scale can be disregarded. Instead, electromagnetic forces are dominant;
3. Instead of classical mechanics, quantum mechanical models are utilized for describing movement and energy on the nano scale;

4. Random molecular movements are of higher significance on a nano scale. Soils that contain nanoparticles with intra-particle voids usually exhibit higher liquid and plastic limits because of the following three reasons:
   (a) A higher specific surface leads to a larger amount of water encompassing the outer surface of particles;
   (b) The presence of nano-pores causes water accumulation in these pores, resulting in an increase in the available water capacity in the soil;
   (c) The nanostructure of soil particles is another factor in the increase in water accumulation capacity. The existence of nanofibers in soil usually enhances the thixotropic property of soil and increases its shear strength. In addition, these soils possess a much lower bulk density due to the occurrence of nano-pores.

3. Case study

According to the literature, nano-particles can increase the shear and compressive strength of fine-grained soils. Thus, relying on the mentioned nano-particles' ability, the chief objective of the current study consists of stabilizing the wall of the real excavation. For this purpose, a site located at Shiraz University of Technology is selected. Since the current case study is a research program and the certainty of the desired stabilization method needs to be controlled, it is preferable to test a landscape far from any adjacent building, considering safety aspects. It is of importance to note that this research program can be planned and carried out on the other excavation sites.

To explore the subsurface layers, three boreholes BH.1 to BH.3 were drilled to the depths of 20.0 m, 15.0 m, and 15.0 m from the natural ground surface, respectively, because the standard issue in geotechnical projects is scattering distributed boreholes within the considered area. The relative locations of the boreholes are plotted in Figure 1. Regarding the injection operation that is supposed to be conducted adjacent to the excavation wall, for a better recognition of the existing soil profile in the excavation wall's active area, the location of the boreholes was selected outside the excavation zone. Meanwhile, it is worth mentioning that borehole drilling performances were conducted according to the instruction recommended by ASTM D6286/D6286M-20. Therefore, a rectangular or triangular arrangement, including equilateral triangle or isosceles triangle placement of boreholes, is recommended as suitable. According to the following figure (Figure 1), the triangular arrangement of boreholes was selected although the boreholes were placed in a rectangular arrangement. In terms of the drilling method, it is worth noting that various boring tools and machines are used to drill boreholes across the world. The most conventional ones are auger drilling, wash boring, percussive drilling, and rotary drilling. The selection of machines depends on the site's geographical location, ground material, borehole diameter and depth, and sampling quality. In the present study, a rotary drilling technique was used. It is a rotational and downward force crushing materials inside the borehole. It is generally used to drill rocks or cemented soils. In this method, drilling bit heads rotate and penetrate the ground. Drilling bit heads are divided into solid and hollow bit heads. In cases where the aim is to sample the drilled mass, hollow bits with a bore-barrel are used; otherwise, solid bits are used and drilled crushes are transferred to the ground level through the rotation of drilling fluid [47].

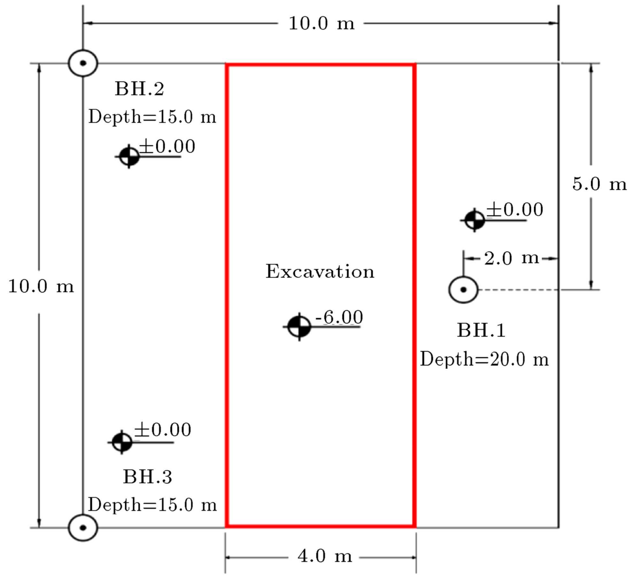

Figure 1. Excavation zone and layout of boreholes.

4. Geotechnical soil properties of site

For each borehole, the field test (i.e., Standard Penetration Test, SPT [48]) and laboratory tests (i.e., grain size analysis [49], Atterberg limit tests [50], water content [50], permeability of the falling head [51], and direct shear tests [52]) were performed. It is worth noting that all tests have been performed according to their related ASTM standards to meet the criteria. As a common practice, to prevent the reduction of natural soil moisture after drilling boreholes, undisturbed samples were poured into standard plastic bags by correctly packaging samples. The boreholes database is given in Tables 1 to 3. At the end of the drilling, the water table was traced back. The results showed that the water table did not encounter the end of the borehole's depths.

Table 1. Soil properties of borehole No. 1.

Depth (m)	Classification	Plasticity index (%)	Unit weight (kN/m^3)	Water content (%)	Permeability $(m/s)\times10^{-6}$	Cohesion (kN/m^2)	Friction angle (degree)	Passing #200 (%)	SPT At depth (cm)		
									15	30	45
0–2	CL	9.60	–	13.50	–	–	–	88.54	17	19	20
2–4	CL	16.96	–	13.90	–	–	–	74.38	11	14	13
4–6	CL	14.28	–	20.90	–	–	–	97.80	14	17	22
6–8	CL	15.70	–	21.50	–	–	–	98.29	12	13	17
8–10	CL	12.92	19.60	18.70	2.51	14.00	28.60	94.26	10	10	15
10–12	CL	10.88	–	21.80	–	–	–	98.56	13	18	21
12–14	ML	16.53	–	18.70	–	–	–	99.03	21	19	20
18–20	SC	10.38	21.10	10.70	–	4.00	34.70	21.60	29	21	18

Table 2. Soil properties of borehole No. 2.

Depth (m)	Classification	Plasticity index (%)	Unit weight (kN/m^3)	Water content (%)	Permeability $(m/s)\times10^{-6}$	Cohesion (kN/m^2)	Friction angle (degree)	Passing #200 (%)	SPT At depth (cm)		
									15	30	45
0-2	CL	12.06	–	12.06	–	–	–	90.92	25	23	16
2–4	CL	12.80	–	15.34	–	–	–	96.48	20	18	20
4–6	CL	13.89	–	18.00	–	–	–	95.58	17	17	23
6–8	CL	11.58	19.50	21.90	–	10.00	26.00	98.79	10	14	13
8–10	CL-ML	5.91	–	20.70	1.36	–	–	89.86	12	11	22
10–12	CL	10.49	20.10	18.28	–	8.00	30.50	95.66	10	9	10
12–14	CL	12.43	–	19.12	–	–	–	89.24	21	18	22

Table 3. Soil properties of borehole No. 3.

Depth (m)	Classification	Plasticity index (%)	Unit weight (kN/m^3)	Water content (%)	Permeability $(m/s)\times10^{-6}$	Cohesion (kN/m^2)	Friction angle (degree)	Passing #200 (%)	SPT At depth (cm)		
									15	30	45
0–2	CL-ML	5.41	-	16.50	2.47	–	–	90.18	18	20	18
2–4	CL	13.73	20.20	15.81	–	19.00	24.00	97.50	15	14	15
4–6	ML	14.57	-	18.75	–	–	–	94.78	16	19	21
6–8	ML	12.88	-	20.80	–	–	–	99.46	9	11	14
8–10	CL-ML	6.30	-	16.62	–	–	–	31.21	10	13	16
10–12	CL	12.41	-	18.28	–	–	–	97.82	16	16	14
12–14	CH	29.42	20.20	19.20	–	48.00	22.20	99.80	10	18	22

5. Experimental programs for investigation of nano-clay effects on soil site parameters

As discussed earlier, addition of different additives to the soil is a soil stabilization technique. Nanoparticles are an example of such additives. Nanoparticles such as nano-clay dispersion appear to induce changes in the pore fluid, thus reducing the permeability coefficient and strengthening the restraint of soil particles without changing the soil skeleton [37]. Nano-clays are mineral silicate nanoparticles with a spangle shape. Nano-clays are in different types, including montmorillonite nano-clay and kaolinite nano-clay. Since such particles are used on a nano scale, even a negligible amount of them

Table 4. Physical and mechanical properties of nano-clay (montmorillonite) [53].

Mineral type	Moisture (%)	Color	Specific surface area (m^2/gr)	Particle size (nm)	Density (gr/cm^3)	pH	Electric conductivity coefficient (MV)	Ion exchange rate (meg/100gr)
Montmorillonite	1–2	Yellow	500-750	1–2	2–5	7.3–7.6	25	48

Table 5. The chemical composition of nano-clay [53].

Symbol	Fe_2O_3	TiO_2	CaO	K_2O	SiO_2	Al_2O_3	MgO	Na_2O	LiO
Percentage (%)	5.62	0.62	1.97	0.86	50.95	19.60	3.29	0.98	15.45

significantly affects soil properties. The present study evaluates the effect of nano-clay on the stabilization of the excavation wall to assess the effect of nano-clay on the site soil profile. For this purpose, a complex of laboratory tests was conducted.

5.1. Nano-clay preparation

Following earlier reviews, the montmorillonite nano-clay provided from Sigma Aldrich, US improved the studied soil properties. Table 4 shows physical and mechanical properties, and Table 5 shows the chemical composition of the used nano-clay. Although the Sigma-Aldrich [53] nano-clay outsells other similar samples in the local market, the decision has been made to use that.

The Scanning Electron Microscopy (SEM) image of the used nano-clay has been captured. Since every nano-material had its spectrum, the spectrum of the studied nano-material should be derived to control it. There are two available methods for determining the structure and composition of materials categorized as powder, crystals, and metals, which are limited to use. The best suitable method for determining chemical composition besides the crystals and powders' structure is X-Ray Diffraction (XRD) analysis, although the XRF is useful in determining metals' structure. Therefore, as the material studied in this research is the nano-clay powder, the XRD is believed to be the most useful one. A spectrum of the studied nano-materials in compliance with nano-clay as XRD analysis has been obtained. XRD is a non-destructive test method used to analyze the structure of crystalline materials and their existence in a material to reveal chemical composition information. The colored lines as red and green show two parameters of XRD analysis including Gaussian and Cauchy curves. Notably, more information about the XRD analysis graph and its different parameters is accessible in the study of Jian and Hejing [54] and Dutrow and Clark [55].

The first step in soil shear strength improvement by nano-clay at the laboratory is choosing a suitable mixing method. In this respect, there are two main methods including dry mixing and wet mixing methods. As in the dry mixing method, the soil and additive are mixed in the dry form; the method is called the dry mixing method [56]. However, the dry mixing method includes various types (e.g., ball milling-like and double dry mixing methods) and the best appropriate type can be selected in terms of the dispersion required. Another technique examined in this research is the wet mixing method. The most crucial objective of choosing a proper mixing method is to spread the nano-clay particles among the soil particles uniformly. Since nano-particle suspensions are used, this method is known as the wet mixing method. To this end, distilled water, as a substance, can be used as one of the driving factors to uniformly distribute nano-clays among the layers of soil particles to obtain a more uniform distribution than the dry mixing method.

5.2. Nano-clay suspension preparation using wet mixing method

To mix soil and nano-clay, the wet mixing technique was selected [57]. This technique spreads nano-clay particles on soil layers in a more uniform fashion than other techniques such as dry mixing. Following the above discussions, it is decided to produce nano-clay suspension. For this purpose, distilled water is served as a liquid suspension because of its non-destructive effect on tests. For suitable dispersal of particles in suspensions, especially at the laboratory, the hydrometer mixer is the most common, although some other machine mixers exist in the industry. A hydrometer mixer is used in the hydrometer method of testing subgrade soils, and a heavy-duty mixer operates at a speed above 10,000 RPM (no load). This study employed a hydrometer mixer to produce a stable suspension. The Stokes' equation considers the settlement of suspended particles and this settlement takes too much time which, in turn, provides enough time for the dispersion of nano-clays on soil layers [58].

Also, as indicated in Table 4, it is required to mix soil with nano-clay for preparing a suspension and physical and mechanical properties of the nano-clay. Thus, to implement the combination-preparation process, nanoparticles are assumed to be spherical particles rather than spangled shapes. This study determines the ppm which describes the concentration of nano-clays in water. In this way, 1 ppm means 1 unit out of 1 million, i.e., 10^6, thus 1% of 1 ppm

10^4 ppm. Hence, 1% concentration of nano-clay and distilled water solution obtains 10,000 ppm of solution. This is the main reason for considering ppm equal to 10,000 [59–61]. According to this consideration, in this research, the steps necessary to prepare the nano-clay suspension are categorized as follows:

- Producing nano-clay suspension with an equivalent weight percentage of the studied soil and a concentration of 10,000 ppm as described above. To this end, 1% (2 g) of nano-clay, equivalent to 200 g of soil passing through sieve #40, was weighed. Considering 10,000 ppm concentration, 198 g of distilled water was added to the mentioned 2 g nano-clay (200 ml suspension solution). Meanwhile, what clinches the argument is that each 10,000 ppm concentration is equal to 1% weight, also considered as weight content;
- Mixing the solution by a hydrometer mixer for an hour to spread nano-clay particles in distilled water uniformly. Immediately after this treatment, the obtained nano-clay suspension was added to the 200-gr saturated soil site;
- Considering all of the above, the obtained solution was thoroughly mixed. Then, the mixture was dried in an oven at 110°C to be used in experimental tests.

5.3. Different concentrations of nano-clay effects on shear strength parameters

Soil parameters essential to slope stability discussion are shear strength parameters [62]. In the present paper, the direct shear test with different percentages of nano-particles was conducted to study the nano-clay effects on shear strength parameters. Direct shear strength tests were done on specimens with 1, 3, 5, and 7% weight concentrations of nano-particles in line with ASTM D3080 [52]. These tests were carried out under controlled strain with a 0.04 mm/min velocity and normal stresses of 1.07, 1.57, and 2.07 kg/cm^2. Figures 2 to 4 show the results of these tests on specimens with different nanoparticle ratios and under further normal stress.

The soil samples stabilized with different percentages of nano-clay have improved their effective shear strength with an increment in internal friction angle and a reduction in soil cohesion compared to virgin soil sample with 0% nano-clay, as summarized in Table 6. According to this table, friction angle increases with an increase in nano-clay percentage. This result shows that the stress-strain behavior of soil with 0% nano-clay is similar to that of ductile material, and soil stabilization gradually converts its stress-strain behavior from ductile to brittle nature.

Figure 5 shows the variations of normal stress versus shear stress in different percentages of the nano-clay dispersed. Upon increasing different percentages

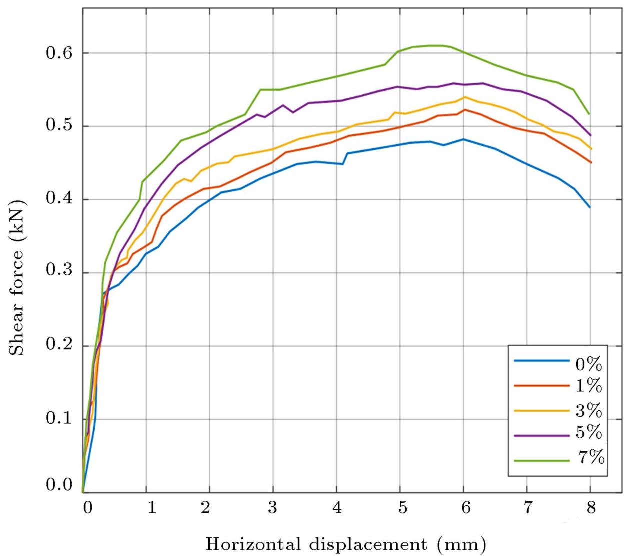

Figure 2. Direct shear test results for specimens with different nano-clay ratios (normal stress 1.07 kg/cm^2).

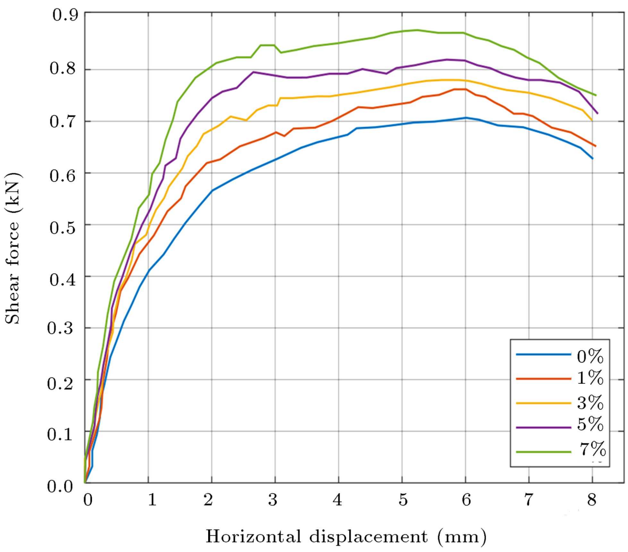

Figure 3. Direct shear test results for specimens with different nano-clay ratios (normal stress 1.57 kg/cm^2).

Table 6. Variation of shear strength parameters under different percentage of nano-clay.

Specimen with nano-clay (%)	Cohesion (kN/m^2)	Friction angle (degree)
0	25	24.2
1	21	25.5
3	16	26.6
5	9	27.6
7	7	28.0

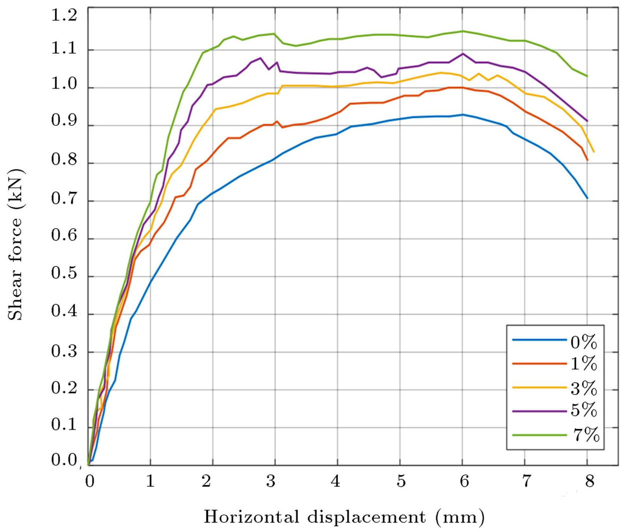

Figure 4. Direct shear test results on specimens with different nano-clay ratios (normal stress 2.07 kg/cm^2).

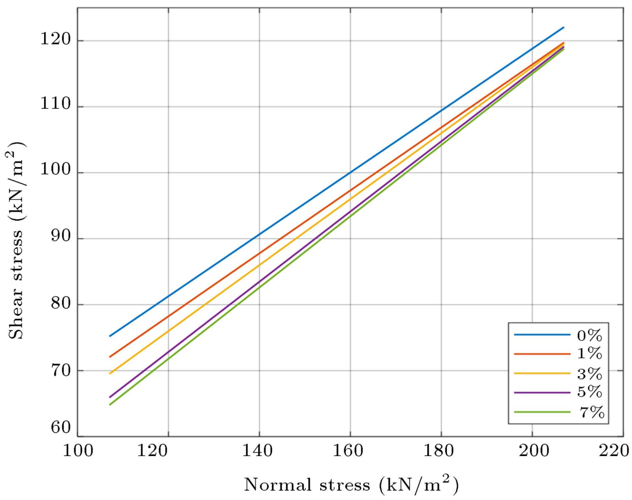

Figure 5. Variations of normal stress versus shear stress (kN/m^2) for different percentages of nano-clay.

of nano-clay dispersion in soil samples, the cohesion coefficient (c) decreased as the intercept of lines. Furthermore, the slope of lines shows that the internal friction angle (ϕ) increases with nano-clay percentages. The summarized results in Table 6 indicate that the internal friction angle (ϕ) increases by about 15% with the addition of 7% nano-clay. With an increase in the nano-clay ratio of soil samples, the cohesion decreases gradually.

According to Figure 5, which has almost been drawn based on the Mohr-Coulomb circle, graphs of effective stress for the soft soil stabilized with 0 to 7% of the nano-clay are presented. The failure envelope was drawn to the best-fit tangent line. Meanwhile, Figure 5 summarizes the values of effective cohesion (c') and effective friction angle (φ') obtained from the Mohr-Circle graph. The result shows an increment in

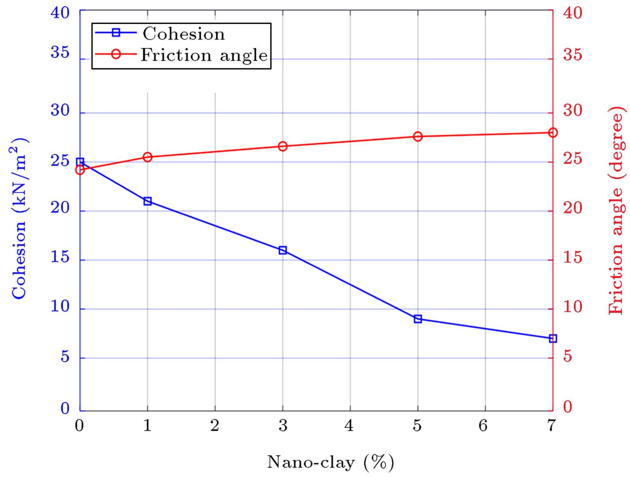

Figure 6. Variations of different percentages of nano-clay versus cohesion (kN/m^2) and friction angle (degree).

effective internal friction angle following the addition of some nano-clay percentages. It is indicated that the addition of a small percentage of nano-soil could achieve the best result for effective strength and high internal particle bonding between the soil particles and produce the greater effective shear strength [27,63].

Figure 6 shows different percentages of nano-clay versus shear strength parameters including the cohesion coefficient and internal friction angle. According to this figure, increasing the nano-clay content in the soil will increase the interlock contact and frictional forces between soil particles; thus, the friction angle will increase. On the contrary, the Mohr-Coulomb criterion requires an inverse relationship between the cohesion coefficient (intercept elevation in Figure 5) and friction angle (slopes of the straight lines in Figure 5). When the friction angle increases to promote the shear strength of the soil, the cohesion coefficient decreases. This trend can be justified according to the stabilization performance of the nano-clay. According to the SEM images in this study, the nano-clay cannot fill the voids, but may create frictional contact and bonding between particles, thus representing itself as the friction angle.

5.4. Different concentrations of nano-clay effect on Atterberg limits

After treating the studied soil by 1, 3, 5, and 7% equivalent weights of nano-clay, the Atterberg limits test was conducted on the samples mentioned in the previous section. The test results, shown in Figure 7, indicate that as the ratio of nano-particles increased, the Plasticity Limit (PL) and Liquid Limit (LL) increased. Still, the PL increased more than the LL; therefore, the Plasticity Index (PI) decreased. However, this process was reversed after 1% weight concentration. Table 7 shows the values of the test results [63].

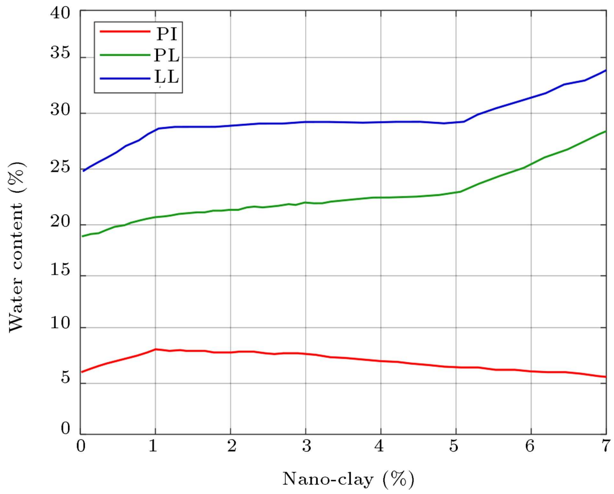

Figure 7. Variations of Atterberg limits versus different percentages of nano-clay.

Table 7. Variation of Atterberg limits for different percentages of nano-clay.

Specimen with nano-clay (%)	LL (%)	PL (%)	PI (%)
0	24.74	18.83	5.91
1	28.52	20.66	7.86
3	29.27	21.85	7.43
5	29.02	22.68	6.34
7	33.58	28.01	5.58

6. Stabilization of excavation wall in a case study

The variations of the shear strength parameters of the site samples with the contents of 5 to 7% of nano-clay remain approximately constant. Therefore, it was decided to consider 7% of the nano-clay for injection into drilled boreholes to stabilize the excavation wall.

The next subsection presents stabilization of excavation wall steps including determination of the safe site depth of excavation without bracing, drilling boreholes, intubation and filling tubes around, and injection of nano-clay into boreholes.

6.1. Determination of the safe site depth of non-stabilized excavation

Before elaborating on the loading test results, the authors used computer for help in analyzing the excavation wall and modeled it through the related software. After determining the specifications of the site soil samples at the laboratory, it was decided to estimate the safe excavation depth without stabilization [64].

There are many slope stability analysis methods in the domain of engineering, and the two most common ones are limit equilibrium and FEMs. These two methods are concisely compared with each other as follows:

1. The limit equilibrium method must search for a critical surface by using geometry. In the FEM, the critical surface is automatically determined by various software products;
2. The advantages of the limit equilibrium method: The limit equilibrium method of slices is based purely on the principles of statics, that is, the summation of moments, vertical forces, and horizontal forces. The method is not concerned with stress, strain, and displacements and as a result, it does not satisfy displacement compatibility;
3. The advantages of FEM: FE method models slopes with a very high degree of realism (complex geometry, sequence of loading, presence of material for reinforcement, the action of water, and laws of complex soil behavior) and also, it visualizes better the deformation of soil in place;
4. Limit equilibrium method requires only a simple Mohr-Coulomb soil model. The FEM must have a complete stress-strain model for soil;
5. Limit equilibrium method cannot compute displacement. The FEM can compute displacement;
6. Limit equilibrium method cannot model progressive failure. The FEM can model progressive failure.

According to the above, the PLAXIS 2D Geotechnical FEM software was used to analyze several excavations with different depths to obtain the related safety factor, which is close to 1.0. For engineers, PLAXIS 2D is a go-to finite element analysis application for soil, rock, and associated structures. In case the user attempts to solve the rock-mass response, surface and building settlements, stability and displacement of excavation pits, consolidation in undrained situations, or bearing capacity of structures, our intuitive digital workflows and sound computation offer analysis trusted by geotechnical practitioners worldwide [65]. In this analysis, the shear strength parameters were considered for non-stabilized conditions ($c = 25$ kN/m^2 and $\phi = 24.2°$). The results showed that the safe excavation depth was equal to 6.0 m, with the obtained safety factor of 1.04. In the next step, to calculate the load-induced failure of the desired excavation, the surcharge on the non-stabilized wall of excavation was modeled. It was concluded that the required load causing the failure of the non-stabilized wall was about 22 kN/m^2, being equal to 1.30 m height of the soil with a unit weight of about 17 kN/m^3. Figure 8 shows a schematic view of excavation walls with the corresponding loading. The modeling of non-stabilized excavation to determine its FS and deformation of the wall before loading has been done, and their figures have not been presented for the sake of brevity.

Moreover, Figures 9 and 10 show the modeling of non-stabilized excavation and deformation of the wall

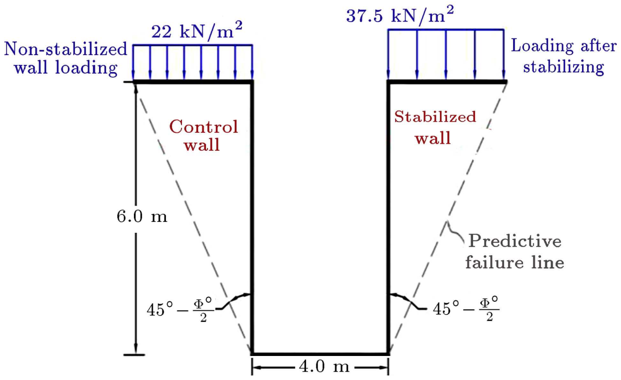

Figure 8. A schematic view of excavation walls with applied loadings.

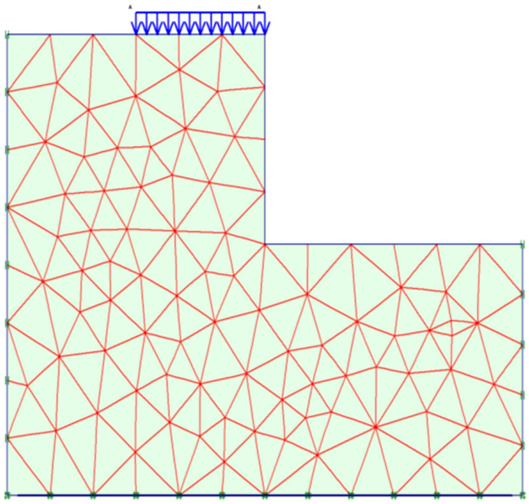

Figure 9. Modeling of non-stabilized excavation wall after loading ($FS = 0.89$).

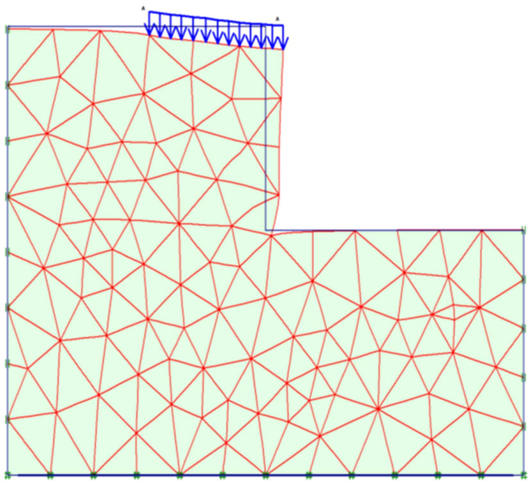

Figure 10. Deformation of non-stabilized excavation wall after loading (extreme total displacement =7.78 cm).

after loading. Obviously, the loading of the excavation wall decreases the FS of the non-stabilized wall from 1.04 to 0.89. Wall excavation should be stabilized to withstand 22 kN/m^2 of the surcharge without failure.

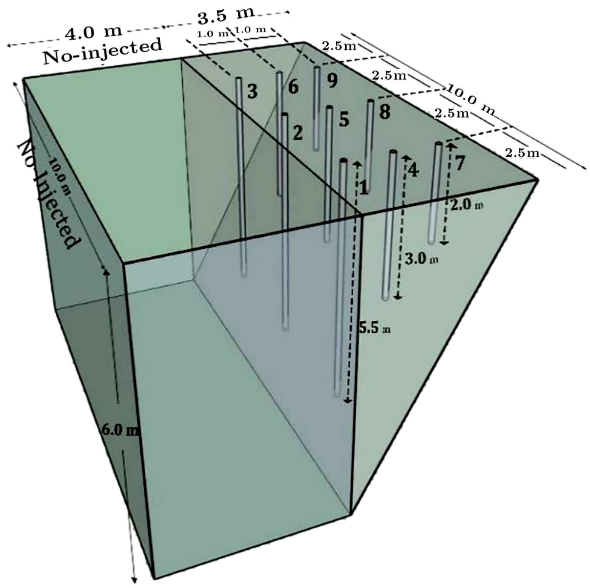

Figure 11. Locations of drilled boreholes.

6.2. Excavation and drilling of boreholes

A hydraulic excavator conducted the excavation operation in order to minimize shakes. The rotary drilling method was used to drill the injection boreholes. The operation of drilling boreholes on the top side of the excavation wall has been done for the stabilization process. Figure 11 shows the arrangement of the drilling boreholes. In this part, the objective is to stabilize the probable failure wedge. For this purpose, 9 boreholes with different depths were used. The distance between the boreholes was considered based on the site soil permeability coefficient and radius of injection.

6.3. Intubation and filling tubes around

After drilling injection boreholes, polyethylene-made tubes with closed ends were placed inside the boreholes. Some holes were generated on the tubes with a 25 cm distance from each other. Nano-clay emulsion was injected through these holes. Building sand was used to fill tubes around to conduct injection operations more accurately and let the injected substance penetrate deeply. To prevent the exit of nano-clays from boreholes, the head of each injection borehole at a depth of 20 cm was filled by grouting.

6.4. Injection of nano-clay in boreholes

Injection is a conventional method of improving soil properties [66]. Injection improvement can be used for different purposes such as reducing soil permeability, increasing soil strength, decreasing soil formability, and filling empty spaces [67]. Prior to the injection operation, nano-clay suspensions with 7% nano-clay weight content were prepared at the assessed site. A hydrometer mixer mixed the obtained solution for an hour to disperse nano-clay particles in water uniformly. A packer bucket was used to inject nano-clays into

Table 8. Borehole injection specifications.

Borehole no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Borehole depth (m)	5.5	5.5	5.5	3.0	3.0	3.0	2.0	2.0	2.0
Injected amount (Lit)	24.30	24.30	24.30	13.30	13.30	13.30	8.90	8.90	8.90

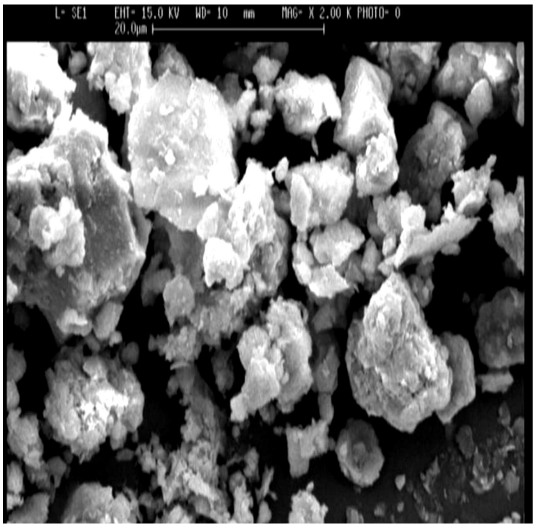

Figure 12. The SEM image with 5 cm radial distance from injected borehole.

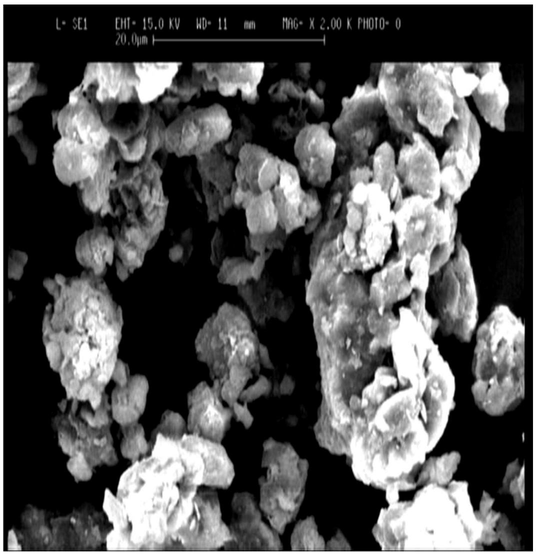

Figure 13. The SEM image with 25 cm radial distance from injected borehole.

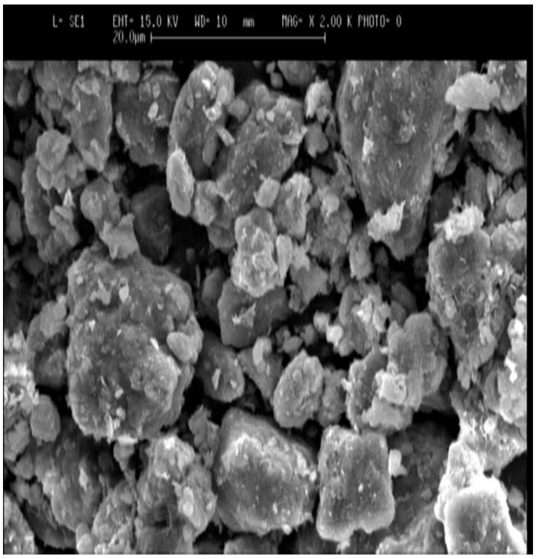

Figure 14. The SEM image with 50 cm radial distance from injected borehole.

boreholes. This handy device supplies a maximum of 8 bar pressure and has a 20 Lit capacity.

The obtained suspension was poured into the packer bucket when nano-clay emulsion was prepared. The suspension was injected with a pressure exceeding 5 bars for each borehole. The injection volume for each borehole is shown approximately in Table 8. According to Table 8, the summation of the injected volume is equal to about 140 Lit with respect to boreholes' dimensions. It was also swirled chronically during the injection process to prevent the sedimentation of the prepared solution. Then, the prepared solution was spilled in a packer buckle for the borehole injection. In this case, the weight concentration of the nano-clay as solute is 7%. Hence, it is proved that about 10 kg of nano-clay is required approximately to provide 70,000 ppm for the desired result.

Some samples were taken from different radial distances of each borehole including 5, 25, and 50 cm. SEM images of the samples with different radial distances from boreholes centers are shown in Figures 12 to 14. It can be seen that with an increase in the radial distance from the center of the injection boreholes, the percentage of the nano-clay dispersion decreases (bright points in the figures).

7. Loading of excavation walls

Following the injection operation and after a month, excavation walls were loaded to evaluate the efficiency of injection operation because of the curing time of the proved appropriate samples at the laboratory, which was 28 days. The walls were based on the calculated load in Subsection 5.1 (2.2 m of site soil) by soil bags placed over walls, and the back of the bags was supported by earth filling. This procedure was executed for both excavation walls. Nano-clay stabilized the right wall, and the left one served was non-stabilized. Figure 15 shows the image of the stabilized wall of excavation loading. The left wall was

Figure 15. Loading nano-clay on the stabilized wall.

Figure 16. Few seconds before non-stabilized wall failure.

loaded to compare the nano-clay-stabilized wall with the control wall. It was expected that this wall should be disrupted against the minimum possible loading. According to expectations, this wall was disrupted after 1m loading. Figure 16 shows the image of this wall several seconds before failure, and Figure 17 shows some seconds after failure.

8. Comparison of soil nailing and nano-clay stabilization methods

Soil nailing is a common technique used for soil im-

Figure 17. Few seconds after non-stabilized wall failure.

provement and slope stabilization [68–71]. If suitable soil and site conditions are selected, a quick and economical way of constructing earth retention support systems and retaining walls is provided [72]. It creates less noise, fewer traffic obstructions, and less impact on nearby properties. These techniques can also be considered to be environmentally-friendly. This feature allows excellent working space close to the excavation area, one-time grouting, and time and labor saving. The technique is also flexible and easily modifiable. In contrast, this method is subject to some limitation including: nail encroachment into the retained ground which renders it an unusable underground space, the declining tendency toward the high ground due to drilling technique, particularly on the coarse-grained soil, being only suitable for excavation above the groundwater. Since the nailing technique is one of the most common slope stabilization methods, it will be logical to compare the nailing technique with the proposed method in this research.

This study considered the soil nailing method to draw the economic comparison. Hence, the excavation geometry and loading were modeled to provide the restraint of excavation walls. For this purpose, the desired excavation was restrained by 3 rows of nails with size $\Phi 28$ which was also placed at an angle of 15° on the horizon, as shown in Figure 18. Figure 19 shows the logical safety factor of the soil nailed wall, and Figure 20 indicates the acceptable maximum lateral displacement of the modeling.

Economic analyses indicate that stabilization of excavation walls with the injection of nano-clay may be about 9% more expensive concerning the soil nailing method. Therefore, the nano-clay injection method is

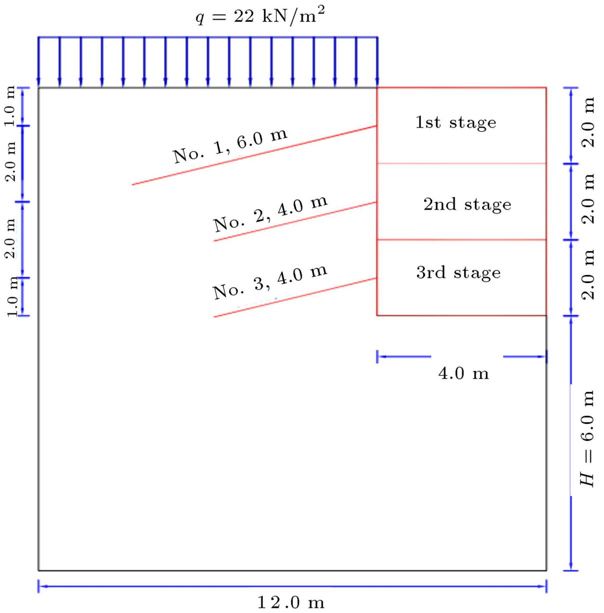

Figure 18. The desired excavation and soil nailed wall characteristics.

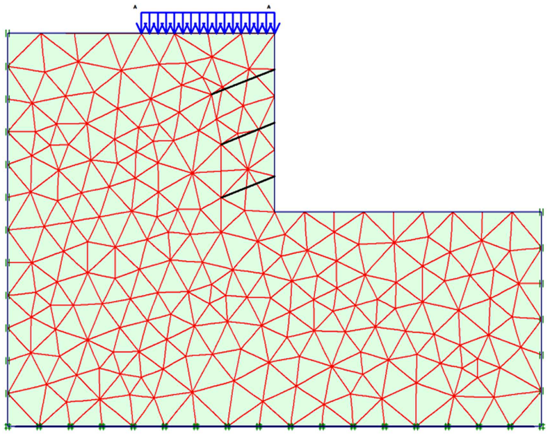

Figure 19. Modeling of soil nailed wall excavation after loading ($FS = 1.1$).

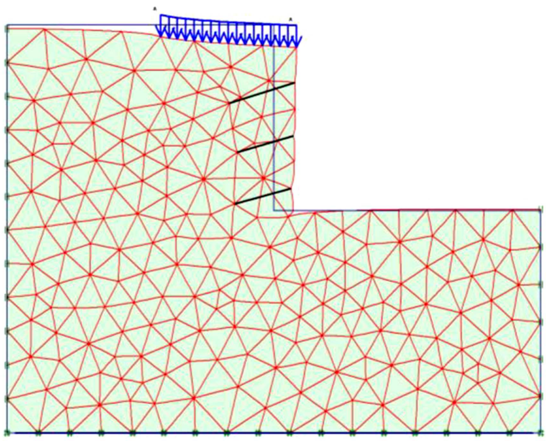

Figure 20. Lateral displacement of soil nailed wall excavation after loading (maximum lateral displacement = 4.55 cm).

proven to be efficient in terms of profit in stabilizing excavation walls and is relatively equal to the soil nailing method in this regard. It is reasonable to stabilize the excavation walls using this method for performance costs. Meanwhile, this modern stabilization method has already been proven to be more environmentally friendly than other traditional methods and it is worthy of running the excavating project using the proposed method.

9. Discussion

As discussed earlier, nanotechnology is a rapidly emerging technology with vast potential to create new materials with unique properties and to produce new and improved products for numerous applications. In recent years, nanotechnology is also gaining popularity in the field of civil and geotechnical engineering. The application of nanotechnology to geotechnical engineering in the case of dealing with soil appears in two ways (according to Section 2): first, study of soil structure on a nano scale and second, soil manipulation at an atomic or molecular level through the addition of nanoparticles as an external factor to the soil. A mixture of soil and some special additives could enhance the soil strength parameters. This procedure was implemented in the past to stabilize and improve weak soils. The presence of nanomaterial in the soil could significantly affect the physical and chemical behavior of the soil due to the very high SSA of nano-materials, surface charges, and morphological properties. Nano additives are used directly in the soil or material stabilization. Nano additives acting like a binder and strength material include nano-Silica and nano-clay, which are the major additives associated with soil stabilization. Clays are layered minerals with space in between the layers where they can adsorb positive and negative ions and water molecules. Clays undergo exchange interactions of adsorbed ions with the outside, too. Nano-clays are nanoparticles of layered mineral silicates. Based on their chemical composition and nanoparticle morphology, nano-clays are organized into several classes: montmorillonite, bentonite, kaolinite, hectorite, and halloysite.

Moreover, this paper uses nano-clay additives in different amounts to stabilize soil and investigate their effects and results. Due to the smaller dimensions of the nano-clay, nanoparticles possess a very high specific surface and react more actively with other particles in the soil matrix. The existence of even a minute amount of nano-clays equaling 7% can produce extraordinary effects on the engineering properties of soil, and it seems to be suitable to improve the geotechnical properties of soft soil sites for engineering applications. Accordingly, it is worthy that the soil cohesion remarkably decreases (by 70%) compared to that of the undisturbed soil. The maximum increment in shear strength was observed in the soil with a 7% nano-clay weight concentration. In line with these explanations, the internal friction angle increases by 15% upon adding 7% nano-clay. While the nano-clay ratio of soil samples increases, the cohesion decreases gradually. It was found that the soil cohesion remarkably decreased (by 70%) compared to the cohesion of the undisturbed soil. The maximum increment in shear strength was observed in the soil with a 7% nano-clay weight concentration. After injection operation and spending one month, it can be seen that the amount of loading that induces failure increases from 1.3 m height of the site soil before stabilization to 2.2 m after stabilization. Hence, the injection of nano-clay to the excavation wall increases wall stability so that soil can bear more applied load from site soil. The economic analysis involved a comparison between the nailing technique as one of the most common methods of slope stabilization and the nano-clay injection proposed in this research. The nano-clay injection might be about 9% more expensive. So, it is affordable to use the proposed methods due to their numerous advantages.

10. Conclusions

The effectiveness of using nano-clay in soil stabilization is regularly investigated through laboratory and field tests to evaluate the compressive and shear strength of soils. Using different additives is among several ways proposed for the improvement of such soil characteristics as shear strength. Due to their extremely small size, exceptionally high surface area, surface charges, and nano-porosity, these additives interact quite actively with other soil matrix particles that usually affects the index, consolidation, and strength properties.

The present study attempted to investigate the effects of adding nano-clays on the soil shear strength by considering a real site database depending on field and laboratory tests. In another part of the research, in order to determine an efficient depth with a factor of safety close to unity, the factor of safety of a non-stabilized excavation wall and its deformation before and after loading was obtained using an FE model. Based on the investigation, the following conclusions can be achieved:

- Each ratio of the added nano-clay increased the Liquid Limit (LL) and Plasticity Limit (PL) of the site soil. Accordingly, the extent of increase in the PL was greater than that in the LL. The increase in Plasticity Index (PI) continued up to 1% of the ratio of the nano-clay content after which the process was reversed;
- The results indicated that the internal friction angle increased by 15% with the addition of 7% nano-clay. However, as the nano-clay ratio of soil samples increased, the cohesion decreased gradually. It was found that the soil cohesion was remarkably reduced (by 70%) compared to the cohesion of the undisturbed soil. The maximum increment of shear strength was observed in the soil with a 7% nano-clay weight concentration;
- An Finite Element Method (FEM) software program was employed to analyze several excavations with different depths to obtain the related FS close to 1.0. The analysis demonstrated that the safe depth of excavation equaled 6.0 m with the obtained safety factor of 1.04. In the next step, the surcharge on the non-stabilized excavation wall was modeled to calculate the failure-induced load of the desired excavation. It was concluded that the required load causing the failure of the non-stabilized wall was about 22 kN/m^2, being equal to 1.30 m height of the soil with the unit weight of about 17 kN/m^3. Obviously, the loading of the excavation wall decreases the FS of the non-stabilized wall from 1.04 to 0.89. In fact, the excavation wall should be stabilized to withstand 22 kN/m^2 of the surcharge without failure;
- The summation of the injected volume was found equal to about 140 Lit with respect to the boreholes' dimensions. In this case, the weight concentration of the nano-clay as solute was 7%. Hence, it was proved that about 10 kg nano-clay was required to provide approximately 70,000 ppm for the desired result;
- Following the injection operation and after one month, the excavation walls were loaded to evaluate the efficiency of the injection operation. It can be concluded that the amount of loading that induced failure increased from 1.3 m height of the site soil before stabilization to 2.2 m after stabilization;
- From the captured Scanning Electron Microscopy (SEM) images of the samples with different radial distances from the borehole centers, it can be deduced that the radial distance was about 50 cm. As the radial distance from the center of the injection boreholes increased, the dispersion of nano-clay decreased;
- Injection of nano-clay to the excavation wall increased wall stability so that the soil could bear more applied load from the site soil;
- A small amount of nano-clay equaling 7% could significantly stabilize soft soils. It is, therefore, suitable to improve the geotechnical properties of soft soil sites for engineering applications;
- Economic analyses indicated that the stabilization of excavation walls with the injection of nano-

clay might be about 9% more expensive concerning the soil nailing method. Therefore, the nano-clay injection method was proved to be efficient in terms of profit in stabilizing excavation walls and was relatively equal to the soil nailing method. It is reasonable to perform stabilization of excavation walls for performance costs through this method.

Considering the limitation of the current study and to continue this research in the future, the following items can be mentioned:

- Given that the current research has been done on an area with fine-grained soils and many excavating operations are likely to be performed at sites containing coarse-grained soils, it is suggested that the effects of the nano-clay on excavation wall stabilization of coarse-grained soils be investigated. It is also possible to test and control other injection methods that differ from the proposed method in the current paper. Evaluation of the effect of nano-clay on excavation wall stabilization in a short period of time (after about one month) was carried out in this research. It is also highly recommended that the long-term effects of nano-clay injection be studied further;
- In a broader view, investigation of nano-clay impacts on the earthen dam clay core to further study the seepage effects through a field investigation and case study;
- In this paper, a deterministic analysis of nano-clay effects on slope stability was done. Hence, it would be worthwhile to perform a reliability analysis using the random field method considering the dispersion and permeability of nano-materials.

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