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NUMERICAL SIMULATION OF PERVIOUS CONCRETE PILE IN LOOSE AND SILTY SAND AFTER TREATING WITH MICROBIALLY INDUCED CALCITE PRECIPITATION

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ABSTRACT: It is essential to provide a stable foundation system for construction projects to reduce the geotechnical risk of failure due to static or dynamic loads. Pile foundations are recommended to increase bearing capacity and decrease the dynamic oscillations of soils. Recently, soil stabilization using microbially induced calcite precipitation (MICP) was widely used to increase shear strength parameters and reduce the hydraulic conductivity of sand. In this study, the technique of using MICP was reviewed based on previous studies and analyzed using Plaxis 3D to evaluate the enhancement of a single pervious concrete pile under static, free vibration and earthquake stages of loose and silty sand. In the static stage, under the applying load to reach prescribed displacement of 76 mm, the results of loose sand demonstrate that the static load capacity was increased from 470 kN of untreated loose sand to 582, 598 and 612 kN after treating by MICP along the shaft and tip of a concrete pile with 0.5,0.75 and 1 m, respectively. In the earthquake stage, the result of treated loose sand such as vertical and lateral displacement was insignificant compared with untreated loose sand. The Plaxis 3D models have clarified the benefit of using MICP with the pile foundation model.

Keywords: Soil improvement, Pervious concrete pile under static and dynamic load, Numerical analysis

1. 1INTRODUCTION

Post-grouting methods have been used to improve the load-carrying capacity of deep foundations by increasing shaft and/or tip resistances of the pile. Post-grouting was widely utilized to improve the tip resistance of drilled pile. However, the grouting process around the pile shaft is complex and difficult quality control [1], [2]. A pervious concrete pile is used as an injection point to improve the soil-pile interaction and capacity load [3]. This technique can be applied to solve this problem. Only a few studies have used the permeable pile (pervious concrete pile) to simplify the grouting procedure of MICP along the shaft and tip of pile without applying pressure. The results of research [1] demonstrated that the improving of pile capacity under axial compression was up to 2.5 times higher the amount of pile without bio-grouting. Moreover, a $CaCO_3$-cemented zone around the pile was extended from the effective pile diameter (76 mm) to approximately 165 mm. The pile length was increased roughly by 25 mm. Soil clumps were noted surrounding the pile tip, which pointed out the breaking and failure of the cemented soil around the pile tip. It could be concluded that the failure was occurring near the pile tip of the cemented soil.

Microbially induced calcite precipitation (MICP) is a biological process that uses to improve granular soils due to increasing shear strength parameters. MICP has emerged as a green, low cost, and sustainable technique for soil improvement [4]. Due to the urease enzyme activity of bacteria in existence of urea and calcium chloride, the calcite (calcium carbonate) is formed after a series of chemical reactions. Umar [5] clarified that the principle of MICP method is as follows: the reaction of hydrolysis of urea , $CO(NH_2)_2$, with water leading to the formation of ammonia (NH_3) and carbon dioxide (CO_2).

$$CO(NH_2)_2 + H_2O \longrightarrow 2NH_3 + CO_2 \qquad (1)$$

The ammonium (NH_4^+) and hydroxyl ions (OH^-) induced by diversion of ammonia (NH_3) in the presence of water. Then, the carbon dioxide (CO_2) which generated by urease activity or respiration, decomposes rapidly to produce bicarbonate (HCO_3^-) and hydrogen ion (H^+) after reacting with water [6].

$$2NH_3 + 2H_2O \longrightarrow NH_4^+ + 2OH^- \qquad (2)$$

$$CO_2 + 2H_2O \longrightarrow HCO_3^- + H^+ \qquad (3)$$

The bicarbonate (HCO_3^-) combined with hydrogen and hydroxyl ions to create carbonate ions (CO_3^{2-}), which then combines with calcium ions Ca^{2+} (from dissolved calcium chloride) to precipitate calcium carbonate ($CaCO_3$).

$$HCO_3^- + H^+ + 2OH^- \leftrightarrow CO_3^{2-} + 2H_2O \qquad (4)$$

$$Ca^{2+} + CO_3^{2-} \longrightarrow CaCO_3 \qquad (5)$$

Calcium ions quickly combine with urea hydrolysis and water to produce calcium carbonate and ammonium.

$$CO(NH_2)_2 + 2H_2O + Ca^{2+} \longrightarrow NH_4^+ + CaCO_3 \quad (6)$$

MICP processes are affected by many factors including bacterial species and strains, bacterial solution concentration, temperature, pH, cementation solution composition and concentration, grouting technology, and soil properties [7]. Bacillus and Sporosacina bacteria are commonly used in MICP-treated geotechnical technology due to having an excellent ability to create calcium carbonate. The best conditions for microbial to improve the geotechnical properties are temperature around 20 and 40 °C, pH ranges from 7 and 9.5 and the adequate grain size of soil particles ranging from 10 to 1000 μm [7].

Soon [8] used microorganism technique to improve shear strength and reduce hydraulic conductivity of two different soils under 85%, 90% and 95% of maximum densities. The first sample classified as Sandy Silt with high plasticity (MS), while the second sample classified as Well Graded Sand (WS). The research explored the bio-clogging and bio-cementation development depended on bacteria, cementation reagents (e.g., urea and calcium chloride) and soil densities. The best results of undrained shear strength parameter (c_u) and hydraulic conductivity (k) were under 95% densities of Sandy Silt specimen. The c_u improved from 26.2 kPa (untreated soil) to 69.2 kPa (treated soil with MICP). The k decreased from 1.0×10^{-7} m/s of untreated soil to 2.6×10^{-8} m/s of treated soil. The changing in parameters of c_u and k were inflicted by creating the calcite (1.711%) after treatment system. In sandy soil, the effective internal friction angle ($\emptyset'$) was 50° with treated soil while the $\emptyset'$ was 48.8° with untreated soil under 95% of maximum index density. In addition, hydraulic conductivity (k) decreased from 4.4×10^{-4} m/s of untreated soil to 6.7×10^{-5} m/s of treated soil. The reason for this change is that the calcite content is 2.935% because of MICP treated.

MICP technique suffers from some drawbacks when using with fine grains because of bacteria incapable of growth in very low permeability to oxygen and moving freely in tiny pore space [9]. Behzadipour [9] addressed the impacts of plastic and non-plastic fines on the bio-mediated soil improvement of shear strength parameters of sandy soils. The results presented that the presence of fine particles can decrease the efficiency of MICP treatment. The effect of created calcite on shear strength reduces as the fine content increases. The MICP efficiency to treat sandy soils was reduced more than with adding plastic fine compared with non-plastic fines.

The comprehensive experimental tests were carried out by [10]-[12] to investigate the influence of MICP technique on poorly graded sand treated with different percentage of silt. Zamani [10] studied the behaviour of monotonic and cyclic undrained direct shear tests of untreated and bio-cemented. Also, the change in permeability was examined on Nevada sand classifying as uniformly graded and Nevada sand containing 15% silt classifying as silty sand. A result of calcite precipitation due to MICP, the normalized shear strength increased from 0.15 to 0.38 for sand and from 0.23 to 0.38 for silty sand. Moreover, the reduction in permeability was reflected directly on excess pore water pressure. For example, the excess pore water pressure reduced about 75% when the permeability reduced from 5.04×10^{-5} m/s to 4.47×10^{-6} m/s of Sand. Also, the excess pore water pressure decreased 35% with reduction in permeability from 2.56×10^{-5} m/s to 2.45×10^{-6} m/s of silty sand.

The Seep/W and Sigma/W programs used to evaluate the changes in injection rate and the influence radius of MICP process progress [12]. The results of numerical modelling presented that the rates of injection could be increased of Nevada sand. However, it remains unchanged of Nevada sand with 15% silt content. In addition, the higher levels of pore water pressure were generated due to the presence of fines (silt) during the injection process, which requires higher strength enhancement to prevent the development of excessive plastic strains. The key parameter to determine the radius of treatment is to improve the shear strength and stiffness relative to the quantity of the hydraulic conductivity level and its change rate.

The purpose of this study is to focus on using Plaxis 3D program to assess the effect of MICP treatment on the ultimate loading capacity and the displacement of constant load under free vibration and earthquake. The research shows that Plaxis is a powerful modelling program for assessing and calculating pervious concrete pile that is particularly embedded on sand.

2. CONSTRUCTION PARAMETERS AND FINITE ELEMENT MODEL SETUP

The dimensions of the model have been set with 40 m in X direction, 5 m in Y direction and 40 m in Z direction to minimize the boundary condition effect of dynamic steps that is assumed to have an effective action through the X direction.

The representative properties and model of soil and pile were constructed based on previous studies and recommendations. Tables 1 and 2 illustrate the properties of soils using in this study. The geotechnical properties of untreated and treated soils were gotten from [12]. The properties of pervious concrete pile are illustrated in Table 3. The pile was modelled depending on reference [1] after scaling the dimensions to 10 times. For example, the diameter of pile is 0.76 m while the length of pile is 10.7 m including an embedded length 9.16 m. The treated soil was assumed extending to 0.5, 0.75 and 1 m along the shaft and tip of a concrete pile. The pile was defined as a rigid body using polycurve from side toolbars, the negative interface was selected around and tip of pile from Model explorer.

Table 1 The properties of untreated and treated Sand*

Identification	Sand	Treated Sand
Model	Mohr-Coulomb	
Drainage type	Drained	
Unsaturated Unit Weight, γ (kN/m^3)	17	17
Saturated Unit Weight, γ (kN/m^3)	19.25	20
Void ratio, e	0.709	0.647
Young's modulus (kPa)	5400	16200
Poisson ratio, ν	0.27	0.29
Friction Angle, $\phi°$	32.5	36
Permeability (m/day)	4.52	2.29

*The data were taken or derived from [12].

Table 2 The properties of untreated and treated Silty sand*

Identification	Silty sand	Treated Silty sand
Model	Mohr-Coulomb	
Drainage type	Drained	
Unsaturated Unit Weight, γ (kN/m^3)	17	17
Saturated Unit Weight, γ (kN/m^3)	19.25	20
Void ratio, e	0.709	0.650
Young's modulus (kPa)	8400	12900
Poisson ratio, ν	0.27	0.29
Friction Angle, $\phi°$	32	34.5
Permeability (m/day)	0.386	0.212

*The data were taken or derived from [12].

Table 3 The properties of concrete pile

Identification	Concrete pile
Model	Linear elastic
Drainage type	Drained
Unsaturated Unit Weight, γ (kN/m^3)	22
Saturated Unit Weight, γ (kN/m^3)	22
Void ratio, e	0.149•
Young's modulus (kPa)	20 x10^6
Poisson ratio, ν	0.1
Permeability (m/day)	1.04x10^6•

• The data were extended taken from [1].

To calculate the ultimate static load capacity to reach 76 mm prescribed displacement (10% of pile diameter) and dynamic states of untreated and treated soil, the design steps have been followed. The soil layer (sand or silty sand) was extended until -40 m. The untreated and treated soils were modelled as Mohr-Coulomb model with drain condition. The phreatic level assigns at the ground surface. The pile was modelled as half symmetric to reduce the calculation time. The interface elements were used to incorporate with interface strength reduction factor (Rinter) 0.8 to decrease the skin resistance of the interface that allows sliding between the pile and soil nodes. The geometry of treated soil with 1 m around the shaft and tip of a concrete pile is demonstrated in Fig. 1.

The earthquake was assumed as 0.5 m uniform prescribed displacement across the bottom boundary at X component with fixing Y and Z components. The data of earthquake, which is available in Plaxis, was used for the dynamic excitation under acceleration and drift correction options, as shown in Fig. 2. To avoid spurious reflection of the wave on the model boundaries, the interface is defined along with the vertical and bottom bounds under Free-field and Compliant base.

The element distribution in Mesh mode was set to medium because of the calculation under dynamic taking more than one day to complete. The process of calculation includes the initial conditions phase, simulation of concrete pile with untreated and treated soil, prescribed displacement load under 76 mm, free vibration analysis and earthquake analysis. In prescribed displacement load and earthquake phases, the reset displacement was selected to zero.

The free vibration or earthquake phases was started after completing prescribed displacement load. The free vibration analysed as dynamic option with 5 sec. time interval under boundary conditions in X directions and Z min as viscous while in Y directions and Z max as none. In earthquake phase, the dynamic option with 20 sec. time interval was selected. The boundaries were set to Free-field in the X direction, to None in Y and Z max, and to Compliant base in Z min.

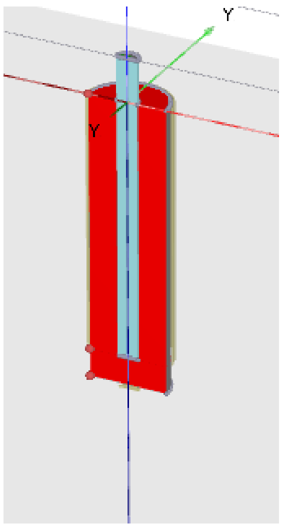

Fig. 1 The geometry of treated soil with 1 m around the shaft and tip of a concrete pile as half symmetric using Plaxis 3D.

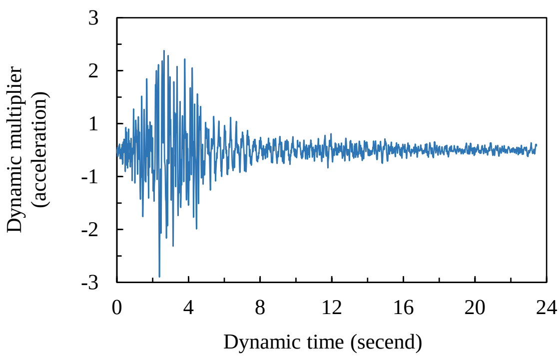

Fig. 2 Acceleration-time used in the study (Plaxis program).

3. RESULTS AND DISCUSSION

Figure 3 illustrates the increase of half pile displacement due to the increasing load of untreated and treated loose sand with MICP. In untreated state, the load versus displacement curve is gradually decreased until the load is approximately reached 135 kN with a vertical displacement around 17 mm. The curve is then reduced sharply until reaching displacement 76 mm with a load 235 kN of half pile. The maximum load capacity of a complete pile is 470 kN. As you can see from the treated soil curves with 0.5, 0.75 and 1 m around the shaft and tip of a concrete pile, the gradient of the load-displacement graph is smaller than untreated soil. In addition, the curves of treated soil are reduced continuously up to approximately the load and displacement reaching 160 kN 13 mm, respectively. The curves of half pile are then dramatically decreased until reaching 76 mm displacement when load capacity of treated soil with 0.5, 0.75 and 1 m are 291, 299 and 306 kN, respectively. The enhancement ratio of treated soil with 0.5, 0.75 and 1 m is increased to 1.24, 1.27 and 1.3, respectively. In addition, the load capacity development is slightly increased after treatment with 0.5 m.

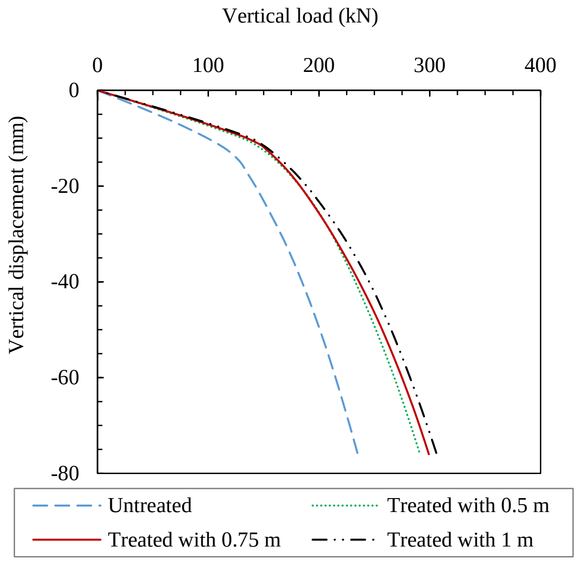

Fig. 3 Load – displacement relationship of untreated and treated loose sand.

The vertical displacement as shading of untreated and treated with 1 m loose sand is presented in Fig. 4. The displacement on the pile tip is more influence compared with the pile shaft. From another perspective, the intensity of displacement of treated loose sand around the pile shaft is higher than untreated sand. It could be because of more load (stress) requiring to attain 76 mm displacement.

Figure 5 presents the effect of MICP on the vertical pile load in silty sand. The maximum vertical load of untreated silty sand is 277 kN to extend 76 mm of displacement. As expected, the untreated silty sand exhibits a higher vertical load compared with untreated loose sand. It could be attributed to the higher contacts between silty sand particles. As shown in Fig. 5, the enhancement of load capacity is around 313 kN when the soil is treated with 0.5m along the shaft and tip of a concrete pile. However, the load capacity is insignificantly increased with 0.75 and 1 m treated.

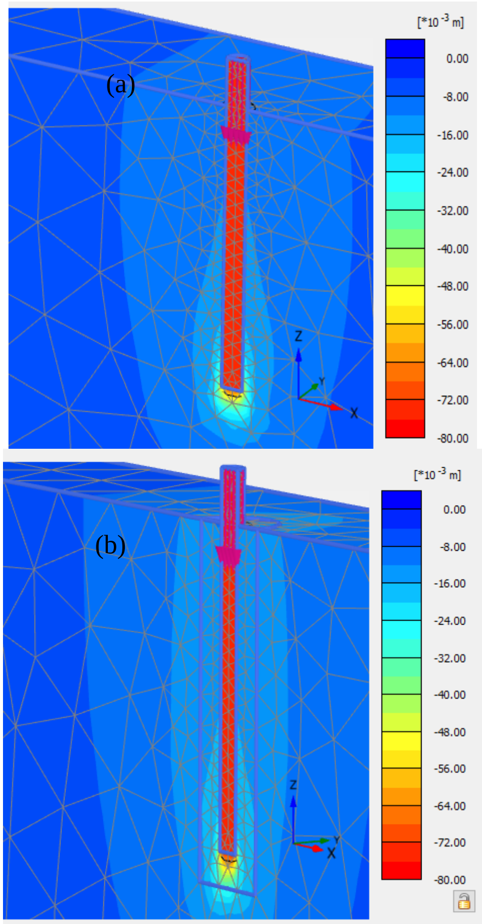

Fig. 4 Vertical displacements u_z to reach -0.076 m: (a) of untreated loose sand, (b) of treated loose sand with 1 m (scaled up 20 times).

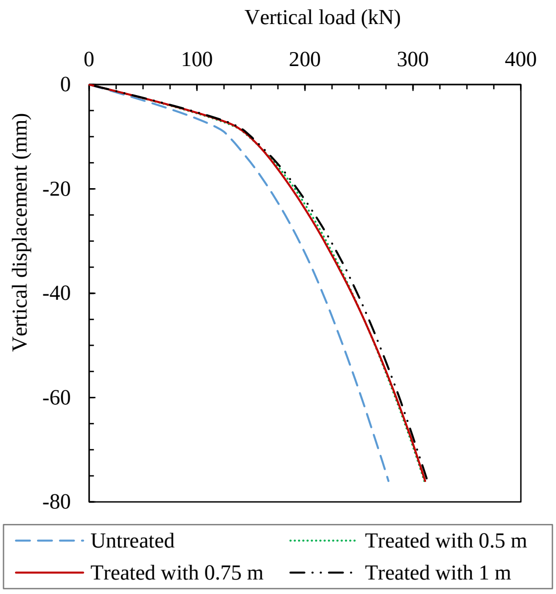

Fig. 5 Load – displacement relationship of untreated and treated silty sand.

As shown in Fig. 6, the effect of changing water table (WT) level on the relation between vertical load and displacement of 0.75 m treated sand along the shaft and tip of a concrete pile. The results show that the vertical load increases when the WT is far from the ground surface. For example, the vertical load to reach 76 mm displacement is 299 kN when the water table is located at the ground surface. However, when comparing the changing of the water table location, it is clear the vertical load is 361, 405 and 443 when the WT is at 2, 5 and 20 m below the surface, respectively. [14] asserted that water saturation caused a significant loss in shear strength and a decrease in the ultimate bearing capacity of the soil. The presence of groundwater plays an essential role in determining how the soil mass impacts to apply loads because of a decrease in effective stress that reduces the soil bearing capacity [15].

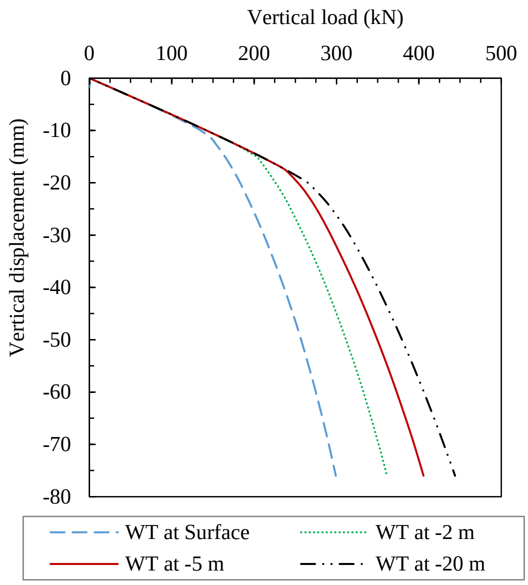

Fig. 6 Load – displacement relationship of 0.75 m treated sand at various water table locations (WT).

Figures 7 and 8 present the vertical displacement shading of 0.75 m treated loose sand with WT at the surface and -2 m, respectively. As you can see, the shading level of different vertical displacements in Fig. 8 extends further from the pile compared with Fig. 7.

Figure 9 shows the change in vertical load versus displacement as a function of pile diameter of 0.75 m treated loose sand with WT at the surface. The vertical load is 158 kN when the pile diameter is 0.5 m. However, the load capacity increases to 298 and 403 kN when the pile diameter is 0.76 and 1 m, respectively.

Figure 10 shows the horizontal displacement (u_x) of free vibration versus time on the top of the pile centre (0, 0, 1.54). The greatest u_x of untreated sand is 7.798 x 10^{-1} mm at 0.955 sec. while the highest u_x of treated sand with 1 m along the shaft and tip of a concrete pile is 6.869 x 10^{-1} at 1.405 sec.

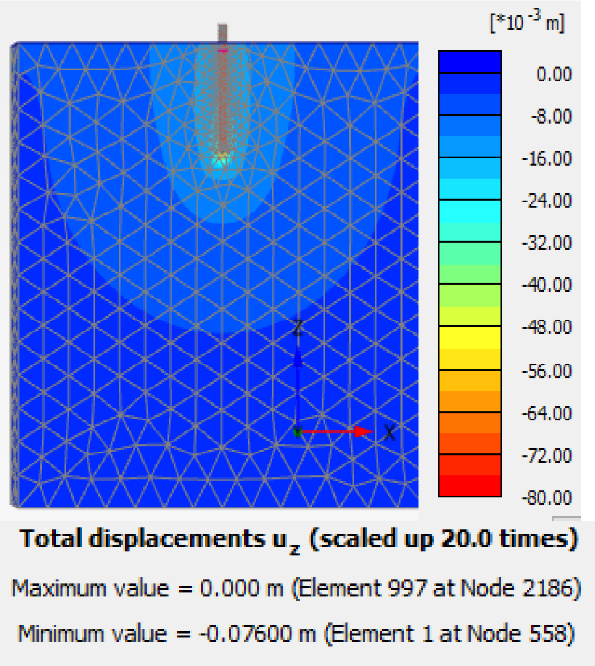

Fig. 7 Vertical displacements u_z to reach -0.076 m of treated loose sand with a water table (WT) at the surface.

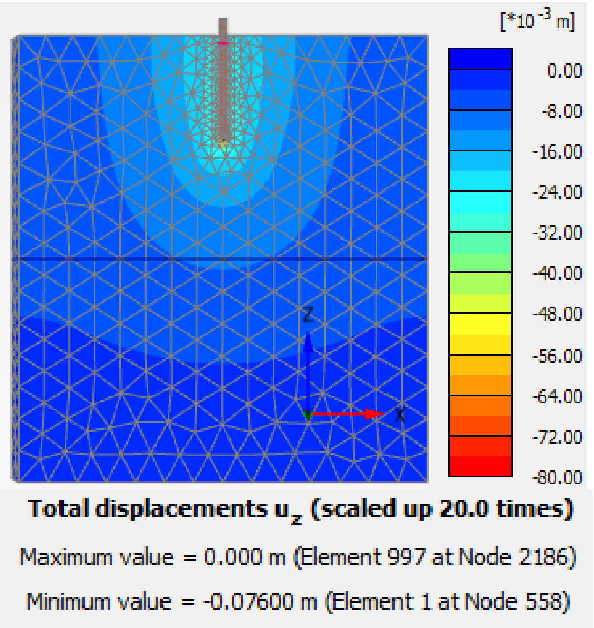

Fig. 8 Vertical displacements u_z to reach -0.076 m of treated loose sand with a water table (WT) at 2 m below the surface.

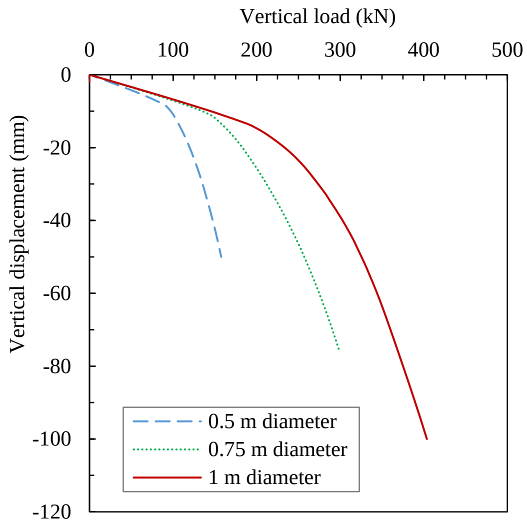

Fig. 9 The relationship between vertical displacements u_z and the load capacity of 0.75 m treated loose sand as a function of pile diameter.

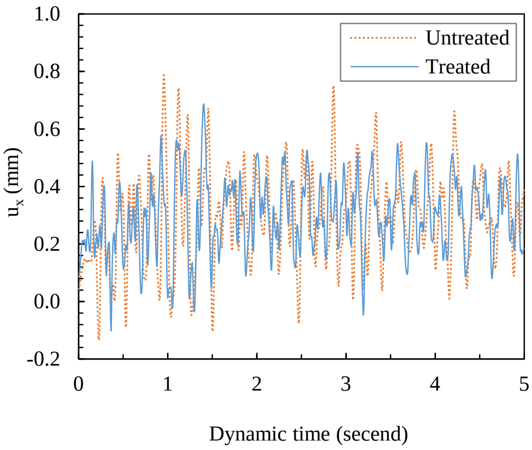

Fig. 10 Horizontal displacement (u_x) of free vibration versus dynamic time.

The vertical displacement (u_z) – dynamic time relationship under free vibration is illustrated in Fig. 11. The free vibration step calculated after reaching 76 mm prescribed displacement due to vertical load. The u_z of untreated sand is decreased to 117 mm at 0.73 sec while u_z of treated loose sand is reduced to 120 mm at 0.73 sec. It might be because the pile under-treated state was carried more load compared with the untreated state when obtaining 76 mm vertical displacement.

Figure 12 illustrates the horizontal movement (u_x) with time on the top of the pile centre (0, 0, 1.54). It observes that the peak value of u_x of untreated and treated sand is an approximately close pattern.

The vertical displacement (u_z) versus time of untreated and treated loose sand under seismic condition is shown in Fig. 13. The displacement of the pile under earthquake condition determined after resetting the displacement to zero in Plaxis program. It appears that u_z is decreased to 35 mm after 1.3 sec. of untreated sand while u_z is reduced to 40 mm at 1.3 sec. of treated sand. It could be happened because of the same reason that mentioned at free vibration step.

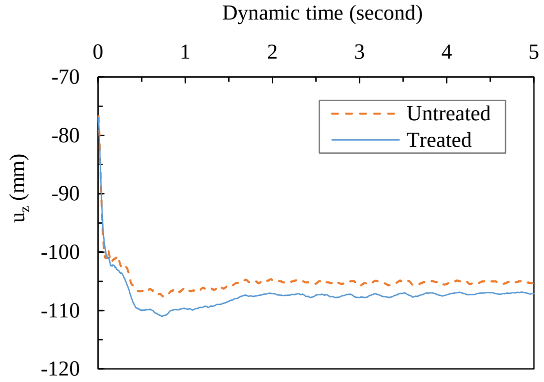

Fig. 11 Vertical displacement (u_z) – dynamic time relationship under free vibration.

Figure 12 illustrates the horizontal movement (u_x) with time on the top of the pile center (0, 0, 1.54). It observes that the peak value of u_x of untreated and treated sand is an approximately close pattern.

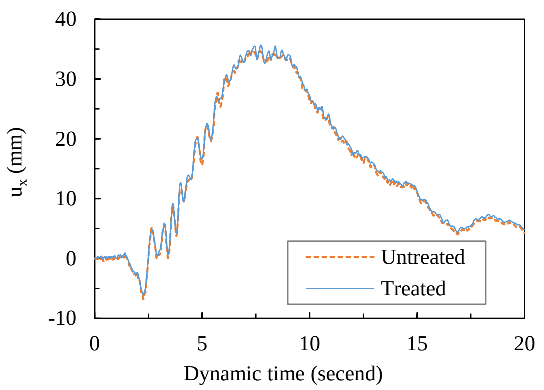

Fig. 12 Horizontal displacement (u_x) versus dynamic time on the top of the pile center (0, 0, 1.54).

The excess pore pressure under earthquake conditions has been noted, as shown in Fig.14. The excess pore pressure is not generated during earthquake conditions. It could be because the loose sand is modeled as a drained state under Mohr-Coulomb. The program does not provide output details when modeling under Mohr-Coulomb with the undrained condition.

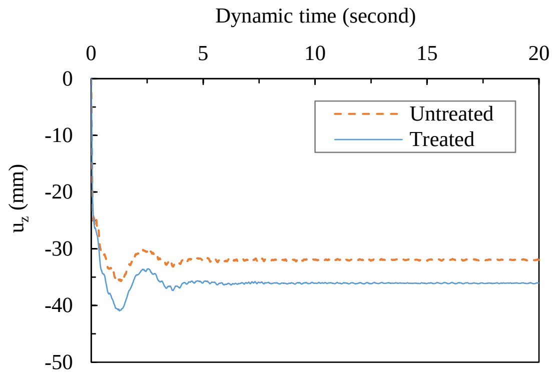

Fig. 13 Vertical displacement (u_z) – dynamic time relationship under earthquake.

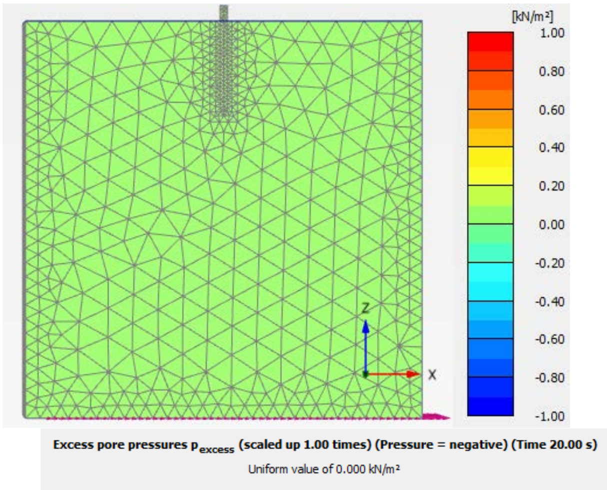

Fig. 14 The excess pore pressure under earthquake conditions of the loose sand with the water table at the surface.

4. CONCLUSIONS

This paper reports the outcomes of finite element modelling and analysis of a single pervious concrete pile in loose and silty sand before and after treated with MICP. The pile was subjected to free vibration and earthquake after evaluating the maximum vertical load. The following conclusions could be drawn as a result of this study.

The results reveal that using MICP has a significant effect on the pile bearing capacity of loose sand compared with silty sand. For example, the ultimate load capacity of the complete pile to displace 76 mm was increased from 470 kN to 582,598 and 612 kN when the loose sand treated with 0.5, 0.75 and 1 m, respectively. On the other hand, the maximum load was improved from 554 kN of untreated silty sand to 620 kN of treated silty sand with 0.5 m around the shaft and tip of the pile. Moreover, the enhancement of load capacity was insignificant increased after 0.5 m treated. The horizontal (u_x) and vertical (u_z) displacement were marginally changed under free vibration and earthquake conditions of untreated and treated loose sand.

5. ACKNOWLEDGMENTS

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