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Influence of end geometry on aged behavior of segmental jacked pipe piles in clay

A.J. Lutenegger
University of Massachusetts, Amherst, USA

ABSTRACT: Small diameter segmental jacked pipe piles are one option for underpinning lightly structures to reduce settlement and restore the structure. Short sections of steel pipe are jacked into the ground through poor soils to achieve the desired load capacity from end bearing on a firm layer using the mass of the structure as the reaction. At the present there are few design guidelines available for jacked piles. A study was conducted to evaluate the influence of end configuration on the installation jacking force and load behavior on jacked segmental pipe piles in clay. Piles with diameters of 73 mm and 89 mm were used. During installation the jacking force was measured to relate jacking force to load capacity. Compression tests were conducted one day after installation to determine short-term axial capacity and then repeated on over a period of 10 days to 750 days to evaluate aging behavior.

1 INTRODUCTION

Underpinning of distressed structures often requires an innovative approach so that the structure can be economically restored to a serviceable state. In the 1890's, Breuchaud developed an underpinning system using sections of steel pipe jacked into the ground using a hydraulic jack and the existing structure as reaction. The system was used extensively in New York to underpin large buildings during construction of the subway system. This system is still used today to underpin light and medium loaded structures, such as residential and light commercial buildings. In many cases there is little to no design performed prior to installation. The selection of pile size, length and number is usually left to the installation contractor who essentially performs installation until the structure begins to lift. The load is then locked off.

Jacked piles have a number of advantages over other available underpinning systems. They are minimally intrusive, they are easy to handle, they can be installed in low headroom and directly adjacent to a structure, the required installation equipment is light-weight, a continuous measurement of jacking force can be obtained. In fact, a jacked pile is the only foundation element that can provide a direct measurement of the axial compression capacity, although the installation force is an instantaneous measurement and may not be equal to the long-term capacity. Generally the installation force is lower than the aged ultimate capacity and therefore is a conservative value.

Steel pipe pile sections are typically installed open ended and internal sleeves are used between sections to give a flush external connection, although in some cases an external sleeve can also be used. Often contactors attach an oversized donut ring to the tip of the lead pile section to reduce the required installation force. The piles can be installed as end bearing elements if oversized couplings or an oversized end is used and the pile is installed until a firm bearing strata is reached to support the required load. If an external flush connection is used and no oversized end ring is used, the pile acts as a side resistance element, with only a nominal end bearing component.

In the current work described in this paper a set of segmental jacked pipe piles were installed and load tested in axial compression to evaluate: 1) any relationship between installation jacking force and load capacity; 2) aging behavior; and 3) influence of pipe tip geometry on both load capacity and aging. The piles described in this paper are a subset of a larger number of jacked piles installed at the test site used.

2 TEST PROGRAM

Tests were performed at a well characterized research site adjacent to the University of Massachusetts, Amherst, Ma. Concrete bridge piers from a previous research project were used as reaction to advance the piles and during load testing. Two different diameter steel pipe piles were installed and tested having

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Table 1. Summary of Piles Tested.

Set	Pile No.	O.D. (mm)	L (m)	End
1	P-1	73	7.3	Ring
1	P-2	73	7.3	Flat
1	P-3	73	7.3	Cone
1	P-6	89	7.3	Ring
1	P-7	89	7.3	Flat
2	P-10	73	3	Ring
2	P-13	73	3	Flat
2	P-12	73	3	Cone

O.D. of 73 mm and 89 mm and wall thickness of 6.3 mm. These sizes represent common commercial size piles used for underpinning. Pile sections were equipped with internal sleeves between sections so that the external surface was flush. The initial set of piles had an embedded length of 7.3 m. A second set of piles was installed and had a length of 3 m to be embedded only in the upper overconsolidated fill and crust. Lengths were chosen to give a range of load capacity to compare with installation forces.

End configurations consisted of: 1) an open end fitted with an oversized steel donut ring "friction reducer"; 2) a closed end using either a flush welded flat steel plate; and 3) a closed end with a flush welded steel cone tip with a 60° apex (similar to a CPT). The oversized donut end ring used on the 73 mm piles had an O.D. of 89 mm and an I.D. of 64 mm giving a slight relief on the inside. The donut end ring used on the 89 mm pile had an O.D. of 105 mm and an I. D. of 80 mm also giving a slight relief on the inside. Flat ends and cone ends were used to investigate whether the end configuration influence the capacity since the piles are dominated by side resistance because of the large length/diameter ratios. Table 1 gives a summary of the piles described in this paper.

3 SITE GEOTECHNICS

Tests were performed at the Geotechnical Experimentation Site located at the University of Massachusetts – Amherst. The soils consist of approximately 1.5 m of stiff silty-clay overconsolidated fill overlying a thick deposit of lacustrine varved clay which extends to a depth of about 25 m. This deposit is locally known as Connecticut Valley Varved Clay (CVVC) and is a lacustrine deposit composed of alternating layers of silt and clay as a result of deposition into glacial Lake Hitchcock. At the location of the test piles, the fill consists of CVVC placed about 40 years ago after excavations at the Town of Amherst Wastewater Treatment Plant, adjacent to the site. Below the clay fill, the CVVC has a well-developed stiff overconsolidated crust that grades into near normally consolidated clay at about 5 m. The site has been previously used for other field studies (Lutenegger 2008, 2009). Figure 1 shows typical piezocone (CPTU-Type 2) results obtained in the upper 10 m. Tests were stated at a depth of 1 m in a small prebored hole filled with water to insure saturation of the porous element. These results show the upper 1.5 m of clay fill, the original surface of the overconsolidated CVVC crust and the transition to softer, near normally consolidated CVVC at around 4.8 m. Below 4.8 m the clay is very soft. Results of field vane tests performed at the site show that the sensitivity of the clay is on the order of 4 to 6.

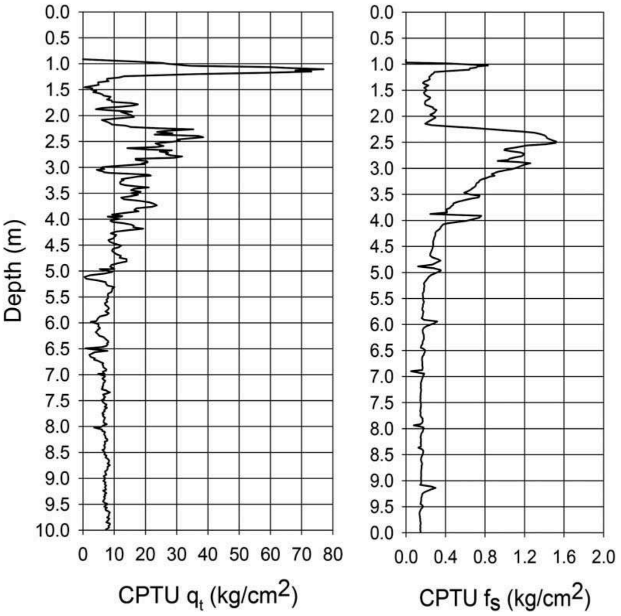

Figure 1. Results from CPTU profile at the test site.

4 PILE INSTALLATION

Piles were installed in 0.9 m sections using a specially fabricated jacking frame attached to the foundation of the piers using anchor bolts. The dead load of the pier and concrete footing provided the reaction for pile installation. The jacking force was measured using an in-line calibrated electronic load cell placed between the top of the pile and the hydraulic drive cylinder. An average jacking rate of approximately 0.15 m/min. was used. During installation, in addition to measuring the jacking force for each 0.15 m. of pile advance, measurements of the length of soil plug inside the open end piles were recorded after each pile extension section was advanced.

5 LOAD TESTS

Load tests were performed using the incremental maintained load method using the general procedures described in ASTM D1143-14 *Standard Test Method for Deep Foundations Under Static Axial Compressive Load.* Load was applied by a single acting hollow ram 250kN hydraulic jack placed on a small load frame attached to the concrete bridge pier. The load was measured using an electronic load cell placed over pile and was read using an electronic digital indicator. Deformation measurements were made using digital dial indicator attached to an independent reference beam. Loads were applied incrementally in the range of approximately 5 to 10% of the estimated ultimate capacity and held for 2.5 min. until a plunging behavior in which load could no longer be maintained was experienced. The plunging load was interpreted as the ultimate load capacity. Failure of most of the piles occurred in 30 to 45 minutes and therefore the results were interpreted as undrained behavior.

6 RESULTS

6.1 *Installation*

6.1.1 *Installation: Set-1 7.3 m flat closed end vs. open ring end*

Figure 2 shows results of the installation force profile for the two different pile sizes for the open pile with oversized end ring and flat closed end; Piles P-1, P-2, P-6 and P-7. As expected, the piles with the oversized ring showed lower installation force as compared to a flush closed flat end pile of the same diameter. The flush end pile accumulates side resistance along the outside of the pile as penetration proceeded. From measurements of the plug length taken inside the open piles during installation, both open end piles became fully plugged after about 6 diameters, despite the fact that the inside diameter of the end ring was slightly smaller than the inside diameter of the pile.

The installation force for the closed end piles consists of both side resistance and end bearing, while the installation force for the piles with oversized end rings largely consists of end bearing, especially after becoming plugged. However, even with an oversized end ring initially producing a small gap between the outside of the pile shaft and soil it is likely that some side resistance would develop along the pile shaft during installation as the soil "rolls" back onto the shaft. The soil along the sides of the pile would be remolded and not necessarily in full contact with the pile along the length. In the upper 2 m the penetration forces are similar.

The profiles of jacking force are similar is shape (but of course different magnitude) to both the CPTU cone tip resistance and sleeve resistance profiles shown in Figure 1 and show the buildup of jacking force through the upper overconsolidated zone and then the reduction as the pile tip passes into the lower softer clay. The piles with an oversized ring show a more pronounced difference in jacking force in the softer clay but show nearly the same behavior as the closed end piles in the upper stiff clay. The jacking force provides an indication of changes in soil layers just like the CPTU, even though the CPTU only reflects end bearing.

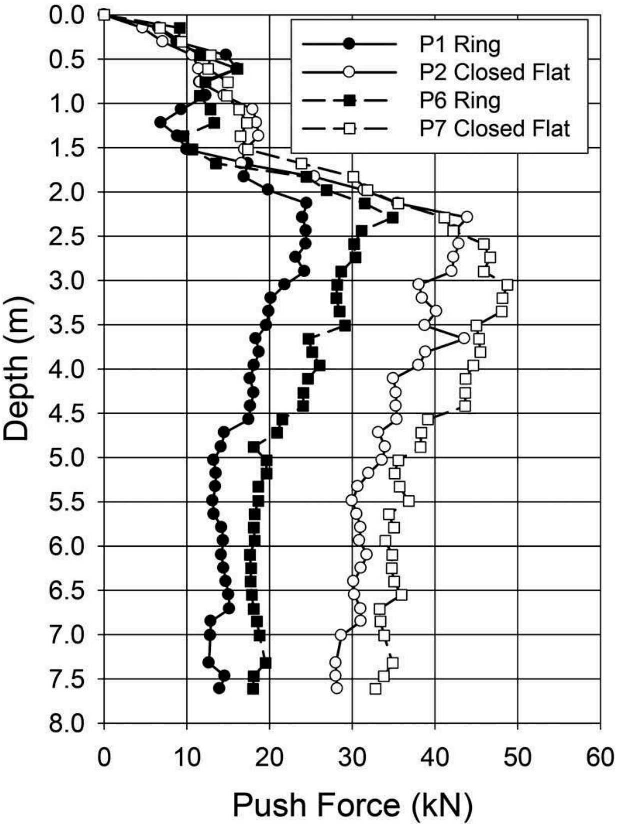

Figure 2. Measured jacking force for oversized ring and closed flat end piles.

6.1.2 *Installation: Set-1 7.3 m flat closed end vs. cone closed end*

Figure 3 shows a comparison of the jacking force measured during installation of the 73 mm piles with both a flush flat end and a flush 60° cone end; Piles P-2 and P-3. From these two tests it appears that there is a difference in the two piles. Most literature would generally suggest that the end bearing would be similar for both piles, which means that the difference in installation force might be attributed largely to a difference in side resistance created by the different geometry of the pile tips. There is actually very little information available on how the geometry of the pile tip might influence the side resistance in clays.

6.1.3 *Installation: Set-2 3 m flat closed end vs. open ring end*

Based on the observations of the jacking force obtained for the 7.3 m long piles with closed flat and cone ends, another set of 73 mm piles having closed flat and cone ends along with a pile with an oversized end ring was installed to a depth of just 3 m, fully embedded in the stiff overconsolidated zone, Piles P-10 and P-13. The jacking force profile is shown in Figure 4 which shows the substantial difference between the two piles.

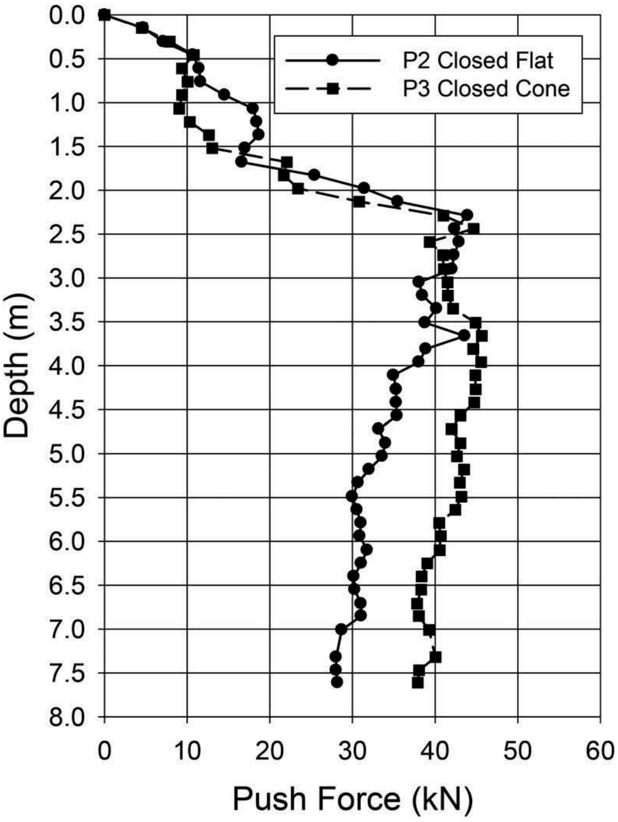

Figure 3. Measured jacking force for closed flat end and closed cone end piles.

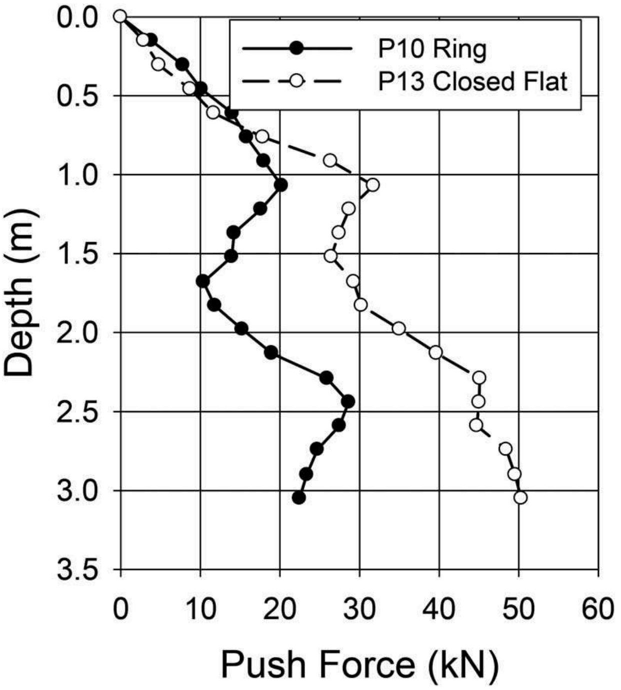

Figure 4. Measured jacking force for shallow oversized ring and closed flat end piles.

6.1.4 *Installation: Set-2 3 m flat closed end vs. cone closed end*

Results of the measured jacking force for the flat closed end and cone closed end for piles embedded to 3 m, Piles P-12 and P-13, are shown in Figure 5. These results show similar results to the longer piles, with the largest jacking force measured on the pile fitted with a cone.

A comparison of Figures 2 and 3 shows that as the piles pass through the heavily overconsolidated zone the jacking force on comparable size and end configuration piles decreases. This suggests that even though the pile is accumulating side resistance with increasing embedment length, the end bearing is decreasing rapidly so that the total jacking force is lower for piles embedded deeper in the softer clay than the shorter piles embedded fully within the overconsolidated soil. Table 2 gives a summary of the measured final jacking force for all piles.

6.2 *Load tests*

A summary of load tests for each of the piles at different ages after installation is given in Table 3. Ages of tests were not exactly the same for all piles

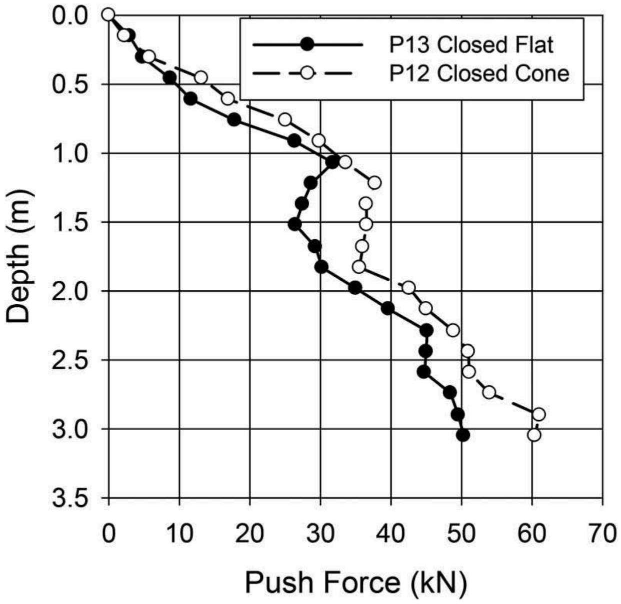

Figure 5. Measured jacking force for shallow closed flat end pile and closed cone end pile.

Table 2. Summary of final jacking force.

Set	Pile No.	Final Jacking Force (kN)
1	P-1	14.0
1	P-2	28.0
1	P-3	36.9
1	P-6	18.1
1	P-7	34.9
2	P-10	22.5
2	P-13	50.3
2	P-12	60.4

because of scheduling and weather, especially after about 100 days. In most cases, the piles exhibited plunging failure at very low displacements, typically on the order of 5 to 10 mm. Figure 6 shows typical results.

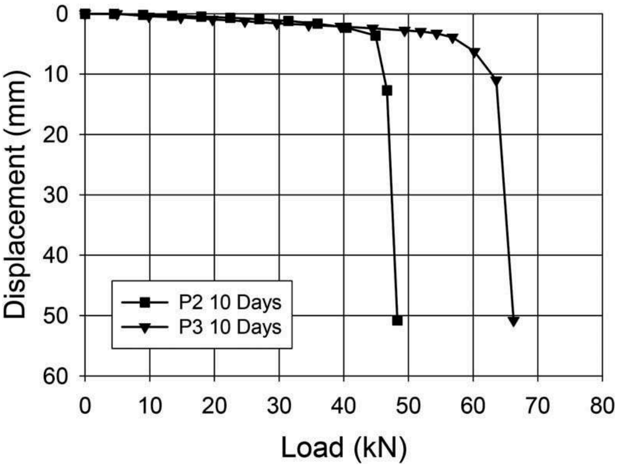

Figure 6. Typical load test results.

6.2.1 *Installation vs. load capacity*

Figure 7 shows a comparison between the measured final jacking force and the measured ultimate load capacity for the first load test conducted after 1 day. The 1 day capacity was selected simply for consistency and to illustrate the capacity that might be gained after just one day of rest. The results show a more-or-less consistent relationship, independent of end geometry for the 8 piles presented in Table 1. In general, there is about a 25% increase in capacity after just one day. Of course other aging periods could also be used, say 10 day or 100 day as might be relative to a particular project.

Table 3. Summary of load tests.

Set	Pile No.	Age (Days)	Q^{ult} (kN)
1	P-1	1	19.1
		10	23.3
		100	42.7
		300	42.9
		676	41.7
	P-2	1	44.3
		10	45.8
		100	72.7
		300	58.9
		689	71.8
	P-3	2	45.4
		10	63.5
		157	106.5
		360	95.0
		745	68.5
	P-6	1	27.4
		10	32.6
		100	35.8
		300	36.4
		674	39.4
	P-7	1	46.0
		10	51.7
		100	76.3
		300	84.4
		689	92.5
2	P-10	1	25.8
		10	25.8
		100	29.7
		361	38.3
		768	30.7
	P-13	1	61.6
		10	60.6
		100	59.5
		334	53.3
		741	53.9
	P-12	1	66.3
		10	81.3
		100	78.1
		346	70.7
		755	58.9

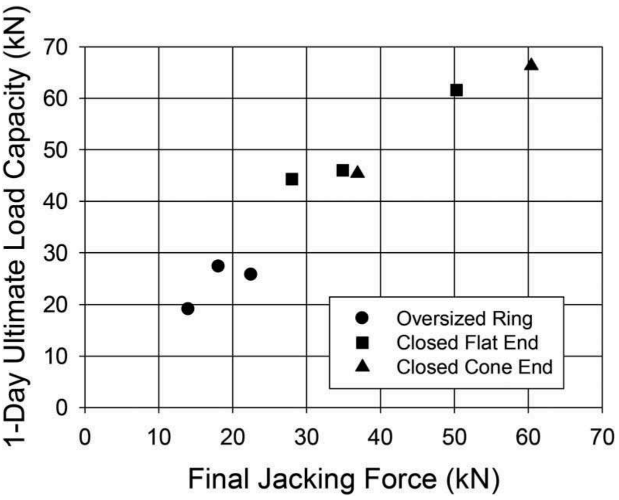

Figure 7. Comparison between final installation jacking force and 1 day ultimate load capacity.

The important point to be made is that the final jacking force gives a conservative estimate of the load capacity for all end configurations, which is expected. During installation, the soil along the pile shaft is undergoing initial remolding and with age, the soil has reconsolidated to a lower water content giving a different undrained shear strength. The remolded, reconsolidated, aged undrained shear strength may be either higher or lower than the initial undisturbed undrained shear strength depending on the sensitivity ratio of the clay and thixotropic behavior.

6.2.2 *Aging*

Figure 8 shows the aging behavior of the 73 mm piles with a length of 7.3 m (P-1, P-2, P-3). During

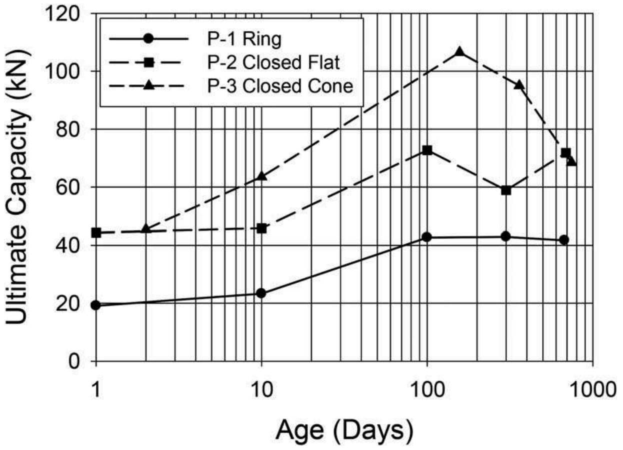

Figure 8. Aging behavior of 73 mm 7.3 m long piles.

the first 150 days, the piles all showed an increase in capacity with repeat loading. Even the pile with the oversized end ring showed an increase in capacity, likely some increase in side resistance as the soil along the shaft reconnected to the pile. It is doubtful that the change in capacity of any of the piles was affected by and substantial increase in end bearing since the pile tips were all located in the lower soft clay. After 150 days all of the piles showed either a decrease in load capacity or stabilized behavior from 150 days to about 750 days. As expected, the pipe with the oversized end ring showed the lowest capacity which is consistent with the lower installation force.

Figure 9 shows the results of the two 89 mm piles with a length of 7.3 m (P-6, P-7). In both cases, the piles showed a consistent continual increase in capacity through 750 days, with the closed flat end pile showing a much larger initial capacity and a large increase in capacity with time. However, even in this case, the pile with the oversized ring also showed an increase in capacity, similar to the 73 mm pile (P-1).

The tests reported herein were performed over a much longer period of time than many previously reported pile tests in stiff clay. For example the results presented by Karlsrud & Haugen (1985) were only performed over 40 days. Fresh tests on different piles at the same site sometimes show relaxation and then an increase in capacity over longer periods of time (e.g. Karlsrud et al. 2014).

Figure 10 shows the aging behavior of the shorter piles, embedded in just the upper stiff clay. The pile with the oversized end ring showed an increase in capacity up to 350 days but then showed a decrease at 750 days. Initially, the piles with the oversized ring showed very little increase in capacity within the first 10 days after installation. With longer aging periods the increase appeared to be more significant.

In this case the closed cone end pile (P-12) in the upper stiff clay showed only a short term increase in capacity but after 10 days showed a steady decrease in capacity. The closed flat end pile (P-13) showed no increase in capacity and actually showed a gradual decrease in capacity after the initial test. This suggests a steady degradation of the side resistance with time.

6.2.3 *Closed cone end vs. closed flat end*

The results shown in Figure 10 also show that while the flat end and cone end closed piles initially showed similar capacity, the pile with the cone end showed a much larger increase in capacity up to about 150 days. This is consistent with the longer piles, shown in Figure 8, at least up to about 150 days. Both sets of tests suggest that the end geometry of a pipe pile in clay may have some influence on the development of side resistance. The author could locate no published data comparing pile capacity of the same diameter and length pipe piles with both a flat tip and a cone tip.

For the two sets of Flat end and cone end piles presented here, there appears to be more than just a random difference in behavior. This difference may help explain, at least in part, some of the observed scatter in empirical correlations between undrained shear strength and undrained side

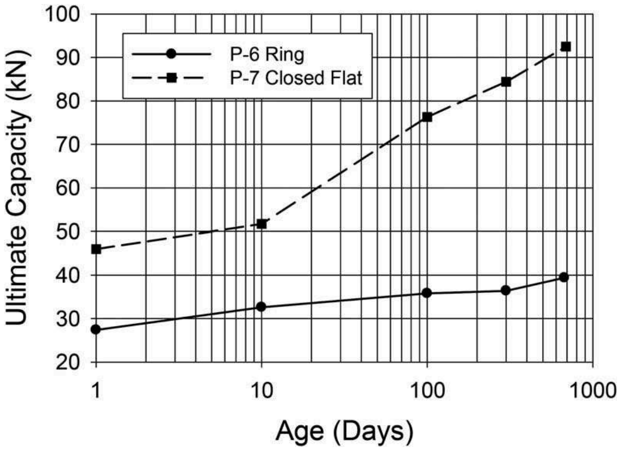

Figure 9. Aging behavior of 89 mm 7.3 m long piles.

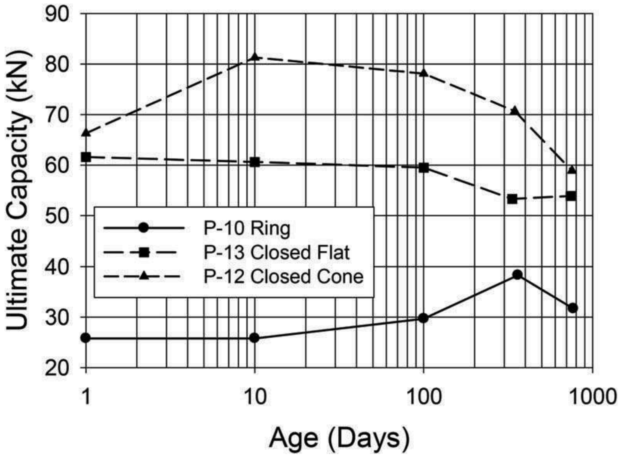

Figure 10. Aging behavior of 73 mm 3 m long piles.

resistance often seen in various design charts. That is, the Alpha value ($\alpha = f_s/s_u$) may be influenced by pile end geometry. This needs additional verification. Pile load tests at other sites using piles with both a flat tip and cone tip are needed.

7 SUMMARY

The results of axial compression tests on small diameter segmental jacked piles in clay showed:

1) Using an oversized end ring on an open end pile requires less installation force than a closed end pile but also provides less load capacity for the same amount of steel;
2) The increase in load capacity of flush closed end pipe piles appears to be primarily the result of additional side resistance developed in the softer clay over time, given the length/diameter ratios of the piles tested;
3) Piles with a 60° apex cone tip gave higher aged capacity as compared to piles with a flush closed flat end, at least up to 150 days; this may be related to difference in the movement of soil away from the pile tip during pile penetration and the degree of remolding experienced by the soil along the pile shaft;
4) No aging occurred with a flat end closed pile in the upper stiff clay; this behavior is contrary to previously reported results and at the present is unexplained;
5) Piles with an oversized end ring showed a small increase in capacity with aging which may be the result of remolded clay reconsolidating against the pile shaft;
6) Several of the piles showed relaxation behavior after repeat loading tests after 150 days. This is likely related to the degradation of shear strength with repeat loading;
7) The results showed a clear relationship between installation force and 1 day load capacity with the load being approximately 20% higher than the installation force after 1 day.

The results presented in this paper suggest that for jacked piles in clay a design based on final jacking force would leave unused load capacity, even for short term (1 day) aging. The use of a "friction ring" may appear to make it easier for the contractor to install piles but these piles developed about 50% of the load capacity of a comparable size and length pile with a closed end, at least for the clays investigated. Results may be different for sands. Closed end piles are clearly more economical in terms of the load capacity developed with the same quantity of steel, but have the added expense of having a tip welded onto the pile. For underpinning applications, the piles are require the same amount of time to install and unless there is a strong layer at relatively shallow depth so that the pile can act an as end bearing element, there is little need to use an oversized "friction ring" on the pile.

The results presented herein are based on repeat tests on the same pile. Aging may be influenced by the "preshearing" of the previous load test since all tests were taken to failure. There is some suggestion in the literature that aging behavior of one time "fresh" load tests on identical piles aged for different periods of time may show greater aging capacity.

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