EFFECTS OF PILE INSTALLATION METHOD ON UPLIFT CAPACITY OF PILES IN SAND

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ABSTRACT. An experimental program using large-scale model piles (embedded length of about 2 m and a diameter of 89 mm) in a large sand test pit was conducted to study the load capacity and displacement under uplift loads. The piles were installed by three methods in the test pit: driving, jacking, and a reference undisturbed method. The sand bed was prepared either in a loose or a dense state. Over thirty tests were conducted and the experimental results were analyzed statistically. The results indicate that initial sand density and method of pile installation is the first and the second most significant factor affecting uplift capacity, respectively. Methods that tend to disturb the sand most result in lower uplift capacity (as low as 50%). The pile head displacement at the ultimate uplift load is in the range of 5 to 12.5 mm and primarily dependent on method of pile installation.

1. INTRODUCTION

Shaft resistance is a major design factor for piles supporting structures subject to significant uplift forces such as transmission towers, harbor structures, and offshore platforms and for anchor piles. The increasing use of pile foundations in offshore and harbor structures has drawn attention to the need for more reliable methods of evaluating shaft resistance of such piles and necessitated accurate assessment of uplift resistance. The behavior of pile shaft under uplift loading has not yet been completely understood [1,2]. Many factors affect its behavior, some of them are related to the characteristics of the pile itself such as type, surface roughness, length and diameter [3,1], others are related to the properties of the soil around it such as strength, deformability, and density [4,5]. Also, the way in which the pile is installed in the soil [6,4,7] and loaded [8] affects its behavior.

The limited information on the effects of pile installation techniques on the shaft resistance of piles indicated that the placement methods have a significant influence on the uplift capacity of piles. This paper presents the results of an experimental study of the effect of pile installation on the uplift resistance of single large-scale model piles in sand subjected to axial loading.

2. EFFECTS OF PILE INSTALLATION

The effects of pile installation are many and not well quantified. The most significant ones are related to the disturbance of the soil structure and the changing of the stresses in the soil mass. The effects of installation are difficult to predict by analytical methods due to the complex phenomenon of soil-pile interaction. Load tests are helpful in estimating pile capacity as well as studying the effects of installation techniques.

Pile installation disturbs the surrounding soil and changes the stress state characterizing the soil in its virgin state. The normal stress on the pile wall (horizontal stress) changes from its initial value to another value at the end of installation. When the pile penetrates into the soil, the soil is compressed, deformed and pushed laterally aside. Closed-end cylindrical piles displace a volume of soil equal to the volume of the pile while open-end pipe piles displace a volume of soil equal to the volume of steel before plugging occurs and may reach that of the closed-end piles when plugging occurs. The soil in the path of the installed pile is brutally

displaced by the advancing pile tip and forced to occupy a zone immediately around the pile shaft. In loose cohesionless deposits, driven piles may cause considerably more soil densification than jacked piles and the degree of densification will depend on the type of hammer used and on the magnitude and frequency of driving strokes. The soil densification is most pronounced in the vicinity of the pile shaft. However, previous investigators [9] showed that the process of sand displacement and compaction below a pile tip is followed by sand movements adjacent to the pile. These movements tend to decrease density in the immediate vicinity of the sides and thus nullify some of the benefits gained by the primary compaction. For dense conditions, loosening may take place in some zones, along with substantial grain crushing and densification in the immediate vicinity of the pile [4].

2.1 Previous Experimental Work

There is relatively little quantitative information on the effects of pile installation on shaft resistance of piles. The limited test data show that the installation method can influence pile behavior [10]. McClelland [6] performed full-scale tests (four piles with 1.25 meter diameter and 14.60 meter embedded length) for studying the effects of installation methods on the uplift capacity of piles in sand. The piles were installed by different procedure (driving alone, driving and jetting, jetting alone). He found that the use of jetting with external return flow followed by driving reduced the ultimate shaft resistance by about 50%, while installation by jetting alone reduced the ultimate shaft resistance to only about 10% of the value for a pile installed by driving only.

Levacher and Sieffert [7] investigated the influences of pile installation on the behavior of steel piles in tension. The model piles had 35-mm outside diameter and 0.90-m embedded depth. The sand was placed into a vat of 750 mm diameter and 1.10 meter depth. The piles were installed by three different methods (bored, driven, and vibro-driven). Test results showed a wide variation in uplift capacity in sand due to the different pile installation techniques. They introduced a placement method coefficient K_{mo} in the equation that calculates the average shaft resistance during uplift loading:

$$f_s = \frac{1}{2} K_o \gamma L \tan \delta K_{mo} \qquad (1)$$

Based on the small-scale model test results, they concluded that the value of K_{mo} lies between 2 and 3. The value of K_{mo} equals to 2.4 for bored piles with relative density less than 0.5, and equals to 2.7 and 3.2 in the case of driven and vibro-driven piles, respectively. It was found that the average ratio of the ultimate pulling resistance of dynamically driven piles to ultimate resistance of statically jacked piles is 0.50 and the average ratio of the ultimate pulling resistance of vibro-driven piles to ultimate resistance of statically jacked piles is 0.67. Other data [11] show smaller lateral stresses on the shaft after installation for driven than pushed piles, suggesting lower shaft resistance for driven piles [10].

3. EXPERIMENTAL APPARATUS AND PROCEDURE

3.1 Test Pit and Loading Equipment

The large-scale model pile tests were conducted in a 3-m by 3-m by 3-m deep (27 cubic meter) test pit located in the Structures and Materials Testing Laboratory, University of Wisconsin-Madison. The test pit has an up-flowing water system which can fluidize the sand and allow it to deposit at a loose state. Subsequently, it can be densified to different densities using a spud vibrator. The test facility allows for rapid deposition and modification of the sand density without removing the sand from the test pit. At the top of the test pit are four equally spaced horizontal reaction beams (W 8 x 24) on which the loading equipment was placed. The test pit has lateral boundaries (the test pit width is about 34 pile diameter) that satisfy the criteria implied by the zone of influence determined from the elastic theory [14] as well as the influence zone found by other investigators [5,9,12,13]. Thus, it is expected that there is negligible boundary effects in this study.

The loading equipment consisted of an MTS hydraulic actuator with a maximum load of 245 kN. The hydraulic actuator piston rod has a stroke of 12.5 cm and can be driven by a function generator capable of driving the pile in load or stroke control in either static or cyclic

mode. A load cell and displacement transducer are mounted in the hydraulic actuator and were calibrated before performing the tests. The piles were pulled out by the hydraulic actuator at a constant rate of displacement (8.4 mm/min.). The readings for the pile movement and load were collected by the data acquisition system while pulling-out the pile. The experimental set up is shown in Figure 1.

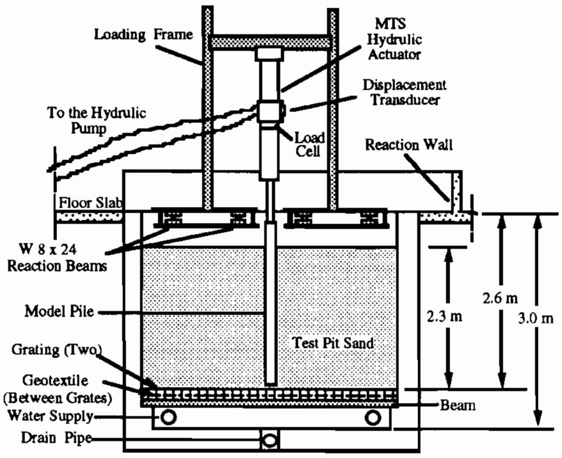

Figure 1: Model pile experimental set up

3.2 Properties of Sand

The soil in the pit is a medium-grained Portage sand designated as Granusil 4020. It is a uniformly graded quartz sand from Wisconsin River with rounded grains containing 99.7 percent silicon dioxide. It has a uniformity coefficient of 1.8 and an effective grain size of 0.216 mm. The sand has a maximum and a minimum density of 17.84 kN/m^3 and 15.52 kN/m^3, respectively and a specific gravity of 2.65 and permeability of 0.084 cm/sec and 0.208 cm/sec in the loose and dense conditions, respectively. The permeability permits liquefaction to occur within the limit of the flow rate that the test facility can generate. The sand has round grains which minimize the friction between the soil and the wall of the test pit. The sand bed was prepared by first fluidizing the sand with an upward flow of water and then letting it settle into loose deposit. For dense condition, the loose deposit was densified by vibration. Details are given elsewhere [15]. The density, uniformity and repeatability achieved after loosening or densifying the sand bed were checked by sand cone method for the near-surface and by a dilatometer with depth. From the results of the density and triaxial strength measurements, the density of the sand in the loose condition was 15.69 kN/m^3 (D_r= 9%) with a friction angle of 30.5°. The density of the sand in the dense condition was 17.45 kN/m^3 (D_r= 85%) with a friction angle of 39°.

3.3 Model Pile

The model pile used in this study was a steel pipe pile having an outside and inside diameters of 8.90-cm and 7.30-cm, respectively. It was 2.75 m long and had a 60° closed conical tip. It could be tested open-ended by removing the conical tip.

3.4 Test Parameters

The selected parameters for the experimental investigation are listed in Table 1. A single-size pipe pile was used in this study and only the uplift load and pile top displacement were monitored. The three methods of installation were chosen because they are the most practical methods that can be used in the available test pit. Undisturbed method represents a unique no-displacement reference state for pile installation. Driving method is dynamic while jacking method is quasi-static. The tests were performed in loose and dense conditions of the sand.

Table 1. Summary of test parameters and their values

A. Constant Parameters:	
- Test Apparatus:	- Test Pit (3 m x 3 m x 3 m)
- Sand Type:	- Portage Sand
- Model Pile:	- Steel Pipe Pile: 89.0 mm outside diameter, 8.0 mm wall thickness
- Loading Rate: (Quasi-static loading)	- 8.4 mm /min.
B. Variable Parameters:	
- Pile Installation Method:	- Undisturbed, Driving, Jacking
- Pile End-Type:	- Open-End & Closed-End
- Soil Density:	- Loose & Dense

3.5 Test Procedure

3.5.1 Undisturbed method (no-displacement installation) : The pile was placed in the test pit while the sand was fluidized by the upward flowing water prior to deposition. The pile was placed by its own weight by releasing it from the crane to the desired depth then turning the upward flowing water off and allowing the sand deposit around the pile. For the loose condition, the drainage valve was opened to let the water drain from the test pit. For the dense condition, and after the flowing water was turned off, the drainage valve was opened until the water level drained down to the surface of the sand, then it was closed. The soil was then densified. After finishing the densification, the drainage valve was opened allowing complete drainage of the water from the test pit.

3.5.2 Jacking method (quasi-static displacement installation) : The pile was pushed into the sand 12.5 cm at a time (the maximum stroke distance) by means of the MTS hydraulic actuator . After the pile had reached the final penetration depth, the total jacking load was recorded for each test.

3.5.3 Driving method (dynamic displacement installation) : The pile was driven into the soil by a hammer weighing 512 N and falling from a height of 30 cm. The driving was achieved by the traditional rope and pulley arrangement. The hammer was lifted by the rope wrapped on a cathead attached to a motor and allowed to fall onto the pile head. The total blow count to drive the pile to the final penetration depth was recorded for each test.

4. EXPERIMENTAL RESULTS

A total of 31 pile pullout tests were performed for 12 combinations of the indicated levels of the three variables listed in Table 1. A minimum of two replicate tests were performed for each combination; however, in some cases 3 or 4 replicate tests were performed. Typically, the difference between the maximum and the minimum shaft resistance per unit embedded surface area from the replicate tests was less than 10% of the average of the replicates. The driven piles however showed a greater range of variability between the replicates. Table 2 shows the values of the measured quantities during the pile pullout tests (the maximum uplift load and the corresponding pile displacement) as well as the calculated unit shaft resistance for the piles placed by the undisturbed method. Typical load-displacement curves are shown in Figure 2. Table 3 shows the corresponding data for the piles placed by jacking with the typical load-displacement curves in Figure 3. Finally, Table 4 shows the data for the piles placed by driving with the typical load-displacement curves in Figure 4.

It can be seen from Tables 3 and 4 that the average unit shaft resistance {($f_s = Q_{net}/ A_s$), where Q_{net} is the net uplift load (uplift load at failure minus the weight of the pile) and A_s is the embedded surface area of the pile} for piles placed by static jacking is higher than those driven by dynamic impact both for the loose and the dense sand. This is in agreement with the findings of Levacher and Sieffert [7].

Table 2. Test results for piles placed by undisturbed method

Soil Density	End Type	Test #	Uplift Load (kN)	Displa-cement (mm)	Embed. Length (m)	Plug Length (m)	Unit Shaft Resistance (kN/m^2)
Loose	Open	TO1	2.94	3.30	1.54	1.22	5.72
		TO2	3.06	5.08	1.65	1.03	5.72
		TO3	3.01	6.35	1.65	0.97	5.58
		TO4	2.95	5.08	1.67	1.27	5.31
	Closed	TC1	3.11	4.06	1.54	-----	6.27
		TC2	3.21	4.57	1.65	-----	6.14
		TC3	3.11	3.56	1.54	-----	6.27
		TC4	2.92	4.06	1.63	-----	5.52
Dense	Open	TO5	10.88	5.08	1.51	1.24	24.75
		TO6	10.98	5.59	1.51	1.01	24.96
	Closed	TC5	11.80	4.57	1.51	------	27.10
		TC6	12.85	5.84	1.48	------	30.13

Table 3. Test results for piles placed by jacking

Soil Density	End Type	Test #	Uplift Load (kN)	Displa-cement (mm)	Embed. Length (m)	Plug Length (m)	Unit Shaft Resistance (kN/m^2)
Loose	Open	TO7	2.76	7.50	1.70	0.32	4.96
		TO8	2.47	10.0	1.65	0.32	4.48
		TO9	2.48	10.0	1.65	0.35	4.48
	Closed	TC7	2.10	10.0	1.70	-----	3.60
		TC8	2.07	10.0	1.70	-----	3.52
		TC9	2.08	8.0	1.65	-----	3.65
Dense	Open	TO10	11.20	7.50	1.58	0.32	24.40
		TO11	11.70	9.0	1.52	0.34	26.48
	Closed	TC10	14.90	10.0	1.65	------	31.58
		TC11	13.48	10.0	1.52	------	30.75

Table 4. Test results for piles placed by driving

Soil Density	End Type	Test #	Uplift Load (kN)	Displa-cement (mm)	Embed. Length (m)	Plug Length (m)	Unit Shaft Resistance (kN/m^2)
Loose	Open	TO12	2.05	12.7	1.65	0.72	3.52
		TO13	1.78	12.7	1.65	0.68	2.90
	Closed	TC12	1.91	12.7	1.65	-----	3.31
		TC13	2.00	12.7	1.70	-----	3.38
Dense	Open	TO14	6.47	12.7	1.65	1.02	13.03
		TO15	5.06	12.7	1.52	0.90	10.83
		TO16	7.08	12.7	1.65	0.97	14.41
	Closed	TC14	6.29	12.7	1.65	------	12.82
		TC15	6.29	12.7	1.65	------	12.82

It can be seen from Figures 2,3, and 4 that the shapes of the load-displacement curves for the two pile-end conditions (open-end and closed-end) are very similar. This observation was true for each method of installation [15]. There was a more apparent peak response in some cases than others irrespective of the end condition, i.e., closed or open. The observed peak behavior was consistent with the degree of disturbance expected in each method of installation. The presence and degree of peak behavior observed in the load-displacement curves indicate that driving causes the greatest disturbance to the surrounding soil. Jacking appears to cause

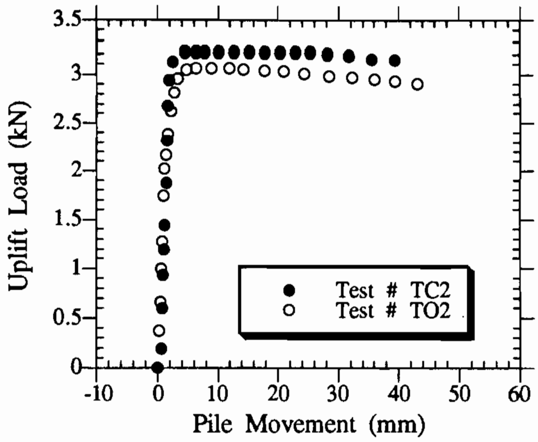

Figure 2 : Load-Displacement curves (undisturbed-loose sand)

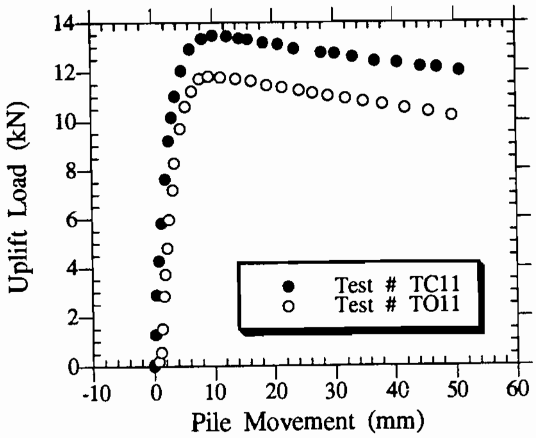

Figure 3 : Load-Displacement curves (jacked-dense sand)

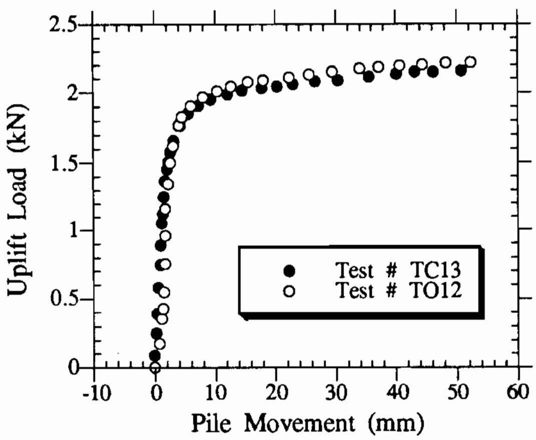

Figure 4 : Load-Displacement curves (driven-loose sand)

some disturbance compared to the reference method of undisturbed placement. Peak behavior is more prominent in the dense condition as would be expected. The displacement at failure increases from the undisturbed to jacked to driven piles, again with increasing expected disturbance during installation. These values are consistent with the values reported in the literature, ranging from 5 to 15 mm [16] and from 6 to 10 mm [4]. The driving method did not show a maximum value of uplift load, therefore it was decided to use the load at 12.7 mm as the failure load as proposed by Kulhawy and Hirany [17] after they examined the available interpretation methods for the uplift tests of piles.

5. STATISTICAL ANALYSIS OF TEST RESULTS

The test results were analyzed by the statistical package (SAS). The statistical analysis was performed for the three variables (listed in Table 1) in three different ways: all test data, test data for the loose sand condition, and test data for the dense sand condition. The statistical analysis of the unit shaft resistance is presented below. Details are given elsewhere [15].

5.1 All Test Data

The failure uplift load was taken as the maximum (peak) uplift load in both undisturbed and jacking methods, whereas in driving method, where there was no peak, failure load was taken as the load at 12.7 mm of pile displacement. The *F*-statistic indicated that there were significant differences in the means of the 12 test combinations performed. The resulting Type IV analysis of variance is summarized in Table 5 with the importance rating of the factors is given in descending order (the most significant factor is the first).

Table 5. Type IV analysis of variance

Source of Variation	Degree of Freedom	*F*-value	*P*-value
1. Density	1	3129.01	0.0001
2. Installation	2	269.41	0.0001
3. Installation x Density *	2	176.59	0.0001
4. Density x End type *	1	26.14	0.0001
5. End type	1	21.77	0.0002
6. Installation x Density x End type *	2	8.80	0.0020
7. Installation x End type *	2	4.52	0.0248

* Interaction (combination) between factors.

5.2 Loose Condition Data

The *F*-statistic indicated again that there were significant differences in the means of the 6 test combinations performed. The resulting Type IV analysis of variance is summarized in Table 6. The importance rating of the factors is given in descending order:
1.Method of installation. 2.Combination of method of installation and pile-end type.

5.3 Dense Condition Data

The *F*-statistic indicated that there were significant differences in the means of the 6 test combinations performed. The resulting Type IV analysis of variance is summarized in Table 6. The importance rating of the factors is given in descending order:
1.Method of installation. 2.Pile-end type.

Table 6. Type IV analysis of variance for loose and dense condition data

	Loose Condition Data			Dense Condition Data		
Source of Variation	Degree of Freedom	*F*-value	*P*-value	Degree of Freedom	*F*-value	*P*-value
End type	1	1.24	**0.287** **	1	16.51	0.0048
Installation	2	140.98	0.0001	2	168.19	0.0001
Installation x End type *	2	14.86	0.0006	2	4.69	**0.051** **

* Interaction (combination) between factors

** Bold means that the value of $p > 0.05$ (not significant).

The analysis of both loose and dense data indicates that pile installation method is the most significant factor which affects the unit shaft resistance in both loose and dense sand.

6. SUMMARY AND CONCLUSIONS

In this study 31 pile pullout tests were conducted using both open and closed-end model piles in both the loose and dense initial conditions of the sand. The model piles were installed in the sand by three different methods (undisturbed, jacking, and driving). The test results were analyzed by the statistical package (SAS). The following conclusions are made with respect to the effect of pile installation method:

1. Method of pile installation is the second most significant factor (after the initial sand density) affecting uplift capacity. Installation methods which causes less disturbance give higher uplift capacity (undisturbed > jacking > driving).

2.The average unit shaft resistance of driven piles is about 52% of the piles placed by the undisturbed method both in loose and dense sand. The average unit shaft resistance of jacked piles is about 70% of the piles placed by the undisturbed method in loose sand; however, it is about the same as the undisturbed in dense sand.

3.The displacement needed to mobilize the ultimate uplift load (shaft resistance capacity) are consistent with the values reported in the literature. The displacements are about 5.0 mm for undisturbed method and about 9.25 mm for jacked piles. Driven piles do not show a peak values in their load-displacement curves in dense or loose sand due to placement disturbance of the initial sand structure.

4. Method of pile installation is the main factor which affects displacement at failure whereas initial sand density and pile-end type have negligible influence.

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