A Proposed Approach of Improving Soil Around a Single Lateral Loaded Pile Model by using Nano-Silica Sandy Soil Mixture Material

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Abstract. This research presented a new method to improve the individual pile's lateral behavior embedded into sandy soil using silica oxide nanoparticles material. A small-scale model test with many percent of nano-silica material (0, 0.3, and 0.6%) is used at different locations around the pile, such as an adjacent or at a distance of 10 mm away pile face and along pile front or pile behind in addition to untreated soil condition. The nano-silica material is placed into a steel box model as a plane-strain form. The obtained results are presented as relationships among applied lateral load with horizontal, vertical displacement, and rotation. The experimental work results have been validated by comparing with some of the present results (ultimate lateral pile of untreated soil) published by other workers. It clear that the obtained result is in good agreement with Hansen (1961). It is concluded that the perfect percentage of improving the soil by silica oxide nanoparticles was in the (0.6)% because this percentage gave the highest lateral load than that of other percentages at the same lateral and vertical displacement. This is because nanoparticles found in the soil improve the soil's strength by improving the interaction between soil particles by nanoparticles and filling the voids between soil particles with nanoparticles. All the tests that were obtained for the nanomaterial were mixed and let for three days, and one test was mixed and let for 30 days. This process was for the percentage 0.6 %, so from the results, the perfect period was for three days from the beginning of the mixture of the nanomaterial; this may occur due to the evaporation of the water from the mixture and that lead to a decrease in the interaction between the mixture and the sand in the container when adding the mixture to the physical model.

Keywords. Sand, Lateral pile, Nano-silica, Improving soil, Horizontally loaded pile, Horizontal and vertical displacement of the pile.

1. Introduction
The structures that are building on piles are often subjected to horizontal forces from lateral force such as wind force, traffic, and seismic phenomenon, so the horizontal forces acting on the tall or heavy structures like bridge abutments, offshore structures such as quays and harbors are also these structures subjected to large lateral forces caused by wind, water waves, and ship berthing. The horizontal forces transmitted to the pile and analyzed as a concentrated force and/or moment acting on the head pile. In the structures with piles used to resist vertical load only, there may exist moments from load eccentricities caused by faulty construction. The piles' analysis and design subjected to laterally loads and moments are very important to be in the safe side. It is essential for the stability and serviceability of structures (William Higgins et al.,2013, [1]). Many studies show the addition of the
colloidal silica to the sandy soil and caused improving the strength of the soil, unconfined compressive strength, liquefaction, and the sandy soil strain. The sand grouted compressive strength with colloidal silica increases linearly with increasing the percentage of the colloidal silica (Yonekura and Miwa 1993, [2]). (Persoff et al.1999, [3]) showed that the sandy soil improved with colloidal silica from 10% to 20% increases the unconfined strength of the soil to the 158 KPa to 317 KPa respectively, the same results were tested on the sand in other studies the treated samples with colloidal silica 5-20% showed varied strengths from 32 to 222 KPa (Gallagher and Mitchell 2002, [4]). (Kodaka et al. 2005, [5]) also observed, the addition of the colloidal silica to the soil lead to noteworthy improvement of the cyclic shear strength after colloidal silica addition. On the other hand (Diaz Rodriguez et al. 2008, [6]; Kodaka et al. 2005, [5]) observed the soil's untreated samples suffer from collapse during a few additional loading while the treated samples with the colloidal silica tested very little strain during the cyclic loading. Mollamahmutoglu and Yilmaz, 2010,[7], discussed the nano-gel generation's regularity with the time and the effect on the nano-sand mixture's strength.

2. The experimental work
Standard laboratory tests are carried out to estimate the physical and chemical properties of the soil used as the following:

2.1. Physical tests

2.1.1. Grain size distribution method. The sieve analysis test was performed according to the (ASTM. D422), [8], and the curve of the sieve analysis is shown in Figure (1). The results of the sieve analysis test are listed in Table (1).

![Figure 1. Grain size distribution curve.](image1)

| C_u | C_c | Soil Classification       |
|-----|-----|---------------------------|
| 3.16| 0.69| Poorly Graded Sandy Soil |

2.1.2. Proctor test method (ASTM. D 698), [9]. This test is performed according to specification ASTM D 698, [9]. From the compaction curve, the maximum dry density is 17.74 kN/m³, as shown in Figures (2) and Figure (3).

![Figure 2. Mixing of sandy soil with water.](image2)
2.1.3. **Unit weight of soil in place.** A field unit weight is carried out by the sand-cone method (ASTM. D 1556), [10]. The test was conducted at the soil's site in the Najaf sea area. The unit weight and water content of the soil in the site were 15.51 kN/m$^3$ and 2%, respectively.

2.1.4. **Direct shear test.** Three samples were tested in shear box test under normal stresses (15.7, 31.4, and 54.9 kN/m$^2$) by using ASTM D3080. The cohesion and angle of internal friction of soil are 0 kN/m$^2$ and 31 deg.

2.1.5. **Chemical tests.** Table (2) shows the chemical properties of the soil.

| No. | Test | The results % |
|-----|------|---------------|
| 1   | Gypsum / CaSo4.2H2o | 5.96          |
| 2   | So3  | 2.8           |
| 3   | T.D.S | 3.45          |
| 4   | Organic material | 5.7           |
| 5   | E.c. | 7.1           |
| 6   | PH   | 6.9           |

2.1.6. **Silicon oxide nano powder used.** Silicon Oxide nanopowder / SiO$_2$ nanoparticles (SiO$_2$, 99.5+%, 15-20 nm, P-type, porous), the properties of the Silicon Oxide nanopowder are shown in Tables (3) and (4).

| Table 3. The properties of the Silicon Oxide nanopowder. |
|----------------------------------------------------------|
| Silicon Oxide nanoparticle purity | 99.5+% |
| Silicon Oxide nanoparticle APS | porous particles-15-20nm |
| Silicon Oxide nanoparticle color | White |
| Silicon Oxide nanoparticle SSA | 640cm$^2$/g |
| Silicon Oxide nanoparticle morphology | Porous (size 2-6 nm) |
| Silicon Oxide nanoparticle bulk density | <0.10g/cm$^3$ |
| Silicon Oxide nanoparticle actual density | 2.4g/cm$^3$ |

Silicon Oxide nanoparticle ultraviolet reflectivity - > 85% .
Silicon Oxide nanoparticle hydroxyl content - >45%.
Silicon Oxide nanoparticle making method – plasma CVD.

Table 4. Silicon Oxide nanoparticle certificate of analysis – PPM.
Silicon Oxide nanoparticles certificate of analysis - PPM

| Al | Fe | Ca | Mg | Cl |
|----|----|----|----|----|
| <20| <10| <20| <10| <10|
Figure (4) Image of Silicon Oxide nanoparticles used in the model tests.

![Image of Silicon Oxide nanoparticles](image_url)

**Figure 4.** Silicon oxide nanoparticles.

2.1.7. **Steel container and pile.** The container is made from steel plates, its content from the door that’s opened to facilitate the emptying of the soil during the expiration of the test, and an arm made from steel used to support the steel cable that used to subject a lateral load to pile by the specific dead weights and the pile was free-standing as shown in Figure (5). The dimensions of the container were (39) cm in height, (35) cm in length, and (15.5) cm in width.

A steel pile is embedded into untreated and treated soil to a constant depth (L=150 mm) with square cross-sections (B=10 mm x B=10 mm). The pile was short rigid pile depending on $T = (EI/\eta h)^{1/5}$, the value of the embedded length (L) less than (2T) so the pile its short rigid (Broms, B.B. (1964)), [11].

The properties of steel containers and model piles are listed in Table (5).

| Properties                                | Values |
|-------------------------------------------|--------|
| Tensile Strength, kN/m²                   | 200 000|
| Modulus of Elasticity in compression or tension ($E_p$), MPa | 200 000|
| Poisson’s Ratio ($\nu$)                   | 0.29   |
| Unit Weight ($\gamma$), kN/m³             | 78.5   |

The dimensions of pile and container are chosen in which no effects of the side boundary of the container can be observed. In other words, the stress effects extend to (8 – 12 pile diameter) in the direction of lateral loading and (3–4 pile diameter) in the direction perpendicular to the loading (Prakash,1962).

![Diagram of steel container](image_url)

**Figure 5.** The steel container.
2.1.8. The method of mixing nano silica with soil. During the mix of the nano-silica with the soil, must be careful to avoid the risks that could be occurred and may affect the respiratory system when the nanoparticles interfere by smelling in the mixing step or when weight it by taking out the nano-silica of the envelope.

The treated soil samples are prepared by mixing the nano-silica to dry sandy soil for a period of 15 min, then adding the water to the mixture in percent 4% to produce a homogeneous treated sample after 15 min that could be used at a specific location of the pile after a period 72 hours (Asskar, Ali, and Saman 2015), [12], as shown in Figure (6).

![Figure 6. Silicon Oxide nanoparticles with the soil.](image)

2.1.9. Prepare of model. For the untreated model test, the soil into the steel box is prepared by adding water content corresponding to natural surface water content in the field (4%) to dry sandy soil, then mix until the soil sample becomes a homogenous sample. The homogenous mixture is poured into the steel box in three layers with (50 mm) thickness. Each layer is compacted to a unit weight equal to the natural wet unit weight in the field (15.5 kN/m$^3$). Each model's soil sample dimensions are 150 mm in height, 155 mm in width, and 380 mm in length. The method of installing the pile into the soil was a jacked pile, as shown in Figure (7).

The soil–water mixtures are compacted into three-layers for the treated model test, each layer with (50 mm) thickness. After that, the steel pile is placed and supported by temporary bracing systems (steel bar) to avoid errors during its installation. Also, a steel partition box is used to make the trench at a specific location (with dimensions (10mm in the thickness direction of the steel box and 150 mm or 75 mm in the depth direction of the pile, the width trenches equal to the steel box width) for laying treated soil, as shown in Figure (8).

![Figure 7. Pile installing and trench making.](image)
After the end of the soil's compaction process, the nano-silica–sand mixture was added to the vertical trench with weight equal (140) gm. at a three-layer form each layer of 50 mm, as shown in Figure (9) and Figure (10).

Figure 8. Trench making.

Figure 9. Adding the treated soil.

Figure 10. Model set-up.
2.2. Model tests for untreated and treated soil located adjacent to front and behind of the pile. Table 6 shown the ultimate lateral pile and Figure 11 shwn the configuration of laterally loaded of free head pile.

Table 6. The ultimate lateral pile (N).

| Item | The theory for the ultimate lateral pile | ultimate lateral pile (N) |
|------|----------------------------------------|---------------------------|
| 1    | Hansen (1961)                          | 72.54                     |
| 2    | Brom’s (1964)                          | 217.62                    |
| 3    | Fleming et al. (1992)                  | 226.3248                  |
| 4    | Meyerhof (1981)                        | 1.30572                   |
| 5    | Present work                           | 47.29                     |

Figure 11. Configuration of laterally loaded of free head pile.

2.2.1. Model tests for untreated and treated soil located adjacent to the pile front. In this category, the model tests are divided into four parts depending upon the nano-silica percentage (0, 0.3, 0.6, 1.2) %, which is mixed with normal soil. The mixture is placed in the front of the pile, the lateral and vertical displacement is generated due to gradually applied load, as shown in Figures (12) and (13), and the pile rotation is measured from Figure (11), and the results of the analysis are shown in Figure (14). It can be noted from Figures (12) and (13) that the perfect percentage of improving the soil by silica oxide nanoparticles was 0.6% because this percentage gave the highest lateral load than that other percentage at the same lateral and vertical displacement. This is because nanoparticles found in the soil improve the soil's strength by improving interaction between soil particles and nanoparticles by filling the voids between soil particles with nanoparticles. The model test with (0.3) % nanoparticles is intermediate states between (0.6, 1.2)% due to the low value of nanomaterial. When adding nanomaterial is high (1.2) %, at low applied load, the lateral displacement of the untreated model test is greater than that of model test with (1.2) % until it reaches to load 44 KN, the behavior becomes opposite. This behavior's main reason is appropriately due to increased nanoparticles, leading to high required water to hydrate Nano-particles. Figure (14) shows that the same behavior of pile rotation to horizontal and vertical displacements. Figure (15) shows the photo images of four model tests at a constant lateral load of the pile. When the horizontal, vertical displacements and pile rotation are continuous, it can be noted for the test model without nanomaterial, the cracks
of the soil are in all direction and greater than that with other models that improved with nanoparticles.

Figure 12. Applied load versus lateral displacement for untreated and treated soil in the pile front.

Figure 13. Applied load versus vertical displacement for untreated and treated soil in the pile front.

Figure 14. Applied load versus pile rotation for untreated and treated soil in the pile front.
2.2.2. Model Tests for untreated and treated soil located in a pile behind. This series of model tests are similar to those for the model test in the previous category, but the nanomaterials are located at the pile behind with percents (0.3, 0.6, 1.2) %, in addition to the untreated soil model. The values of the lateral displacement, vertical displacement, and rotation of the piles are drawn with the applied lateral load, as shown in Figures (16), (17), and (18), respectively. It can be noted from these figures the perfect percentage of improving the soil by silica oxide nanoparticles can be selected at (0.6)% because this percentage gave the highest lateral load than that other percentage at specific values of the lateral displacement and the vertical displacement. This behavior depends on the fact when nanoparticles are found in the soil, that leads to improving the strength of the soil by improving the interaction between soil particles by nanoparticles and fills the voids between soil particles with nanoparticles, but this behavior is opposite when the nanomaterial increased to (1.2) %. In other words, the lateral capacity of the pile of model test with (1.2) % is lower than that of model test with (0.6) %, but it becomes equal to that of model test with (0.3) %. The fact this behavior is due to the increase in the number of nanoparticles led to increasing the specific area in which the amount of water required to hydrate the nanoparticles is very high. In general, adding the nanoparticles to the soil located at the pile behind leads to increased lateral pile capacity and a decrease in the horizontal displacement, vertical displacement, and pile rotation. Figure (19) illustrates the pile's failure mode at the ultimate lateral pile capacity for untreated and treated soil with Nano-particles (0.3, 0.6, 1.2) %. A crack around the pile in all directions can be observed with the increase of the applied lateral loads for the model test with untreated soil.

Figure 15. Failure mode of pile for untreated and treated soil in the pile front.

Figure 16. The relationship between the applied load and lateral displacement for untreated and treated soil in a pile behind.
Figure 17. The relationship between the applied load and vertical displacement for untreated and treated soil in a pile behind.

Figure 18. The relationship between the applied load and pile rotation for untreated and treated soil in a pile behind.

Figure 19. The failure shapes of the pile for untreated and treated soil in a pile behind.
3. Conclusions

1. Generally, the addition of the silica oxide nanoparticles to the soil leads to an increase in the interaction between particles of the sand and also lead to many changes in the structure of the soil particles (such as the higher specific surface in the nanostructure) and finally, the ultimate lateral resistance of pile increased.

2. For any nanomaterial location (at pile front or behind), the percent (0.6%) of nanomaterial is very useful in improving the lateral pile's performance.

3. When the nanomaterial with (0.3 and 0.6%) placed in the adjacent front pile, the values of the ultimate lateral resistance of the pile are more significant than that for cases of the nanomaterial at the adjacent behind the pile, but opposite behavior can be noted for the nanomaterial with (1.2%).

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