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EFFECT OF SAND DENSIFICATION DUE TO PILE-DRIVING ON PILE RESISTANCE

FAISAL I. SHALABI[1] & TALAT A. BADER[2]

[1]Associate Professor, Department of Civil Engineering, King Faisal University, Al-Ahssa, Saudi Arabia

[2]Assistant Professor, Department of Civil Engineering, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

ABSTRACT

Bearing capacity of pile foundation depends on pile side (skin) resistance and tip (end-bearing) resistance. Side resistance of piles in sands is usually evaluated based on the angle of friction between the pile and sand which depends on sand and pile material frictional properties. In literature, the angle of internal friction of sand is mostly evaluated based on SPT (Standard Penetration Test) or CPT (Cone Penetration Test) data. For pile side resistance, the obtained SPT or CPT results are not precisely considering the effect of sand densification around the pile as a result of pile driving, which is expected to increase the angle of internal friction of initially loose sand. In this work, an attempt was made to evaluate pile side and tip resistances based on the actual density of the densified sand as a result of pile driving. Medium scale laboratory tests using sand box were performed on different pile materials and different sands at different initial relative densities. The lateral deformation of the sand due to pile driving was measured using embedded extensometers connected with external LVDTs. The final density of the sand around the driven pile and the corresponding pile side resistance were then evaluated based on the lateral sand movement and the new sand density around the pile. The results show that most of the sand lateral movement due to pile driving is concentrated in a zone extended almost three times the pile diameter from the pile centerline, and the extent of this zone increases as the sand initial density increases. Also, the results show that as the sand relative density increases, the ratio of the pile side resistance to the total resistance decreases and the side resistance increases linearly with the increase in sand initial relative density. By considering the void ratio, the results of this work show that the initial void ratio of the sand is a key factor and it is correlated very well with the side and tip resistances of the driven piles with a correlation coefficient factor, R^2 of 0.95 and 0.90 for the side and tip resistances, respectively. Considering the change in sand relative density due to pile driving, it was found that the normalized change in pile side resistance due to the change in sand relative density decreases with the increase in the percentage change in the sand relative density.

KEYWORDS: Driven Pile, Resistance, Sand, Lateral Densification

INTRODUCTION

Many approaches and techniques are used to evaluate pile axial capacity ranging between interpreting the results of load-deformation of in-situ full or large scale load tests (Skempton, 1953; Davison, 1973; Crowther, 1988; Fellenus, 1990; Meyerhof,1992; Nabil, 2001), which relatively are considered an expensive approach, or using dynamic methods (Isaac, 1931; Smith, 1960; Rausche et al., 1985; Warrington, 1997), which are based on the results of pile driving or wave propagation results, or using finite element and numerical methods (Pressley and Poulos, 1986; Sheng et al., 2005; Masouleh and Fakharian, 2008; Comodromos et al., 2009; Yan and Geo, 2010; Gui, 2011), which require reliable constitutive models that represent the real soil behavior and the interaction between the soil and the pile, or using the analytical methods (Burland, 1973; Bhushan, 1982; Kulhawy et al., 1983; Neely, 1991, Kulhawy, 1991; Eslami and

Fellenius, 1997; O'Neill and Reese, 1999), which are based on the properties of soil and pile materials evaluated from laboratory or in-situ tests such as the results of CPT or SPT. This approach is relatively less expensive than the other approaches but using SPT and CPT do not consider the real large scale change in soil properties around the driven piles.

Even though an extensive work has been carried out to evaluate pile ultimate capacity using the different approaches mentioned above, still the behavior and performance of piles is one of the challenges to be fully understood or predicted for the geotechnical engineers. This challenge came from the lack of the complete information available regarding the mechanism that controls the load-deformation characteristics and the stress-strain behavior of soils around piles as a result of pile driving or installation.

Axial bearing capacity of pile depends on its side and tip resistances. For piles driven in sand, the side resistance depends on the effective horizontal stress, σ'_h, which is a function of the effective overburden stress, σ'_{vo}, and the frictional properties between pile material and sand (ϕ_f). The angle of friction between the pile material and the sand, ϕ_f, was correlated with the effective angle of friction, ϕ' (Kulhawy et al. 1983; Kulhawy, 1991). As example, for rough concrete pile the value of ϕ_f /ϕ' is 1.0, while for smooth steel pile the value of ϕ_f /ϕ' is in the range of 0.5-0.7.

The side resistance of driven piles in sand was also found to be a function of the lateral displacement of the sand. Kulhawy et al. (1983) used the ratio of lateral earth pressure after construction (K) to the one before construction (K_o) to evaluate the pile side resistance. As examples, K/K_o for large displacement driven pile is ranging between 1.0 and 2.0 while for drilled slurry shaft the ratio is between 0.7 and 0.9.

As can be seen from many previous studies, the friction between the pile material and the sand, ϕ_f, and the effect of lateral sand movement due to pile driving are correlated with the angle of friction of sand before pile driving. The angle of friction of sand is expected to be change after pile driving as the relative density of the sand is changed.

The objective of this work is to evaluate the side resistance of short driven piles in sand as a result of the change in sand relative density. To investigate this problem, medium scale laboratory testing setup was designed. Different pile (timber and concrete) and sand gradation materials were used in this work in order to investigate the effect of pile material on side and tip resistances of bored and driven piles. Two types of sands were used at different relative densities. Piles were tested inside sleeves in order to evaluate the side and tip resistances separately. Lateral deformation of sand was measured during pile driving in order to evaluate the change in sand density close to the pile sides. The deformation was measured by impeding radial steel rods inside sleeves in the tested sand and connected to external LVDTs. Axial load was applied at the top of the driven pile in order to investigate the axial capacity of the pile. Unit side and tip resistances of the tested piles were correlated with the relative density of the sand evaluated after pile driving and with the initial void ratio of the sand.

MATERIALS USED

Sand: Different locations were investigated in Al-khobar and Al-Dhahran (Saudi Arabia) to select the proper sands. A site near the Half-Moon beach was found to be promising for the maximum sand grain size. Samples were taken and sieve analysis was performed to get the sand gradation. Two different natural sand materials were selected based on grain size distribution, as shown in Figure 1. The results show that sand-1 is uniform (SP sand according to USCS) with coefficient of uniformity, Cu=2.6 and coefficient of curvature, Cc= 0.78, and sand-2 with Cu=5.1 and Cc = 2.1 (SP sand. It is close to the well-graded classification).

Direct shear tests were performed to evaluate the shear strength of the two sands at loose and dense conditions.

The results showed that the peak angles of internal friction of sand-1 are 42^o and 38^o for dense and loose conditions, respectively. For sand-2, the peak angles of friction are 46^o and 40^o for dense and loose conditions, respectively. Results of relative density tests showed that sand-1 has minimum and maximum void ratios of 0.50 and 0.92 respectively, while for sand-2 the values of minimum and maximum void ratios are 0.37 and 0.58 respectively. Table-1 summarizes the properties and the classification of the two used sands.

Piles: Timber and concrete piles were used for testing. The piles were 5 cm in diameter and 60 cm in length. Flat end, 60^o and 45^o tip angle piles were used in the tests. Piles inside sleeve tubes were also tested in order to evaluate the side friction and tip resistances separately.

TESTING PROGRAM AND TESTING SETUP

The testing program of evaluating pile side resistance and lateral deformation of short piles focused on testing different piles material (Timber and concrete) under different grain size distributions and different initial relative densities of two sands (loose, medium dense, and dense conditions). Driven and bored piles were considered in testing. Steel sand box was designed and manufactured with lateral extensometers connected with external LVDTs to measure the lateral movement of sand during pile driving. The results of deformation were used to evaluate the new relative densities of the tested sands as a result of sand lateral movement. To measure the side and tip resistances separately, a steel sleeve was designed so that each resistance can be evaluated during any stage of testing.

The testing program was executed using universal compression testing machine. The sand was placed at different initial relative densities condition in steel box. The box was 60 cm in diameter and 65 cm in height. Three extensometers were embedded at two levels in the sand box at different distances from the sides of the pile (at 0.5B, B, and 2B, where B is the pile diameter). Outside the box, the extensometers were attached to LVDTs' to measure the lateral movement of the sand as a result of pile driving. The axial deformation and load of the tested piles were evaluated throughout an axial LVDT and a load cell attached to the head of the pile. Figure 2 shows the pile inside the sand box tested in the universal testing machine. All the tests were performed at the department of Civil Engineering laboratories at King Fahd University of Petroleum and Minerals.

ANALYSIS AND DISCUSSION OF THE RESULTS

In this section, the results of the tests were analyzed and discussed. The discussion focused on the effect of pile end shape, pile type, sand relative density and void ratio, construction method (bored versus driven), and sand lateral deformation on the pile unit side and tip resistances. It should be mentioned here that failure was considered at pile deformation of 20 mm. Figure 3 shows a sample of load deformation and sand lateral movement of driven timber pile tested in dense sand-1.

Effect of Pile Material on Pile Resistance

Results of driven pile tests in loose sand-1 conditions (relative density, Dr. = 24.5%) using smooth timber and precast concrete piles show that the unit side resistance (f_s) and unit tip resistance (q_t) normalized to the effective vertical stress (σ'_v) evaluated at the mid depth of the sand layer are almost identical for the two pile materials, as shown in Figures 4 and 6, respectively. For bored piles, results of the normalized side resistance show that the two types of pile materials also have almost the same values of side resistance, as shown in Figure 6. For the tip resistance, Figure 7 shows that the precast concrete pile has slightly more resistance than the timber pile.

Effect of Pile End Shape on Pile Resistance

Figures 4 through 7 show also the effect of pile tip (cone) angle on pile resistance constructed in loose sand. For driven piles, the results show that as the pile tip angle increases, the pile side and tip resistances increase. It can be seen from these figures that, for flat end pile, the resistance is almost 30-40% more than that of the 45^{o} tip angle pile. For bored piles, the results in Figures 6 and 7 show that there is almost no effect of pile tip angle on pile resistance.

Effect of Construction Method on Pile Resistance

The effect of pile construction method on pile resistance was also investigated. Figure 8 shows the normalized side resistance with the tip angle for both driven and bored piles constructed in loose sand. In this figure it can be seen that for bored piles, the normalized side resistance is not affected by the tip angle, and it has an average value of 0.53, while driven piles, the results show that the normalized side resistance increases with the tip angle and it is considerably higher than that of the bored pile. For 45^{o} tip angle, the driven pile has side resistance of almost four times than that of the bored pile. This deference in resistance is due to the effect of lateral sand densification due to pile driving. For the tip resistance, Figure 9 shows also that the tip resistance of the driven pile is higher than that of the bored pile, and the difference between them increases with the increase in the tip angle. This behavior of tip resistance is expected because some densification took place underneath the tip while driving is going on, especially for the flat end pile. The results show that the tip resistance of the flat end driven pile can be 3 times more than that of the flat end bored pile.

Sand Lateral Movement Due to Pile Driving

Results of pile driving show that the sand lateral displacement decreases as the distance from the pile side increases. Figure 10 shows that for loose sand the lateral displacement started even before the pile tip reached the level of the measuring LVDTs, and the displacement leveled out after the pile tip passed the LVDTs' level. In a way to find the effective horizontal distance of sand lateral displacement, the results of lateral displacement were presented normalized to the pile diameter, as shown in Figure 11. In this figure it can be seen that the lateral sand displacement is effective within a zone extended almost three times the pile diameter from the pile centerline, and the extent of this zone decreases as the sand relative density decreases.

Sand Relative Density and Pile Resistance

Attempts were made to investigate the effect of sand relative density on pile side and tip resistances. Figure 12 shows the relationship between the sand initial relative density before driving and the ratio of side resistance to the total resistance of the tested piles. In this figure it can be seen that as the sand initial relative density increases, the resistance ratio linearly decreases. Figure 13 shows the normalized side resistance with the sand initial density for both driven and bored piles. In this figure it can be seen that the normalized side resistance of both piles increases linearly with the increase in sand initial relative density with a slope for driven pile higher than that of the bored one. For the tip resistance, Figure 14 shows that the normalized tip resistance of driven piles increases with the increase in sand initial density and the relationship is almost parabolic in shape.

To investigate the effect of sand lateral densification for different initial relative sand densities (D_r) on the change of pile side resistance, the change in relative density due to pile driving was evaluated based on the results of Figure 11, which shows the effective densification zone around the pile. As can be seen in Figure 15, the effect of sand densification due to pile driving presented as a change in the normalized pile side resistance ($\Delta fs/\sigma'_v$) decreases linearly with the increase in the normalized change in sand relative density ($\Delta D_r/D_r$).

Effect of Sand Properties and Initial Void Ratio on Pile Resistance

Attempts were made to investigate the effect of sand type and initial void ratio on pile side and tip resistances. Figures 16 and 17 show that when the sand resistances are correlated with sand relative density, sand-2 (almost have well gradation) has normalized side and tip resistances higher than that of sand-1 (uniform gradation) at the same relative density.

When the results of sand resistance correlated with the sand initial density, the results show that there are good relations between the resistance and initial void ratio as can be seen in Figures 18 and 19. In these figures it can be seen that the normalized side resistance decreases exponentially with the void ratio with correlation coefficient, R^2 of 0.95, while the normalized tip resistance decreases also exponentially with the void ration with correlation coefficient, R^2 of 0.90.

CONCLUSIONS

This study attempted to evaluate short pile resistance due to the change in sand relative density due to pile driving. The work considered different sands, pile materials, and pile tip angles. To get the tip and side resistances, piles inside sleeves were tested for driven and bored conditions at different sand relative density. Extensometers with LVDTs were used to get an idea about the sand relative lateral movement during pile driving. The conclusions drawn from this study are as follows:

- Timber piles and precast concrete pile have almost the same unit side and tip resistances.
- Pile tip angle has an effect on the side and tip resistances of driven piles, while for bored piles the tip angle has almost no effect.
- Most of sand lateral movement due to pile driving is effective within a zone extended almost three times the pile diameter from the pile centerline. As the sand initial density increases, the extent of the effective zone increases.
- As the relative density of the sand increases, the ratio of side resistance to the total pile resistance decreases. It was found that the average normalized unit side resistance of both driven and bored piles increases linearly with the increase in sand initial relative density
- It was found that the normalized change in pile side resistance due to the change in sand relative density due to pile driving decreases with the increase in the percentage change in the sand relative density.
- The initial void ratio of the sand was found to be a key factor that affects the pile side and tip resistances. As the initial void ratio decreases, both side and tip resistances increases. The current study founded very good correlations between pile resistance and the sand initial void ratio.

ACKNOWLEDGEMENTS

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APPENDICES

Table 1: Properties and Classification of the Used Sands

Property	Sand-1	Sand-2
Gradation C_u C_c	 2.6 0.78	 5.1 2.1
Specific Gravity, Gs	2.67	2.66
Void ratios e_{max} e_{min}	 0.92 0.50	 0.58 0.37
Angle of friction, ϕ' (Direct Shear) Loose Dense	 38^o 42^o	 40^o 46^o
Classification (USCS)	SP	SP

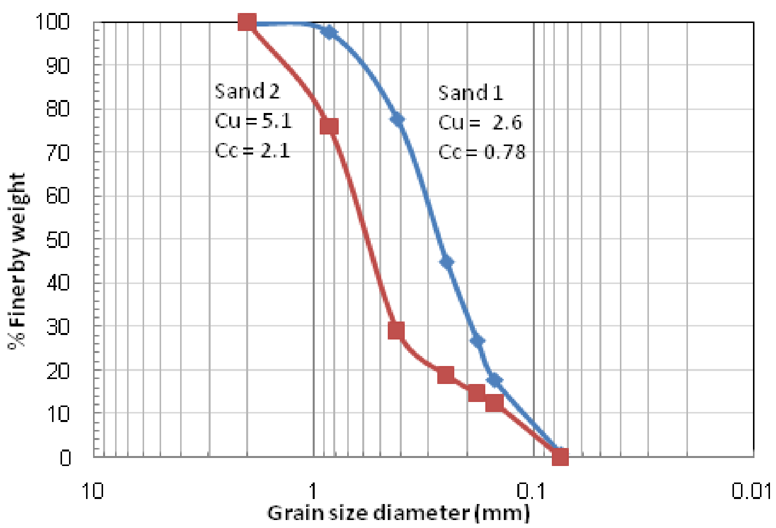
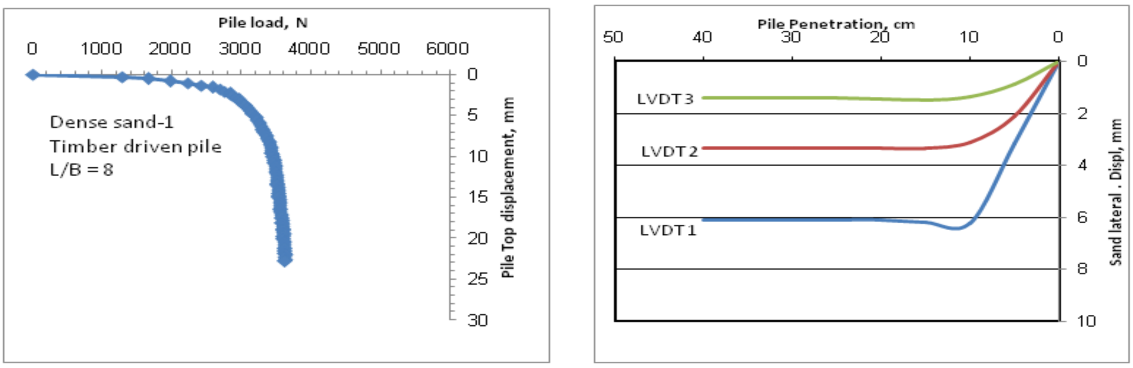


Figure 1: Grain Size Distribution of the Tested Sands

Figure 2: Pile inside the Sand Box for Testing



a) **b)**

Figure 3: a) Pile Load Deformation and b) Sand Lateral Displacement of Driven Timber Pile

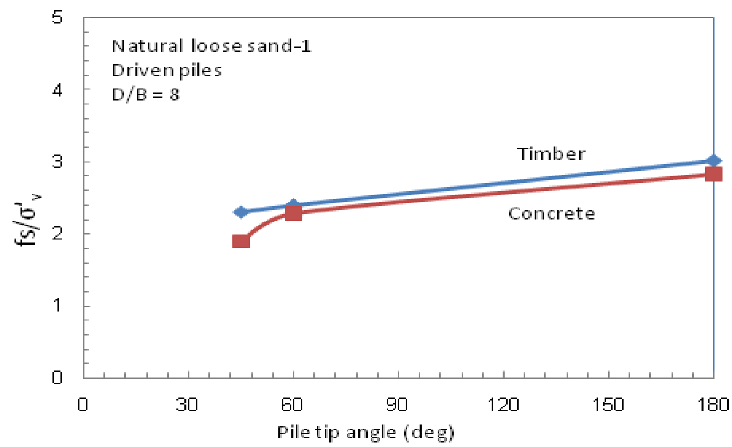


Figure 4: Normalized Unit Side Resistance with Tip Angle for Driven Timber and Concrete Piles (Sand-1, Loose Condition)

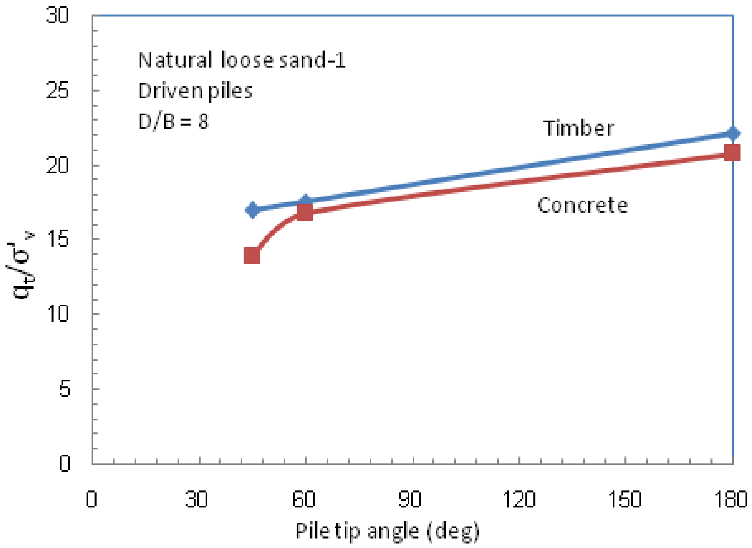


Figure 5: Normalized Unit Tip Resistance with Tip Angle for Driven Timber and Concrete Piles (Sand-1, Loose Condition)

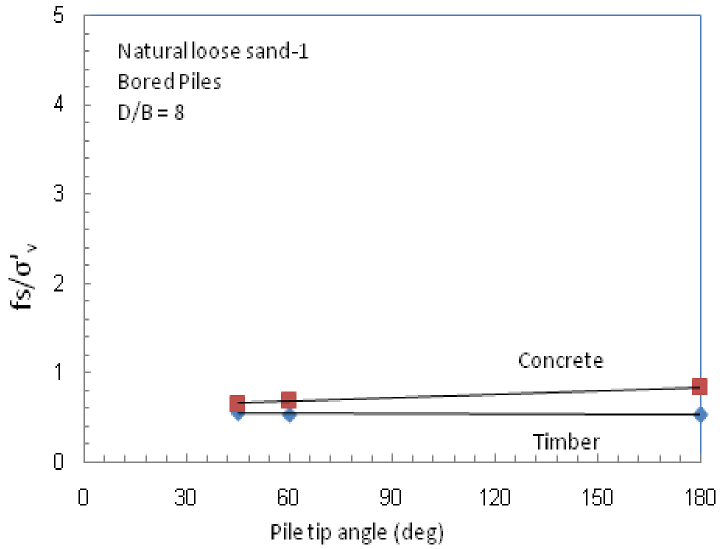


Figure 6: Normalized Unit Side Resistance with Tip Angle for Bored Timber and Concrete Piles (Sand-1, Loose Condition)

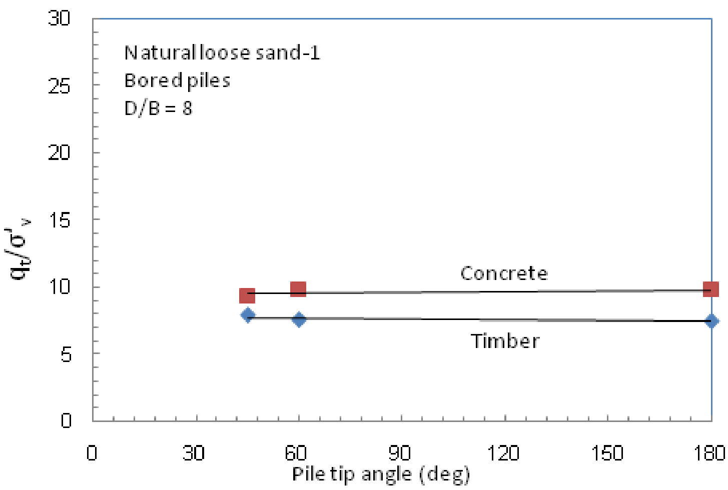


Figure 7: Normalized Unit Tip Resistance with Tip Angle for Bored Timber and Concrete Piles (Sand-1, Loose Condition)

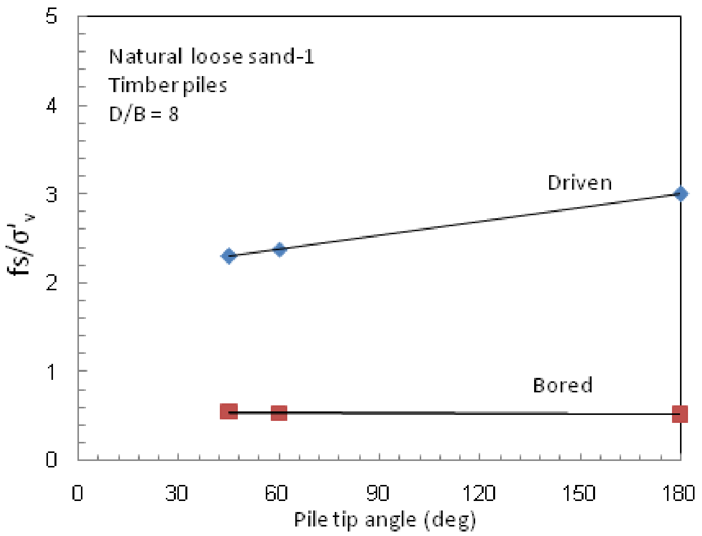


Figure 8: Normalized Unit Side Resistance with Tip Angle for Driven and Bored Timber Piles (Sand-1, Loose Condition)

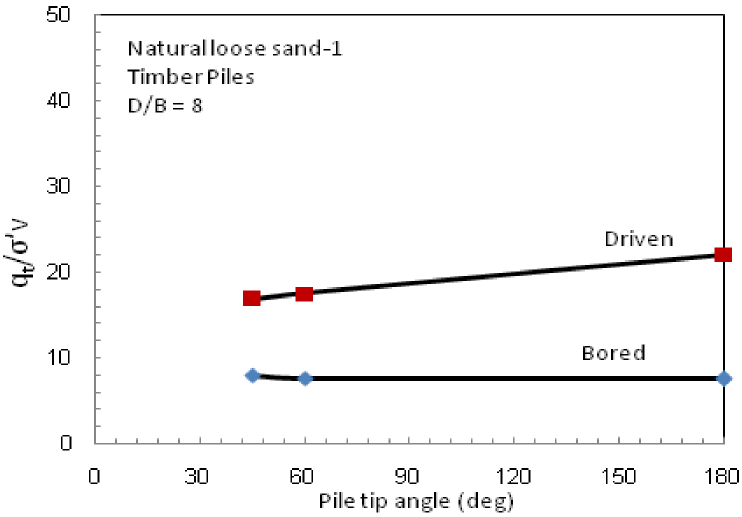


Figure 9: Normalized Unit Tip Resistance with Tip Angle for Driven and Bored Timber Piles (Sand-1, Loose Condition)

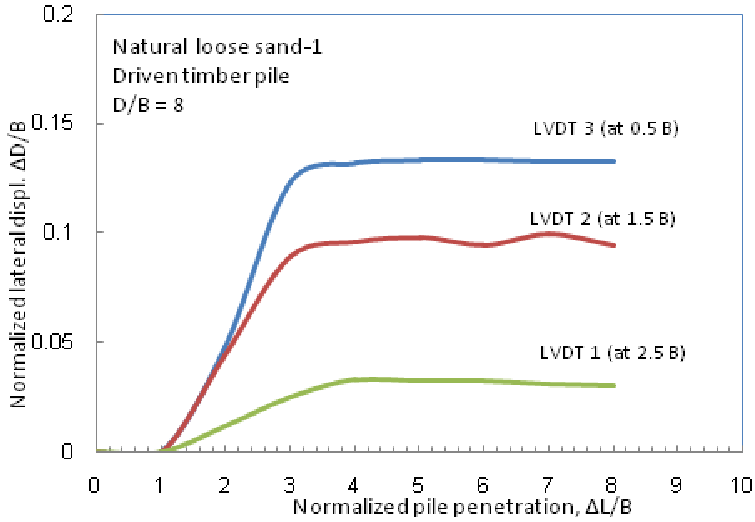


Figure 10: Normalized Lateral Displacement with Normalized Pile Penetration for Driven Timber Pile (Sand-1, Loose Condition)

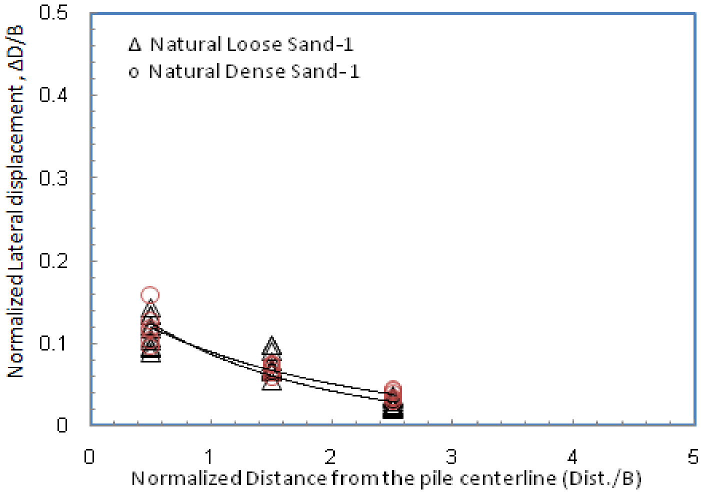


Figure 11: Normalized Sand Lateral Displacement with Normalized Distance from the Pile Centerline. (Sand-1, Loose Condition)

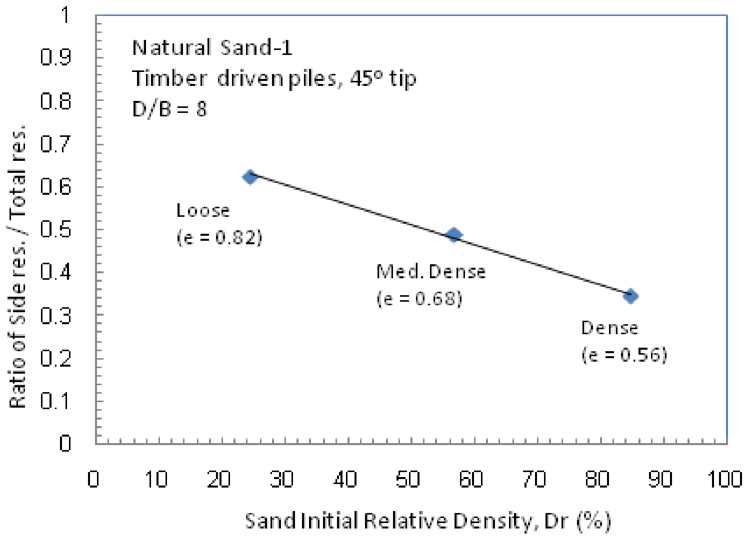


Figure 12: Ratio of Unit Side Resistance to Total Resistance with Sand Initial Relative Density of Driven Timber Piles (Sand-1)

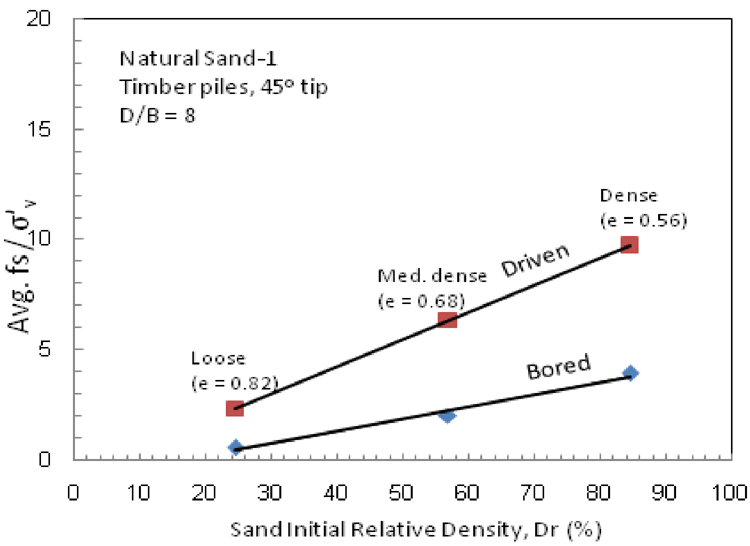


Figure 13: Normalized Unit Side Resistance with Sand Initial Relative Density of Driven and Bored Timber Piles (Sand-1)

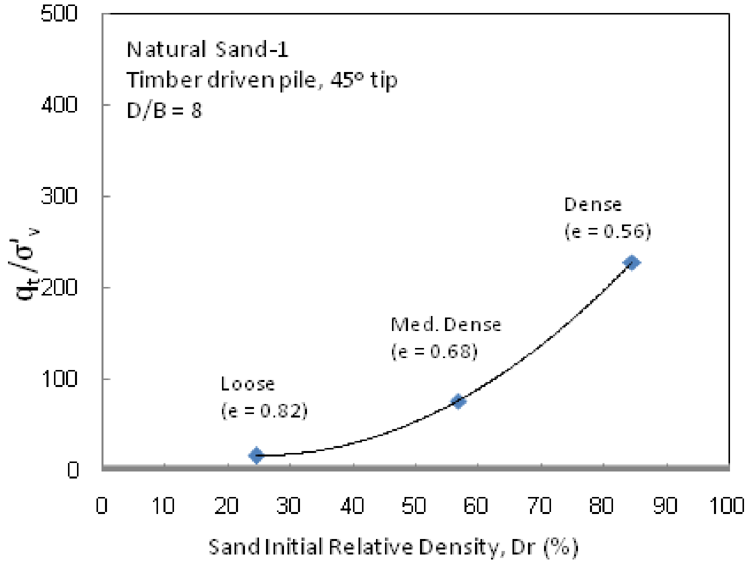


Figure 14: Normalized Unit Tip Resistance with Sand Initial Relative Density of Driven Timber Piles (Sand-1)

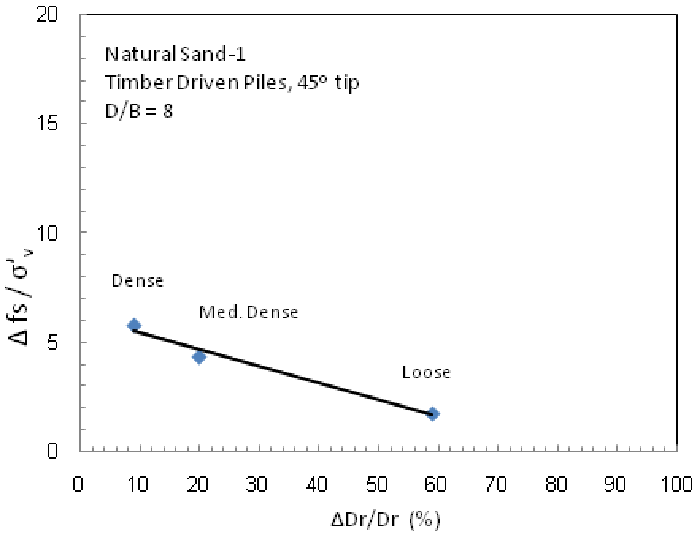


Figure 15: Normalized Change in Unit Side Resistance and Percentage Change in Sand Relative Density of Driven Timber Piles (Sand-1)

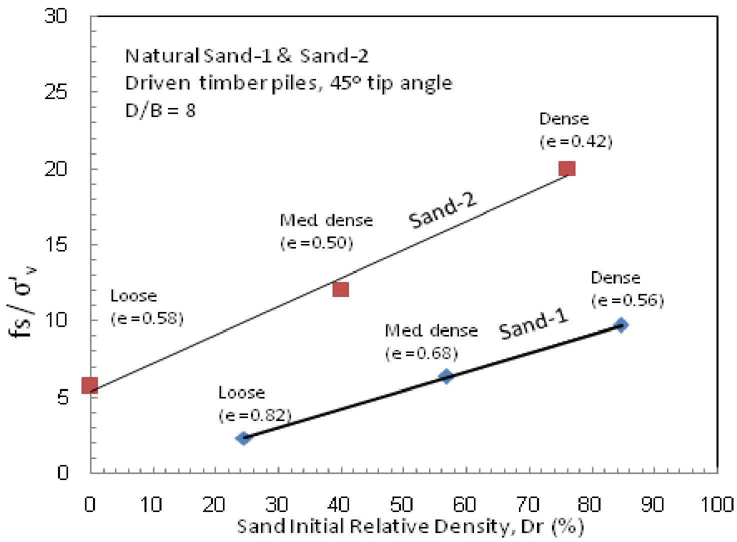


Figure 16: Normalized Unit Side Resistance with Sand Initial Relative Density of Driven Timber Piles (Sand-1& Sand-2)

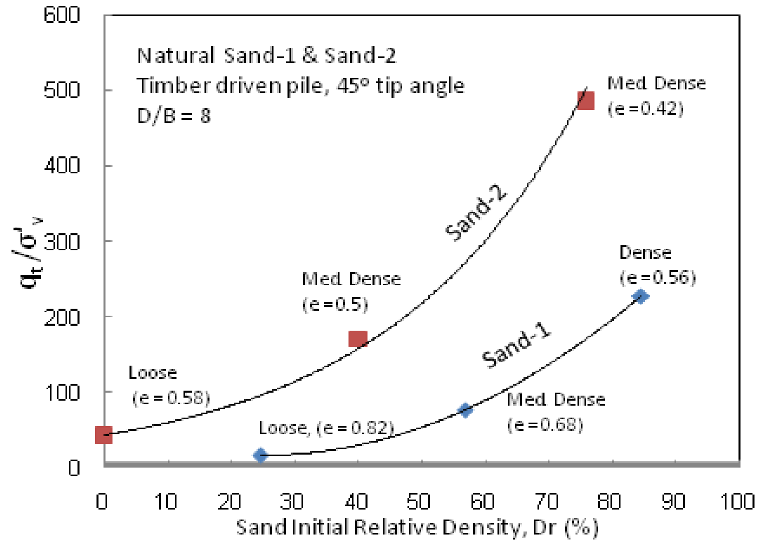


Figure 17: Normalized Unit Tip Resistance with Sand Initial Relative Density of Driven Timber Piles (Sand-1 & Sand-2)

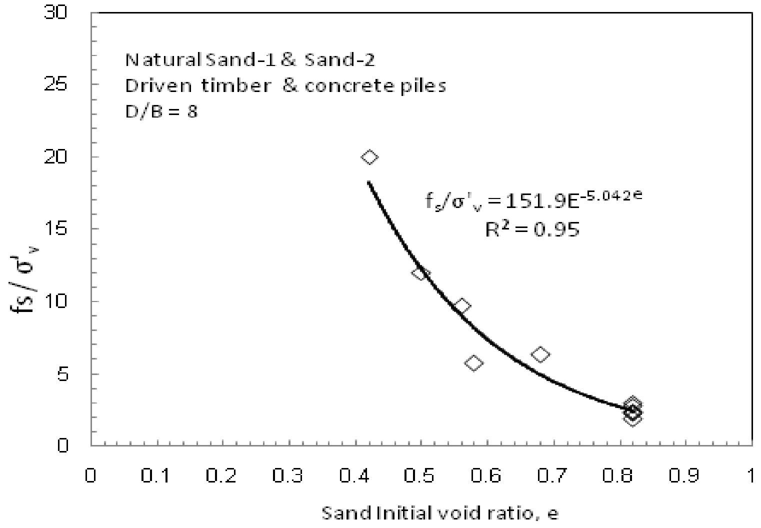


Figure 18: Normalized Unit Side Resistance with Sand Initial Void Ratio of Driven Piles (Sand-1& Sand-2)

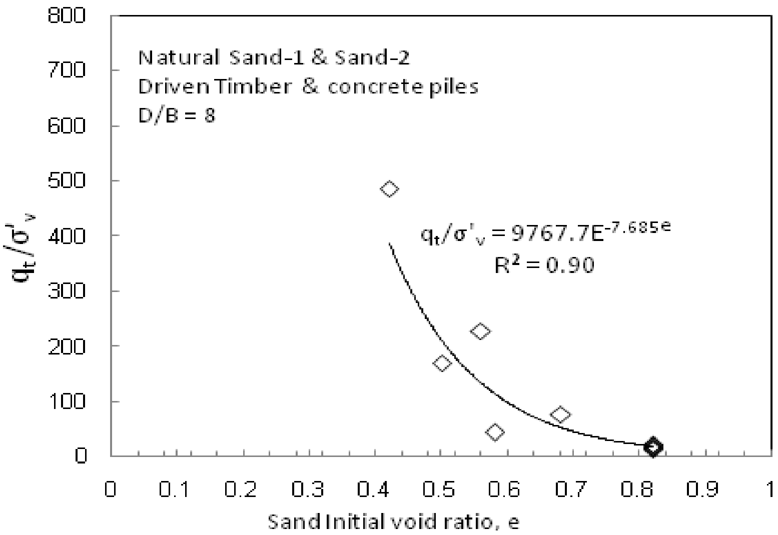


Figure 19: Normalized Unit Tip Resistance with Sand Initial Void Ration of Driven Piles (Sand-1 & Sand-2)