Deformation behavior of single pile in silt under long-term cyclic axial loading

Comportement d'un pieu isolé sous chargement axial cyclique de longue durée dans un limon

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ABSTRACT: Evaluating the response of piles to cyclic loading is a crucial part in the design of piled-embankment over soft ground. In this paper, a series of large-scale model tests were performed to investigate the response of pile in silt under cyclic axial loading. Heavily instrumented piles were used in the tests. The study is focused on the accumulation of permanent dispalecemtn of the piles under long-term cyclic loading. Piles were tested at differernt cyclic loading levels and subjected up to 50,000 cycles of loading in each test. The accumulated settlement was found to be strongly dependent on the characteristics of the applied cyclic loads. The piles were found not to produce any increase in accumulated settlement if the cyclic loading amplitude is less than a certain threshold value. A simple method is proposed to predict the accumulated settlement of single pile due to very large number of loading cycles. The idea of a cyclic deformation diagram for analyzing the influence of charcteristics of cyclic loads on the deformation behavior was also developed.

RÉSUMÉ : L'évaluation de la réponse des pieux vis-à-vis d'un chargement cyclique est un élément essentiel dans la conception des remblais sur sols mous. Dans cet article, une série d'essais sur maquette à grande échelle a été réalisée pour étudier la réponse de pieux sous chargement axial cyclique dans le limon. L'étude est centrée sur l'accumulation des déplacements permanents des pieux sous chargement cyclique de longue durée. Les pieux ont été testés à différents niveaux de charge cyclique et soumis à 50000 cycles pour chaque test. Les tassements accumulés sont fortement dépendants des charges cycliques appliquées. Aucune augmentation de tassements n'est constatée si l'amplitude de chargement cyclique est inférieure à un certain seuil. Une méthode simple est proposée pour prédire le tassement cumulé d'un pieu isolé en fonction d'un très grand nombre de cycles de chargement. L'idée d'un diagramme de déformation cyclique pour analyser l'influence des caractéristiques des charges cycliques sur le comportement en déformation a également été développée.

EYWORDS: Pile; model test; accumulated settlement; cyclic loading

1 INTRODUCTION

Piles are commonly used to support high-speed railway embankment in soft ground, which are exposed not only to the heavy loads from superstructure self-weight, but also to the long-term "one-way" cyclic loads induced by high-speed trains throughout their service life. However, available design experiences on the long-term response of the pile in silt to cyclic axial loading are very limited, due to the fact that the existing data obtained from laboratory tests and field measurement are insufficient. This results in uncertainty in the design and always leads to an over-conservative design of the pile foundation.

The response of pile subjected to cyclic loading is very complex and model test is the most effective and reliable way to study it and its influencing factors. Laboratory and field tests (Chan and Hanna 1980; Lee and Poulos 1991; Karlsrud et al. 1993) have shown that there are two main effects of cyclic axial loading on piles: (1). a reduction in load capactiy and pile-soil system stiffness; (2). an increase in settlement of piles. Poulos (1989) reviewed several cyclic loading tests performed in sand and stated that the accumulation of permanent displacement with increasing load cycles was expected to dominate under "one-way" cyclic loading, particularly if "strain-softening" behavior can occur at the pile-soil interface. The accumulation of the permanent displacement principally depends on the cyclic load level. Briaud and Felio (1986) analyzed the published data and concluded that a load threshold exists above which failure occurs by plunging due to cyclic loading and the value of this threshold is 80% of the ultimate pile capacity on average.

In previous studies, most of the piles were loaded less than 500 cycles of loading. There have been few researches on the response of pile to long-term cyclic loading at present.

This paper describes the results of a series of large-scale model tests on single stiff piles in saturated silt to study the accumulation of permanent displacement of the piles. The tests have been performed using heavily instrumented model piles. A simple method for predicting the accumulation of permanent displacement of pile to long-term cyclic axial loading is proposed. The idea of a cyclic deformation diagram for analyzing the influence of charcteristics of cyclic loads on the deformation behavior was also developed.

2 DESCRIPTIONS OF EXPERIMENTS

2.1 Test site and soil characteristics

The present large-scale model tests were carried out in a big soil tank at Zhejiang University (Fig 1). This soil tank has an dimension of 15×5m in plan view and a depth of 6m.

The soil used in the tests is low cohesive silt. Grading tests showed that the soil contains 10% sand, 85% silt and 5% clay. The characteristics of the soil are summarized in Table 1. Laboratory tests show that the prepared soil had an average water content of 28.5% and an effective internal friction angle of 30^o.

Figure 1. The big soil tank at Zhejiang University

Table 1. Main soil properties

Property	Value
D_{50} particle size (mm)	0.032
Specific gravity, G_S	2.69
Plastic limit, W_L	22.6
Liquid limit, I_L	31.7
Plasticity index, PI	9.1

2.2 Model pile

The used instrumented model pile was closed-ended steel tube pile with an outer diameter (*d*) of 168 mm, a wall thickness of 7 mm. The pile had a cone-shaped tip end with a cone angle of 60^o. The model pile was designed to be assembled from four segments to give a full length of 4.2 m. The instrumentation consisted of axial load cells (ALC), total pressure transducers (TPT) and pore pressure transducers (PPT).

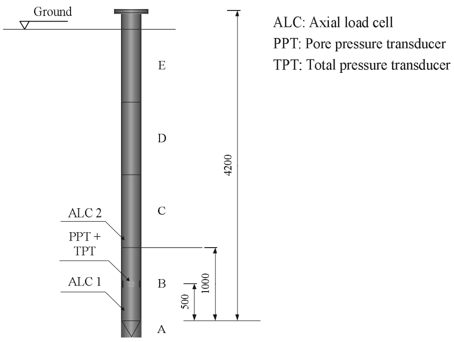


Figure 2. Schematic diagram of the model pile (Unit: mm)

2.3 Characteristics of cyclic loading

The characteristics of the applied cyclic load are uniquely defined using two independent parameters:

$$SLR = P_s / P_u \quad (1)$$

$$CLR = P_c / P_u \quad (2)$$

in which P_u refers to the static ultimate capacity of the pile in compression, and P_s is the minimum in a load cycle and P_c is the cyclic load amplitude. In present study, P_s and P_c simulated the self-weight from the superstructure and the cyclic load induced by the high-speed trains, respectively. A visual interpretation of the load ratios is given in Fig. 3.

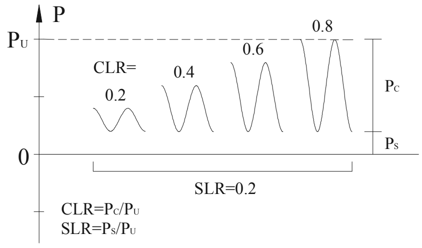


Figure 3. The characteristics of cyclic loading

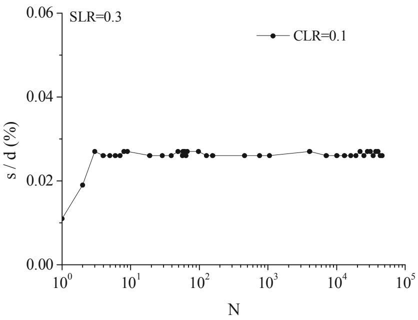
In this study, the cyclic load frequency of 3Hz was used for the tests and the sampling frequency was of 50 Hz.

3 TEST RESULTS

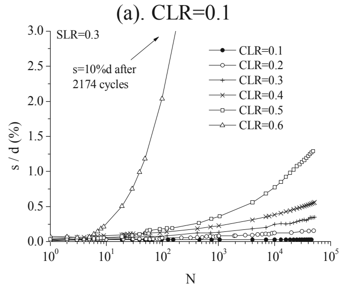
3.1 Accumulated settlement

The overall pattern of accumulated settlement of the pile with SLR of 0.3 is presented in Fig. 4 by normalizing the accumulated permanent displacement *s* by the pile diameter *d*. The values of the CLR in this series ranged from 0.1 to 0.6. It can be found that the ways in which displacement developed is highly dependent on the amplitudes of cyclic load which can be represented by the cyclic load ratio (CLR).

In the test with the smallest CLR of 0.1, extreme small permanent displacement, of approximately 0.04%*d* was produced in the first three cycles and remained nearly constant from cycle No. 3 to 50,000. For the CLRs ranging from 0.2 to 0.5, the permanent accumulated displacement increased gradually with the increasing number of cycles and also with the increasing magnitude of cyclic load. For the tests with the CLR of 0.2, 0.3, 0.4 and 0.5, the permanent displacements at the end of the tests were 0.15%*d*, 0.35%*d*, 0.56%*d* and 1.26%*d*, respectively. The permanent displacement increased rapidly at initial stage and had the highest rate of displacement increase in the first few cycles, and then it kept increasing continuously with a decreased rate of displacement increase and seemed to increase without a final and constant value. For the test with very large cyclic load, such as CLR=0.6, the pile head moved downward in a very "unstable" way marked by a quick plunging during the test and the pile failed with a total accumulated displacement of 10%d in 2,147 cycles.



(a). CLR=0.1



(b). CLR=0.1~0.6

Figure 4. Normalized permanent displacement (s/d) with number of cycles (SLR=0.3)

The aforementioned patterns of behavior shown in Fig. 4 can also be found in other tests with SLR of different values. The accumulated displacement for each test fell qualitatively into any of the three distinct patterns shown in Fig. 4:

(1) no accumulated displacement, as exhibited during the test with CLR of 0.1;

(2) continuing displacement, as exhibited during the tests with CLR ranging from 0.2 to 0.5;

(3) failure, as exhibited during the test with CLR of 0.6.

For the first case, the pile-soil system seems not to be influenced by the cyclic loading and is in elastic range; only small accumulated displacement was produced during the first few cycles. For the second case, the pile-soil system was influenced to some degree and partially entered plastic range; the pile head showed continuing downward movement without any apparent limit and the accumulation of displacement depended on both of cyclic load level and number of load cycles, and high cyclic load level and large number of cycles produced larger permanent displacement. For the last case, the cyclic loading had brought severe damage to the pile-soil system and the pile fully entered the plastic range; the pile head moved continuously downward at a rapid rate up to the end of the test and a plunging failure might occur in some cases.

Thus, to divide the accumulated displacement responses for the tests with a given SLR two critical values of CLR are defined here, named minimum cyclic load ratio (MCLR) and failure cyclic load ratio (FCLR), respectively. For CLR smaller than the MCLR, the pile was in elastic range; for CLR greater than the FCLR, the damage to the pile-soil system was severe and the always caused "failure".

The MCLR was found to be of 0.1 in all the tests and shown to be unaffected by the SLR, and it can be inferred that if the applied cyclic loads remained less than 10% of the ultimate pile static capacity, the response of the pile can be considered to be total elastic and the permanent displacement was negligible after first several cycles.

The FCLR was found to be of 0.5 for the tests with SLR ranging from 0.2 to 0.4. However, in the case of the test with SLR of 0.1, the pile produced large permanent displacement with CLR of 0.4, and it showed the tendency that lesser cyclic loads were required to cause large permanent displacement for the pile with very small SLR. Briaud and Felio (1986) reviewed the previous cyclic load tests and concluded that a threshold of peak load ratio (CLR+SLR) existed above which large permanent displacement occurred and the value of that threshold was about 0.8 on average. However, the tests results suggest that the large permanent displacement depended more on the magnitude of the cyclic load rather than the peak cyclic load. It can be inferred from the results that large permanent displacement occurred if the magnitude of the applied cyclic load exceeds the 50% of the ultimate pile static capacity.

3.2 Prediction method

To investigate the evolution of the permanent displacement in the tests in which the permanent displacement are identified as "continuing displacement", the results are replotted on double logarithmic scales and the evolution of the permanent displacement is evaluated in terms of the dimensionless ratio

$$\frac{\Delta s(N)}{s_s} = \frac{s_N - s_0}{s_s} \tag{3}$$

which expresses the magnitude of the permanent displacement $\Delta s(N)$ caused by cyclic loading in terms of the displacement s_s that would occur in a static load test when the load is equivalent to the maximum cyclic load (as defined by $(SLR + CLR) \times P_u$). The s_0 and s_N refer to the permanent displacement in first and N'th cycle, respectively.

The results, plotted in Fig. 5, show that the trend in the data follows the exponential behavior which appears as straight lines in double logarithmic axes. This suggests that the permanent displacement due to cyclic loading can be predicted by the following power model:

$$\frac{\Delta s(N)}{s_s} = AN^b \tag{4}$$

where A and b are two parameters. It is observed in Fig. 5 that all slopes are almost equal. This suggests that b is independent of the load characteristics within the observed range. It is introduced into (4) to represent the influence of load characteristics on parameter in the following form:

$$A = a(SLR+1)^m (CLR)^n \tag{5}$$

where a, m and n are three calibration parameters. Clearly, when $CLR = 0$, then $A = 0$ and no accumulated displacement will occur under static load. Also, when $SLR = 0$ then $A = a(CLR)^n$ indicates that the accumulated displacement depends only on CLR. Thus, substituting (5) into (4) gives the following model for accumulated permanent displacement:

$$\frac{\Delta s(N)}{s_s} = a(SLR+1)^m (CLR)^n N^b \tag{6}$$

The expression in Equation (6) was fitted to the data in Fig. 5 to empirically determine values of these parameters and back-calculated parameters a, m, n and b for the tests are 0.054, 0.68, 1.24 and 0.23. The predicted results are shown by the dotted lines in Fig. 5 and it appears that the influences of the load characteristics on permanent displacement are reflected well in the prediction. The closeness of the fit up to 5×10^4 cycles indicates that, in the absence of further experimental data, it might be reasonable to extrapolate beyond $N > 5 \times 10^4$. Further data are, of course, required to confirm this hypothesis.

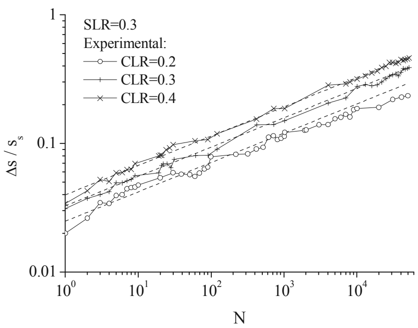


Figure 5. Measured and predicted accumulated displacement
The dotted lines are obtained using Equation (6)

4 CYCLIC DEFORMATION DIAGRAM

Poulos (1988) proposed the idea of cyclic stability diagram to investigate the capacity degradation caused by cyclic loading. In this study, similar concept is used and the idea of a diagram named cyclic deformation diagram is developed. The cyclic defromation diagram for the model piles is shown in Fig. 6. In the diagram, the aforementioned three types of displacement response are represented by different symbols. Therefore, three main regions can be identified on the diagram shown in Fig. 6:

(1) A stable (elastic) region I in which the cyclic loading has no influence on the pile responses and the displacement response is the type of "no accumulated displacement".

(2) A serviceability region II in which the cyclic loading has some influence on the pile response and the displacement response can be identified as "continuing displacement".

(3) A unstable region III in which cyclic loading causes severe damage for the pile to produce very large permanent displacement and in some cases a plunging failure occurs.

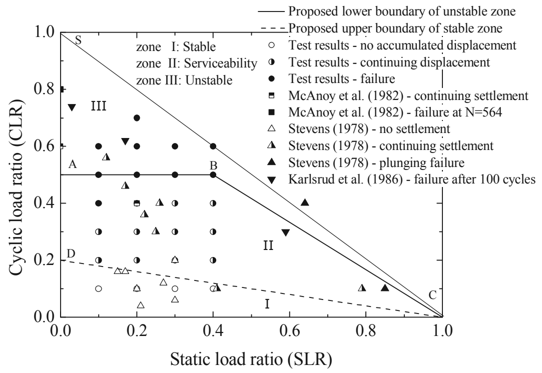


Figure 6. Cyclic deformation diagram for pile in silt (N=50,000)

The upper boundary to the cyclic permanent displacement is the straight line (CS: SLR+CLR=1) that represent the combinations of SLR and CLR necessary to cause a failure of pile without cyclic effects being considered. The other two lines plotted in this diagram represent the approximate boundaries between the stable region, the serviceability region and the unstable region. These lines are defined by the following relations:

Upper boundary of stable zone (line AB and BC):

$$\begin{cases} CLR = 0.5 & 0 \le SLR \le 0.4 \\ 1.2CLR + SLR = 1 & 0.4 < SLR \le 1.0 \end{cases} \tag{7}$$

Lower boundary of unstable zone (line DC):

$$5CLR + SLR = 1, \quad 0 \le SLR \le 1 \tag{8}$$

Fig. 6 also plots the other test results of field or model tests on axial cyclically loaded pile. It can be seen that these proposed lines are consistent with the experimental data and thus it is indicated that the proposed three regions are capable of reasonably identifying the deformation behavior of pile under various load combinations. A diagram such as shown in Fig. 6 represents the permanent displacement of a pile for a specified number of cycles, N. As N increases, the stable region will remain unchanged and the unstable region may increase as the permanent displacement increases.

In the pile design, it is very convenient to determine the deformation behavior of the pile to cyclic loading using this diagram. The most conservative design is to have the cyclic loads in the stable region which means that pile will not be affected by cyclic loading and issues of the permanent displacement can be totally ignored. If the designed cyclic load is in the serviceability region, the permanent displacement accumulates in "stable" way and depends on both of the number of cycles and the load characteristics; and it can be predicted using the proposed simple method mentioned above. For a safe design, it should avoid the cyclic load to be in the unstable region in which cyclic loading will result in very large permanent displacement and even a plunging failure.

5 CONCLUSION

A series of tests were conducted on large-scale model piles subjected to long-term cyclic axial loading. The deformation behavior of the piles in silt to cyclic loading was investigated.

The evolution of permanent displacement highly depends on the magnitude of cyclic load. In general, the accumulation of permanent displacement increases with increasing cyclic load amplitude and increasing number of cycles. However, the pile behaves in an elastic manner and does not accumulate any deformation after the first few cycles of loading if the magnitude of cyclic load is less than 10% of the ultimate pile capacity. Very large permanent displacement, even plunging failure, occurs when magnitude of cyclic load exceeds 50% of the ultimate pile capacity. This suggests that the magnitude of the cyclic load be kept below 50% of the ultimate capacity to avoid large permanent displacement in the design.

These results provide a better understanding of the deformation behavior of pile in silt to long-term cyclic axial loading, and can be used to optimize the designs of pile foundations that resist cyclic loads in service.

6 ACKNOWLEDGEMENTS

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