Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.III)

5-3-9

BEHAVIOR OF SINGLE FRICTION PILES IN SOFT CLAY UNDER REPEATED AXIAL LOADING

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SUMMARY

Model piles in normally consolidated soft clay are axially loaded in a series of laboratory experiments. The load types include monotonic load, one-way repeated load and two-way repeated load. Pore water pressure is measured at the pile surface during the experiments. The excess pore water pressure has close relationship with the pile displacement. Under repeated load of large displacement, the pile load decreases with the number of loading cycles and the average excess pore water pressure increases to a constant value. The permanent displacement under one-way repeated load is dependent on the load amplitude.

INTRODUCTION

Piles are often subjected to repeated axial loads by earthquake, wind and wave. It has been recognized that the behavior of soils subjected to repeated load often differ considerably from the behavior under single cycle of loading and unloading. At a particular stress level, repeated loads lead to larger deformation than that under single cycle of loading and unloading. In addition, the total collapse under repeated load occurs at stress levels well below the maximum under static load. The behavior of piles may be influenced by the nature of soils under repeated load. Experimental studies on the behavior of friction piles under cyclic axial loading have been reported by many researchers. Briaud et al.(Ref.1) reviewed these studies comprehensively.

This paper describes experimental results of piles subjected to repeated axial load. The scope of this paper includes single model friction piles driven into normally consolidated soft clay under quasi-static repeated loading. The experiments also include monotonic loading tests.

MODEL TESTS

Two model piles with the same external diameter 22mm were used in the present tests. Fig.1 shows the apparatus and pile-I mounted with a transducer to measure pore water pressure at the pile surface. In the other pile (pile-II), the shaft load was separated from the total load. The shaft load was determined by subtracting the load at the pile tip (Base load) from the load at the pile top (Total load). The surfaces of both piles (pile-I & II) were made rough by bonding crushed Toyoura sand.

Table 1 shows the properties of the soil used in the model tests. A drainage layer of 40mm thick sand was placed at the bottom of the container shown in Fig.1. A sheet of filter paper was laid on the sand surface. Marine clay from off Kawasaki was mixed with a small amount of Toyoura sand. The mixture was puddled in a soil mixer under a high vacuum for about 5 hours. The soil slurry was poured on the filter paper in the container carefully avoiding air bubbles. After preliminary consolidation, the final confining pressure was applied by air pressure through a rubber membrane on the clay.

Drainage valve at the bottom of the container was kept open during the consolidation. The valve was closed during the tests to make the soil close to undrained condition. The confining pressure was kept constant throughout the experiments. The pore pressure transducer was kept saturated to achieve reliable measurement of pore water pressure.

Table 2 is the list of tests which includes 4 sets of tests. In the first set, Test No.1 was the pile installation followed by Test Nos.2,3 & 4. The apparatus was then decomposed and assembled again for the 2nd set of tests which includes Test Nos.5 & 6. The procedure of decomposition and re-assembly was repeated for the 3rd set (Test Nos.7 & 8) and 4th set (Nos.9 & 10) of tests. Table 3 shows the summary of the pile installation (Test Nos.1,5,7,9) and the static loading tests (Test Nos.2 & 6).

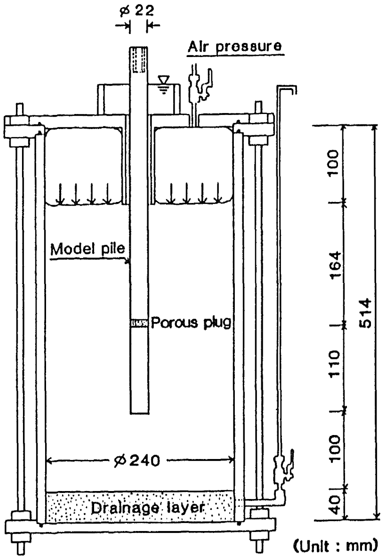

Fig.1 Testing Apparatus and Pile-I.

TEST RESULTS AND DISCUSSION

Excess Pore Water Pressure Fig.2 shows the relationships between load and penetration depth from Test Nos.1,2,3. In Test No.1, the model pile was installed into the soil at a rate of 30mm/min. The pile was unloaded at the specified penetration depth. Excess pore water pressure generated during the pile installation. The drainage valve was then opened to allow the excess pore water pressure dissipate. The excess pore water pressure completely dissipated in about two days. Three days after the pile installation, the drainage valve was closed. The pile was then subjected to a compressive static load (Test No.2). After the test, the excess pore water pressure was allowed to dissipate again. Three days later, the pile was subjected to a one-way repeated loading (Test No.3). Though not shown in Fig.2, this set of pile was further subjected

Table 1 Properties of Soil Used in Experiments

Specific gravity of particles	G_s	: 2.68
Void ratio	e	: 1.44
Water content	w (%)	: 52.1
Liquid limit	w_L (%)	: 64.9
Plastic limit	w_P (%)	: 28.9
Plasticity index	I_P (%)	: 36.0
Undrained shear strength*	c_u (kPa)	: 10 - 11
Sensitivity*	S_t	: 3.7 - 4.0

* obtained with vane shear apparatus

Table 2 List of Tests

Test No.	Type of control	Loading condition	Type of pile	Confining pressure(kPa)	Type of test
1	Displacement	Monotonic	Pile-I	30	Installation
2	Displacement	Monotonic	Pile-I	30	Static loading
3	Displacement	One-way repeated	Pile-I	30	
4	Displacement	Two-way repeated	Pile-I	30	
5	Displacement	Monotonic	Pile-II	35	Installation
6	Displacement	Monotonic	Pile-II	35	Static loading
7	Displacement	Monotonic	Pile-II	35	Installation
8	Load	One-way repeated	Pile-II	35	Q_{max}/Q_{us}=0.47
9	Displacement	Monotonic	Pile-II	35	Installation
10	Load	One-way repeated	Pile-II	35	Q_{max}/Q_{us}=0.83

Table 3 Results of Monotonic Loading Tests

Confining pressure	σ_v'	kPa	30	35	35	35
Undrained shear strength	c_u	kPa	10	11	11	11
Sensitivity	S_t		3.7	4.0	4.0	4.0
Pile installation			No.1	No.5	No.7	No.9
Max. installation force	Q_m	N	99.5	95.0	90.7	85.7
Unit base resistance	q_b	kPa	-	119.7	123.9	116.5
Unit shaft resistance	q_s	kPa	-	2.6	2.3	2.2
Max. excess pore pressure	Δu	kPa	48.7	-	-	-
$(q_b-\sigma_v')/c_u$			-	7.7	8.1	7.4
q_s/c_u			-	1/4.2	1/4.8	1/5.0
$\Delta u/c_u$			4.87	-	-	-
$\Delta u/\sigma_v'$			1.62	-	-	-
Static loading test			No.2	No.6		
Peak test load	Q_{us}	N	235.7	260.2		
Unit base bearing capacity	q_b	kPa	-	131.5		
Unit shaft resistance	q_s	kPa	-	11.2		
Max. excess pore pressure	Δu	kPa	4.9^*	-		
$(q_b-\sigma_v')/c_u$			-	8.8		
q_s/c_u	α-factor		-	1.02		
q_s/σ_v'	β-factor		-	0.32		
$\Delta u/c_u$			0.49	-		

* obtained at peak load

to a two-way repeated loading (Test No.4) after three days of drainage following Test No.3.

Fig.3 is the relationships between excess pore water pressure and penetration depth corresponding to the tests in Fig.2. The pore pressure transducer was located about 110mm above the pile tip. The excess pore pressure started increasing when the penetration depth exceeded about 110mm.

An analysis of field tests (Ref.2) shows that the excess pore water pressure at the shaft of piles driven into saturated soft clay may increase to about $5c_u$ to $7c_u$. In Table 3, the excess pore water pressure from Test No.1 was $4.87c_u$. Another analysis of field tests (Ref.3) shows that the normalized excess pore water pressure ($\Delta u/\sigma_v'$) becomes about 2 during pile installation. In Table 3, the corresponding value from Test No.1 is 1.62. These values from Test No.1 are somewhat lower but in reasonable agreement with those from the field tests of full-scale piles. According to Meyerhof (Ref.2), the excess pore water pressure at the shaft induced by pile loading to failure ranges between $0.2c_u$ and $0.5c_u$. This range covers the corresponding value $0.49c_u$ from Test No.2 in Table 3.

Fig.4 shows the result from Test No.3 under one-way repeated load. The excess pore water pressure increased gradually with the number of loading cycles. The increase became small, however, when the cumulative displacement was small at about 15mm in displacement. After the repeated loading, the pile was subjected to monotonic load from 16 to 22mm. The pore water pressure increased with the downward displacement of the pile.

Fig.5 shows the time histories of normalized load and excess pore water pressure during a two-way repeated loading test with symmetric displacement of ±4.0mm (Test No.4). The load was normalized by dividing the measured load by the peak load in the first cycle. The maximum value of normalized load gradually decreased converging to a value. This value is close to the reciprocal of sensitivity S_t=3.7 in Table 3. The average excess pore water pressure increased with the reduction of normalized load. The average excess

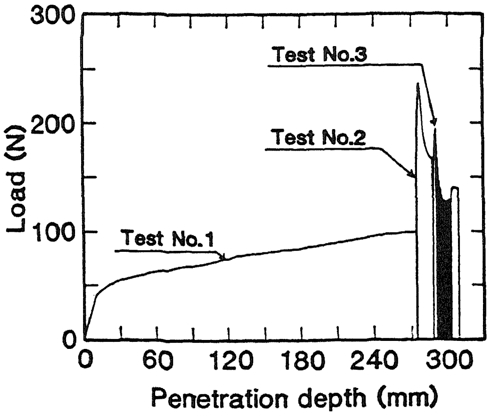

Fig.2 Load and Penetration Depth in Test Nos.1,2,3.

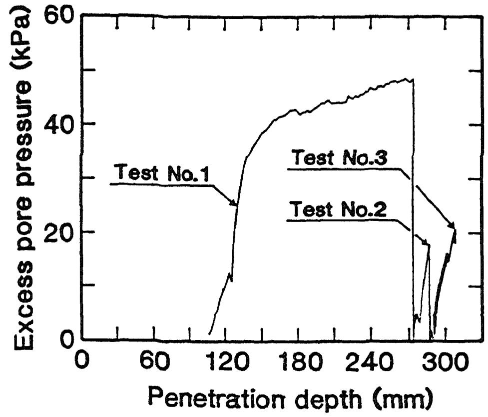

Fig.3 Excess Pore Water Pressure and Penetration Depth in Test Nos.1,2,3.

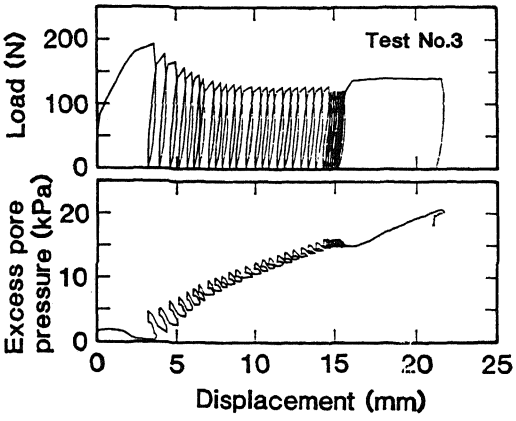

Fig.4 Test Results of Test No.3.

pore water pressure appears to be related to the degradation in the bearing capacity.

Displacement under One-way Repeated Load

Fig.6 shows the relationships between load and penetration depth in the 2nd set of tests in Table 2 (Test Nos.5 & 6). When the depth exceeded about 20mm in penetration (Test No.5), the shaft load increased linearly with the depth, whereas the base load remained constant. When the pile reached about 270mm, the value of $(q_b-\sigma_v')/c_u$ was 7.7 as shown in Table 3. This is close to the conventional bearing capacity factor $(N_c=9)$. In the same test, the value of q_s/c_u was 1/4.2. This is close to the reciprocal of the $S_t(=4.0)$ of the clay.

After 3 days of re-consolidation, the pile was subjected to a monotonic load in Test No.6. There are design parameters α-factor (Ref.4) and β-factor (Ref.5) currently used in practice. For driven piles in normally consolidated soft clay, α-factor is slightly larger than 1.0. β-factor, on the other hand, ranges between 0.25 and 0.40 with average 0.32. The corresponding values from the peak shaft resistance, shown in Table 3, are quite reasonable in comparison with these practical values.

Fig.7 shows the load-displacement curves from Test Nos.6,8 & 10, each followed 3 days of drainage after pile penetration (Test Nos.5,7 & 9 respectively). The load was normalized with the peak load, Q_{us}, under monotonic load (Test No.6).

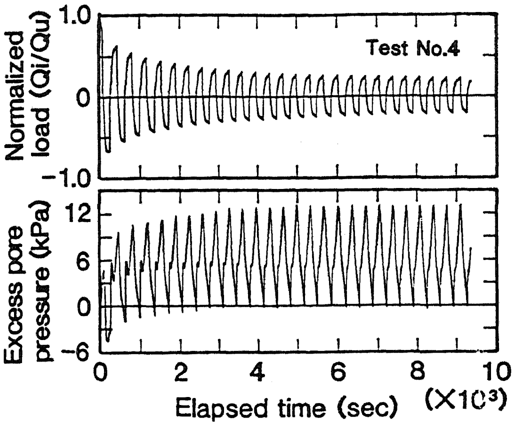

Fig.5 Test Results of Test No.4.

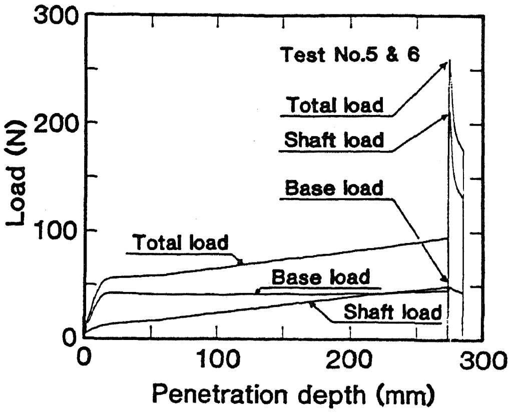

Fig.6 Load and Penetration Depth in Test Nos.5 & 6.

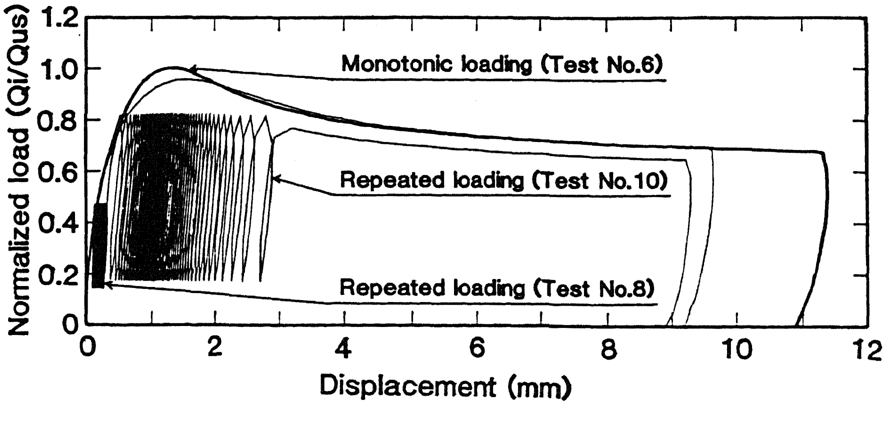

Fig.7 Load-Displacement Relationships in Test Nos.6,8,10.

In Test No.8, the pile was subjected to a one-way repeated load ($0.14 \leq Q/Q_{us} \leq 0.47$) up to 100th cycle. After about 50 cycles of loading, the load-displacement response became stable with very small accumulation in displacement. Immediately after the 100th cycle of loading, the pile was subjected to monotonic load up to about 9.5mm. The peak load of the pile was close to the value under monotonic loading without repeated loading. The post-peak load-displacement curve approached and joined that for the pile without repeated loading.

The behavior of the pile in Test No.10 is in marked contrast to that in Test No.8. In Test No.10, the pile was subjected to a larger one-way repeated load ($0.17 \leq Q/Q_{us} \leq 0.83$). Until the displacement reached about 1mm, the increments of the permanent displacement became smaller with the number of loading cycles. With further cycles of loading, however, the permanent displacement increased with the number of loading cycles ending up with unstable failure. The repeated load amplitude to cause the pile failure was smaller than the peak resistance under monotonic load. It is necessary to establish a new method to evaluate the threshold of repeated load to cause the pile failure.

CONCLUSIONS

An experimental study on model single piles in clay under repeated load and under monotonic load is described. The test results indicate the followings:

1. The pore water pressure at a pile shaft increases during the penetration and loading in normally consolidated soft clay. Under monotonic and one-way repeated load, the excess pore water pressure is apparently influenced by the pile displacement.
2. Under two-way repeated load of controlled large displacement, the pile capacity decreases and becomes close to a constant value. The ratio of bearing capacity to the first peak load became very close to the reciprocal of sensitivity of the clay. The average excess pore water pressure increases and becomes close to a constant value with the decrease in the bearing capacity.
3. The behavior of the pile under repeated load depends on the level of the load amplitude. The repeated load amplitude to cause the pile failure is smaller than the peak resistance under monotonic load.

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