Jour. of the KGS Vol. 17, No. 3. June 2001, pp 77~82

Undrained Behavior of Model Drilled Shafts to Inclined Repeated Loadings

경사반복하중을 받는 모형현장타설말뚝의 비배수 거동

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요 지

반복하중을 받는 현장타설말뚝에 대한 두가지의 주요 관심사항은: (a) 지지력의 변화 가능성 그리고 (b) 누적변형량에 의한 기초의 기능성 저하이다. 이러한 인자들에 대한 평가를 위하여, 모형점토지반에 설치된 24개의 모형현장타설말뚝에 대한 정적 및 동적경사재하시험(12개의 압축 및 12개의 인발)을 수행하였다. 경사반복압축재하시험에서는 반복하중에 의한 지지력의 변화가 무시할 정도였으며, 누적변형량은 송전철탑의 기능성에 영향을 줄 수도 있을 것으로 사료된다. 그러나, 경사반복인발재하시험에서는 과도한 누적변형이 발생하게되어 결과적으로 현장타설말뚝주면과 점토사이의 접촉면적이 감소하는 것으로 나타났다. 접촉면적의 감소 결과, 반복경사인발하중에 의해서 경사인발지지력의 현저한 감소가 일어난다는 사실을 알 수 있었다. 정적경사인발지지력의 50에서 70퍼센트에 해당되는 반복하중을 받는 대부분의 현장타설말뚝들은 인발되었다.

Abstract

There are two major concerns about drilled shafts under cyclic load: (a) possible capacity changes and (b) reduction of foundation serviceability caused by accumulated displacements. To evaluate these factors, twenty four inclined static and cyclic load tests (twelve compression and twelve uplift tests) on model drilled shafts were conducted in model clay deposits. Inclined repeated compression load test results have shown the changes in capacity are minor and the cumulative displacements due to repeated loads may affect the serviceability of the transmission line structure (TLS). Inclined uplift tests, however, resulted in excessive displacement accumulation, which resulted in reduction of contact area between the shaft side and the clay. As a result of the loss in contact area, the dramatic reduction of the inclined uplift capacity due to repeated loading occurred. Most of the shafts were pulled out at a cyclic level of 50 to 70 percent of the static inclined uplift capacity.

Keywords : Drilled shafts, Inclined static and cyclic loads, Capacity changes, Accumulative displacements, Transmission line structures (TLS)

1. Introduction

Drilled shaft foundations supporting transmission line structures (TLS) are often subjected to inclined loads resulting from cyclic variations of combined loads of the axial, lateral, and moment loads. In contrast with the

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design of foundations for normal buildings and bridges where the static vertical compression or lateral capacity dominates, the inclined loading mode could control the design of foundations for TLS. The cyclic load is, moreover, of particular concern because it can be comparable in magnitude to dead load (McManus and Kulhawy, 1991). Among cyclic load sources, wind often dominates. The velocity, direction, and distribution of wind on the structure and overhead lines control the magnitude of the transient forces on the foundations. Unfortunately, there is little knowledge of the behavior of drilled shafts under repeated inclined loads, which are more realistic loading modes for typical TLS. Therefore, this study was conducted to investigate the behavior of drilled shafts under undrained cyclic inclined loads by testing model scale drilled shafts constructed in prepared clay deposits.

2. Model Testing Program

A mixture containing 50 percent kaolin clay and 50 percent silica was mixed with water for soil deposit preparation (McManus and Kulhawy, 1991). A soil deposit termed "Cornell Clay" was then completed by consolidating the mixture. The shafts had an effective diameter (B) of 89 mm (3.5 in), while the depths (D) were varied. Since the common range of D/B for transmission line structure foundations is 3 to 10, D/B ratios of 3, 6, and 9 were selected for this study.

For all inclined load tests, two RDP Electronics model D2/1000E direct current differential transformers (DCDTs) were used in conjunction with the inclinometer to monitor the movement of the shaft butt. Several shafts were equipped with pore water stress or total stress transducers. The loading system includes the MTS actuator controlled by an electro-hydraulic test system with a servo-control loop, the reaction frame designed to permit the desired loading angles of 0, 15, and 45 degrees measured from the vertical. Details on the model testing program are presented elsewhere (Cho and Kulhawy, 1995).

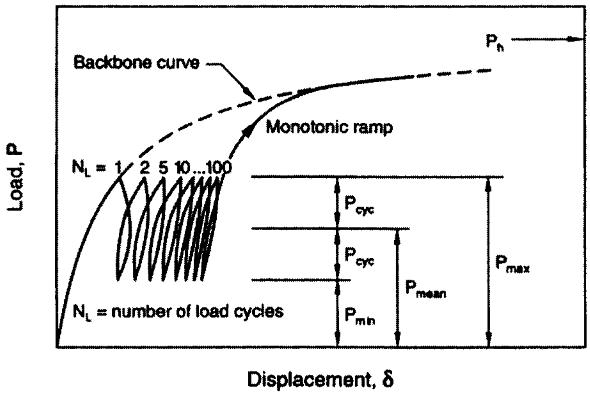


Fig. 1 Components of cyclic load testing

3. Parameters of Cyclic Load Testing

The cyclic test parameters included the mean cyclic load (P_{mean}) and the cyclic load component (P_{cyc}). The notation for the tests is given in Fig. 1, in which P_{mean} = the mean cyclic load, $P_{\max}$ = the maximum applied cyclic load, $P_{\min}$ = the minimum applied cyclic load, $P_{cyc} = P_{\max} - P_{mean} = P_{mean} - P_{\min} = 0.5(P_{\max} - P_{\min})$, and $P_h = P_u =$ hyperbolic capacity or ultimate capacity.

4. Capacity Changes due to Cyclic Loading

A capacity change coefficient (m) is defined to quantify the effect of cyclic loading on the capacity change, as follows:

$$m = P_{uc} / P_u \tag{1}$$

in which P_{uc} = ultimate capacity after cyclic loading and P_u = ultimate capacity without cyclic load. A coefficient less than one ($m \leq 1$) indicates a decrease in foundation capacity. The expected changes in soil behavior or foundation capacity under cyclic load, related to drainage conditions were presented as follows, using the capacity change coefficient (m) (Turner, et al., 1987):

a. Contractive soils under drained conditions ($\triangle u = 0$) cause a decrease in volume ($\triangle V < 0$) and an increase in strength ($m > 1$).
b. Contractive soils under undrained ($\triangle u > 0$) conditions result in no volume change ($\triangle V = 0$) and a decrease in strength ($m < 1$).

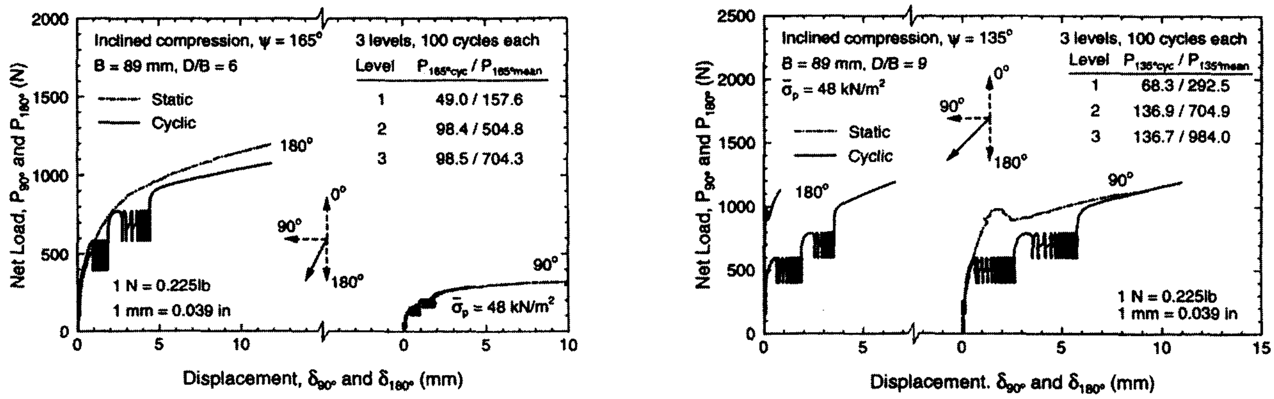
c. Dilative soils under drained conditions ($\triangle u = 0$) indicate an increase in volume ($\triangle V > 0$) and a decrease in strength ($m < 1$).

d. Dilative soils under undrained conditions ($\triangle u \approx 0$) exhibit no changes in volume ($\triangle V = 0$) and strength ($m \approx 1$).

According to previous researches (McManus and Kulhawy, 1991; Mayne, et al., 1992) on the effect of one-way cyclic loading on the axial and lateral capacities in Cornell Clay, the mean values of the capacity change coefficients (m) from axial and lateral load tests are 1.04 and 1.12, respectively. Therefore, the changes in capacity resulting from both axial and lateral undrained cyclic loading in overconsolidated Cornell Clay (case d above) were not considerable ($m \approx 1$).

To compare the changes in capacity and initial stiffness of the cyclic and static load-displacement curves, the comparable load-displacement curves from inclined compression and uplift tests were plotted in Figs. 2 and 3, respectively. The vertical and horizontal load-displacement components are presented separately for easier understanding of the behavior of drilled shafts under inclined loads. The cyclic parameters such as P_{cyc} and P_{mean} of the applied inclined load are given in these figs. These input parameters for cyclic load tests were determined from the static inclined backbone curves.

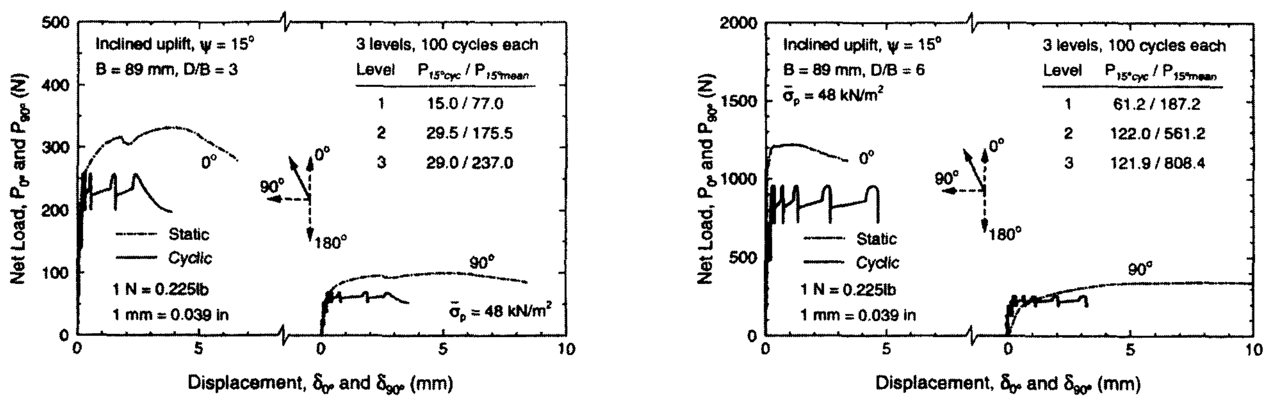
As shown in Fig. 2, no significant changes in inclined compression capacity and initial stiffness could be investigated. As shown in Fig. 3, however, somewhat significant changes in uplift capacity are evident. Most of the shafts under cyclic inclined uplift loading were pulled out at a cyclic level of 50 to 70 percent of the corresponding static inclined uplift capacity.



(a) Comparison of static and cyclic inclined compression (165°) tests with D/B = 6

(b) Comparison of static and cyclic inclined compression (135°) tests with D/B = 9

Fig. 2 Typical load displacement curves from inclined compression tests



(a) Comparison of static and cyclic inclined uplift (15°) tests with D/B = 3

(b) Comparison of static and cyclic inclined uplift (45°) tests with D/B = 6

Fig. 3 Typical load displacement curves from inclined uplift tests

5. Accumulation of Peak Displacements

The cumulative displacement under cyclic loading is another major concern that can affect the serviceability of the TLS. Therefore, it is important to predict the cumulative displacements caused by cyclic loads.

The cyclic cumulative displacements usually can be evaluated by using empirical approaches. In general, a semi-log, a log-log, and hyperbolic relationship between cumulative cyclic displacements at the Nth cycle (δ_N) and the number of loading cycles (N_L) has been introduced in previous studies (Turner, et al., 1987; Poulos, 1982; Cho and Kulhawy, 1995).

The semi-log relationship between δ_N and the logarithm of N_L is given as follow:

$$\delta_N = \delta_{N=1} + B_L \log N_L \qquad (2)$$

in which $\delta_{N=1}$ = displacement at N = 1 and B_L = slope of the semi-log curve. Available test results have shown that the accumulated displacements increase with constant slopes (B_L) ranging from 0.1 to 0.4 within the initial part of cyclic uplift loading, and that B_L increases as the cyclic load level increases (Turner, et al., 1987). Therefore, the curves were becoming appreciably steeper with increasing N_L, especially for higher cyclic load levels, as schematically shown in Fig. 4.

For evaluating cyclic lateral displacements, a log-log relationship between the logarithm of normalized displacements and the logarithm of N_L has been suggested (Poulos, 1982), as follows:

$$\log(\delta_N / \delta_{N=1}) = t \log(N_L) \quad \text{or} \quad \delta_N = \delta_{N=1} N_L^t \qquad (3)$$

in which t = slope of the log-log curve = displacement accumulation parameter.

Alternatively, the prediction of cyclic displacement accumulation may be carried by using a hyperbolic model as follows:

$$\delta_N / \delta_{N=1} = (N-1) / [a + b(N-1)] + 1 \qquad (4)$$

in which a and b = constants from regression analysis. The hyperbolic approximation for fitting the displacement accumulation versus the number of cycles seems to be the best among those described above. Especially for the cyclic test with a greater number of cycles (1000 cycles), the hyperbolic fitting has proved to be much better than the exponential one as shown in Fig. 5. Also, the main advantage of using hyperbolic approximation is that the ultimate cyclic displacement (δ_∞), which will be very useful to design the foundations under cyclic load, can be predicted as follows:

$$\delta_\infty = \delta_{N=1}(1 + 1/b) \qquad (5)$$

The parameter b might be important because its reciprocal determines the asymptotic cumulative displacement. Tables 1 and 2 summarize the calculated asymptotic displacements under cyclic inclined compression and uplift, respectively, using the displacement at $N = 1 (\delta_{N=1})$ and the parameter b found from this study. These cyclic load levels versus asymptotic cyclic cumulative displacements were plotted in Figs. 6 through 8. Hyperbolic regression analyses are given in Table 3. For the inclined

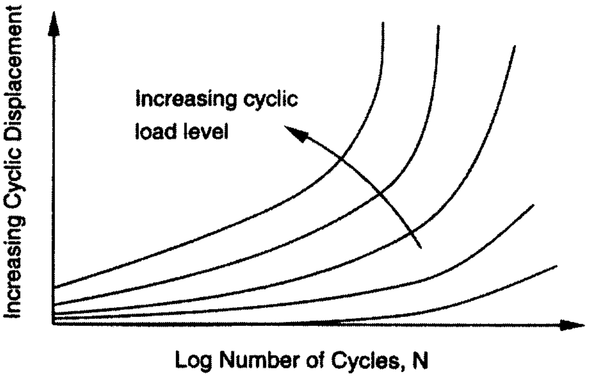


Fig. 4 Accumulation of cyclic displacements with cyclic load level

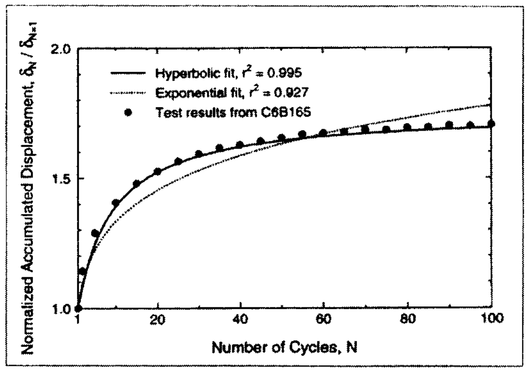


Fig. 5 Comparison of hyperbolic and exponential fitting for horizontal component of cyclic inclined displacement accumulation

uplift tests, there are fewer data points than those from the inclined compression tests because some data were excluded for the following reasons: (a) most uplift shafts were pulled out during the second or third level of loading when the cyclic load level was about 60 to 70 percent of the corresponding inclined static capacities and (b) the displacement measurement during most of the first cyclic load level is influenced by suction forces. Therefore, all of the inclined uplift data from both 15 and 45 degree tests were analyzed together to produce statistically meaningful results.

a - load inclination measured from the vertical

$P_{max}/P_h = (\delta_\infty/B)/[c(\delta_\infty/B)+d]$ in which c and d = constants from regression analyses

As shown in Fig. 6, the horizontal asymptotic displacement component for the 135 degree cyclic loading tests is greater than the vertical asymptotic displacement component at the same cyclic load level because the horizontal load-displacement component curves are softer. However, the horizontal and vertical asymptotic displacements under 165 degree cyclic loading are more or less the same at the same cyclic load level, as shown in Fig. 7. For this 165 degree loading, the resulting displacements of the two components are close to each other because the vertical load component is larger than the horizontal load component by a factor of 3.7 (cot 15°) and this effect might offset differences in the stiffness of the two load-displacement curves.

Table 1. Summary of cyclic cumulative displacement for inclined compression tests

Test	P_{max}/P_h	Horizontal			Vertical		
		b	$\delta_{N=1}$(mm)	δ_∞(mm)	b	$\delta_{N=1}$(mm)	δ_∞(mm)
C3B135	0.18	0.19	0.20	0.23	0.07	0.07	0.08
	0.34	0.38	0.38	0.50	0.12	0.13	0.15
	0.59	0.80	0.80	4.11	0.21	0.65	0.73
C3B165	0.19	0.14	2.14	2.40	0.04	0.17	0.19
	0.55	0.95	2.23	2.51	0.94	1.91	2.15
	0.73	1.39	2.32	3.99	2.27	4.26	4.79
C6B135	0.43	0.04	0.11	2.86	0.08	0.65	0.73
	0.58	0.60	1.89	5.04	0.41	1.01	1.14
C6B165	0.44	0.73	0.99	2.35	0.10	0.19	0.22
	0.59	1.46	2.41	4.06	2.41	4.22	4.74
C9B135	0.22	0.09	0.03	0.36	0.01	0.10	0.11
	0.51	0.27	0.67	3.15	0.70	1.97	2.22
	0.68	1.31	3.38	5.96	2.38	3.54	3.97
C9B165	0.44	0.71	0.47	1.13	2.55	4.83	5.42
	0.59	1.53	1.17	1.93	5.78	9.42	10.58

Table 2. Summary of cyclic cumulative displacement for inclined uplift tests

Test	P_{max}/P_h	Horizontal			Vertical		
		b	$\delta_{N=1}$(mm)	δ_∞(mm)	b	$\delta_{N=1}$(mm)	δ_∞(mm)
C3B15	0.58	0.20	0.20	0.59	0.32	0.11	0.45
C3B45	0.55	0.11	0.19	1.92	0.05	0.02	0.42
C6B15	0.54	0.62	0.12	0.31	1.29	0.12	0.21
C6B45	0.54	0.08	0.13	1.76	0.03	0.05	1.72
	0.72	0.15	0.66	5.06	0.11	0.19	1.92
C9B15	0.53	0.08	0.22	2.97	0.09	0.56	6.78
C9B45	0.20	0.17	0.14	0.96	0.16	0.02	0.15

Table 3. Summary of hyperbolic regression analyses for asymptotic cumulative displacement

Load Inclination, Ψ^a (degrees)	Horizontal				Vertical			
	c	d	r^2	S.D.	c	d	r^2	S.D.
135	1.50	0.32	0.942	0.15	1.61	0.94	0.936	0.17
165	1.69	0.37	0.959	0.09	1.62	0.46	0.620	0.84
15 and 45	1.39	0.37	0.586	0.36	1.25	0.43	0.637	0.63

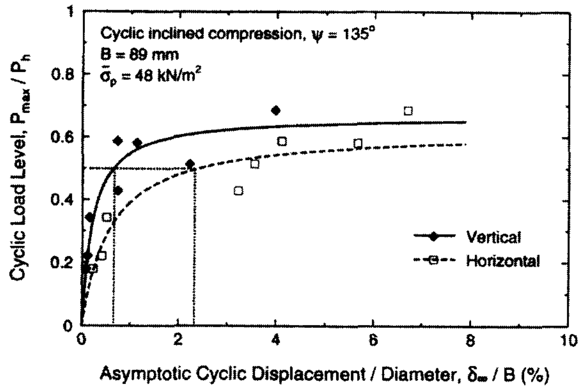


Fig. 6 Cyclic load level versus asymptotic cyclic cumulative displacement for 135 degree inclined compression tests

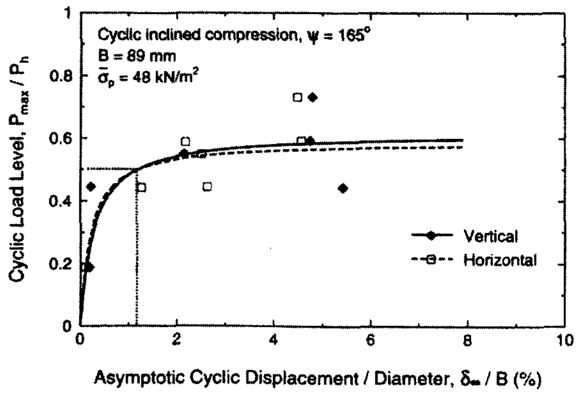


Fig. 7 Cyclic load level versus asymptotic cyclic cumulative displacement for 165 degree inclined compression tests

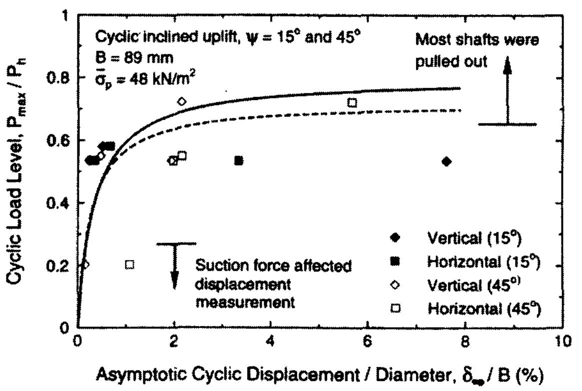


Fig. 8 Cyclic load level versus asymptotic cyclic cumulative displacement for inclined uplift tests

For cyclic inclined uplift loading, as shown in Fig. 8, the asymptotic displacements mostly were obtained from the second cyclic load level. The large dispersion of data points in the cyclic load level range of 0.5 to 0.6 shows that the asymptotic cyclic cumulative displacement can change dramatically in this cyclic load level range. Therefore, in designing drilled shafts under cyclic inclined uplift loads, care must be taken because of the high uncertainty of the cyclic asymptotic displacement in the cyclic load level range of 0.5 to 0.6. Also, the experimental results show that the shafts under cyclic inclined uplift loads, with cyclic load level greater than 0.5, are likely to be pulled out.

6. Conclusions

By conducting twenty four inclined cyclic compression and uplift tests, the findings are as follows:

(1) No significant change in inclined compression capacity due to cyclic inclined loading whereas significant reduction in inclined uplift capacity was investigated.
(2) Most of the shafts under cyclic inclined uplift loading were pulled out at a cyclic level of 50 to 70 percent of the corresponding static inclined uplift capacity.
(3) For evaluating cyclic displacement accumulations, the hyperbolic fitting is a better model than any other mathematical methods suggested by the other authors such as Turner et al. (1987) and Poulos (1982).
(4) Hyperbolic approximation enables foundation designers to predict the ultimate cyclic displacement.

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