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Bearing Capacity of Piles Under Long-Term Vibration

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SYNOPSIS The Bearing capacity of piles under long-term vibration is herein discussed. A real case of continuous subsidence of vibrating pile foundations is presented with a set of vibratory loading tests in-situ and the charqcteristics of settlement-time curves are described. Analyses of the observed data are made and the additional plastic deformation induced in the soil strata under the piles is interpreted. Based on the test data, authors recommend a conception of long-term bearing capacity of piles to be used in the design of pile foundation under vibration instead of the conventional one, and a method of determination of bearing capacity of single pile is presented.

INTRODUCTION

Pile foundations are widely used to transfer the load of superstructures onto the deeper and suitable soil strata for minimizing the foundation settlemeuts, but it is not always the case with the pile foundations subjected to the long-term vibration.

An extensive investigation completed in China has shown that heavy additional settlements of pile foundations have been found in many industrial buildings under long-term vibration and last as long as the dynamic effect exists. The non-uniform settlements of pile foundations usually damage the structures and cracks have been observed. A typical graph of development of vibration pile foundation settlements with time at Qiqihar Rolling Stock Plant is Shown in Fig.1, which implies that neglect of the effect of long-term vibration leads to overestimation of bearing capacity of pile.

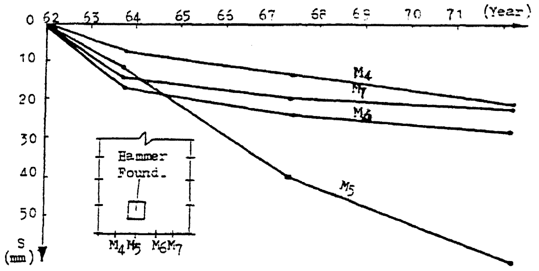

Fig.1. Graph of Development Foundation Settlements Observed at Qiqihar Rolling Stock Plany.

Although many experimental studies have been made on the dynamic properties of soil, the effect of long-term vibration on pile foundations has not yet been adequately investigated. A real case and a set of field tests were described herein and intended to clarify the effect of longterm vibration on the pile foundations and to seek a solution for determination of bearing capacity of piles under long-term vibration.

BRIEF DESCRIPTION OF THE REAL CASE

The forging shop of Qiqihar Gear Plant is a single span structure, 36 18m in size, rested on the alluvial deposits near the Nenjiang River. A 3tf forging hammer is mouted on an open caisson foundation embedded at a depth of 5.6m below.

The columns of superstructure are supported by reinforced concrete pile foundations, each consists of 10 piles. The pile is 6m long, 25 25cm in section. Ultimate bearing capacity of pile obtained by load test is 44tf. Under normal conditions, each pile carries a load of 17.5tf on an average.

Engineering geological Section is shown in Fig.2. Soil at the site stratifies basically from top to bottom in three major layers:

1. Clayey loam, 2 to 2.5m thick with volume weight γ=1.95-2.0tf/m^3, Atteberg limits LL=30-36, PL=18-19.9, plasticity Index I_p=12-16.1, porosity ratio e=0.65-0.68, allowable pressure p_a=24tf/m^2.

2. Fine sand of medium relative density, 2.5-3m thick, angle of internal friction $\phi=30^\circ-33^\circ$, allowable pressure p_a=15tf/m^2.

3. Gravel of medium to high relatve density, allowable pressure p_a=30-35tf/m^2.

Water table is at a depth of about 3.4m.

Records show that the vertical vibration of hammer foundation has a peak acceleration 'a' of about 0.09g ('g' is gravitational acceleration) and a peak amplitude 'A' of about 0.33mm. The peak accelerations and amplitudes of nearby column foundations and their settlements are shown in Fig.3.

Despite good soil condition and inconsiderable

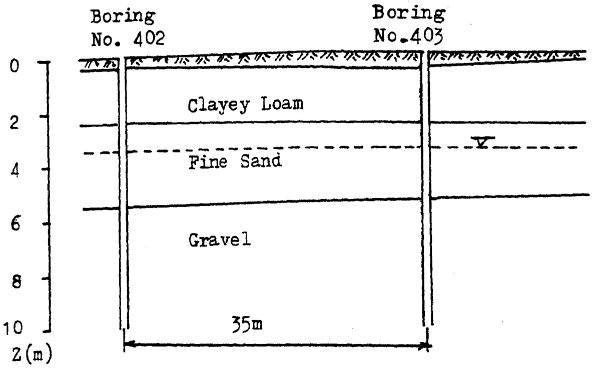

Fig.2. Engineering Geological Section

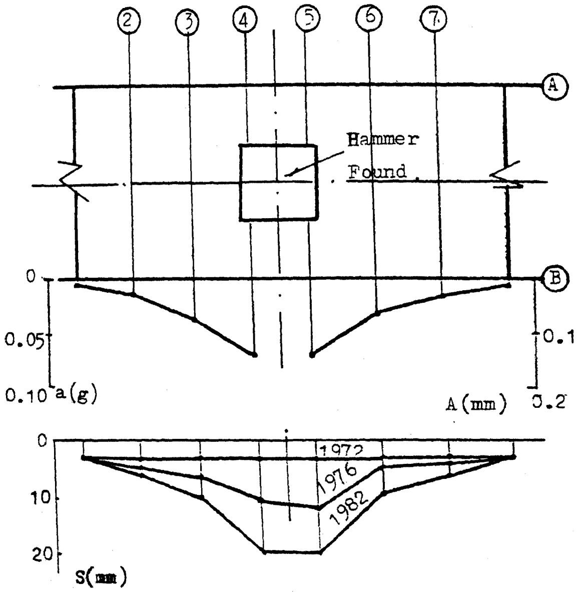

Fig.3. Settlement, Acceleration and Amplitude Curves of Column Pile Foundations along Axes

vibration the settlements of nearby foundations lasted many years with constant rates until the building was damaged and the production stopped.

FIELD EXPERIMENT

To clarify the nature of additional subsidence of pile foundations dynamic load tests were conducted on both steel pipe piles (27.5cm OD 1.2cm, 6.5m long) and reinforced concrete piles (30 30cm, 8.5m long) at the site under the soil condition similar to the above-mentioned. All piles were driven into gravel stratum for about 1-1.5m.

During the test a static load P_s was applied to the top side surfaces of pile through a special loading frame with vibration absorbers and kept constant during bibration. The vibrator which exerted the dynamic load P_d was directly mounted on the top of the testing pile (Fig.4).

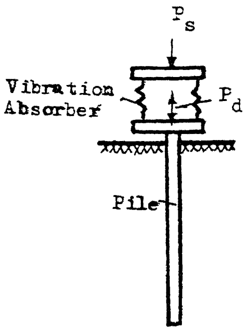

Fig.4. The Principle Scheme of Vibratory Loa ing Test on Pile

Before the dynamic testing static load tests carried out on piles by conventional method. load-settlement curves (Fig.18 and 19, for a= obtained from static pile tests showed that ultimate load P_J=60tf, (and P_J=84tf for reinforc concrete pile). Thus the static load P_s appli on each test pile was 1/3 P_J, 1/2 P_J and 3/4 respectively. Test procedure is as follows:

Firstly, a static load P_s was applied on the stepwise, then alternatively increased and dec ased by 5t, and the corresponding settlements measured. This process was repeated until the increment of settlement in every loading was equal to the elastic rebound in corresponding unloading, then the pile was excited by a vibr tor with constant acceleration for each test (a=0.03g, 0.05g and 0.15g successively). Durat of continuous vibration in each test was no le than 30 hours. Amplitudes and accelerations pile vibration were recorded during the test the settlements of piles regularly measured t accuracy of 0.01mm.

The graphs of the development of additional se tlements of steel pipe piles with time under d ferent vibration levels are shown in Fig.5, 6 7.

The same features in the development of settlements have also been found for reinforced concrete piles (Fig.8, 9 and 10).

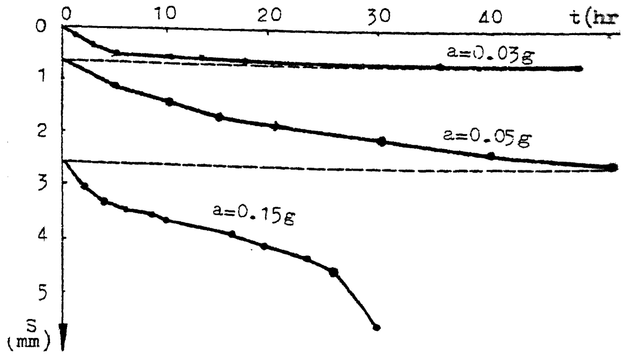

Fig.5. Development of Settlements of Steel Pipe Pile under Different Acceleration for P_s=45tf

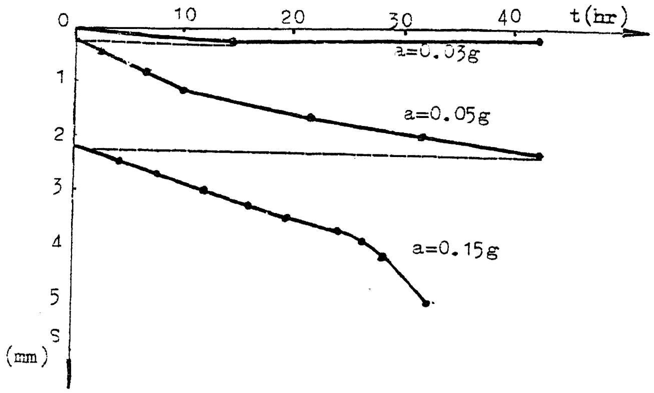

Fig.6. Development of Settlements of Steel Pipe Pile under Different Accelerations for P_s=30tf

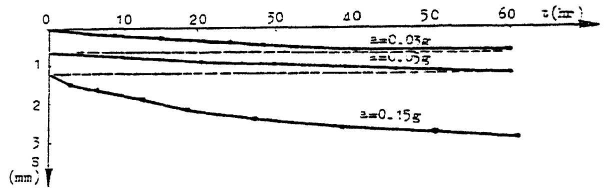

Fig.7. Development of Settlement of Steel Pipe Pile under Different Accelerations for P_s=20tf

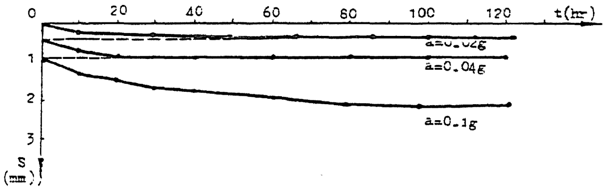

Fig.8 Development of Settlement of RC Pile under Different Accelerations for P_s=28tf

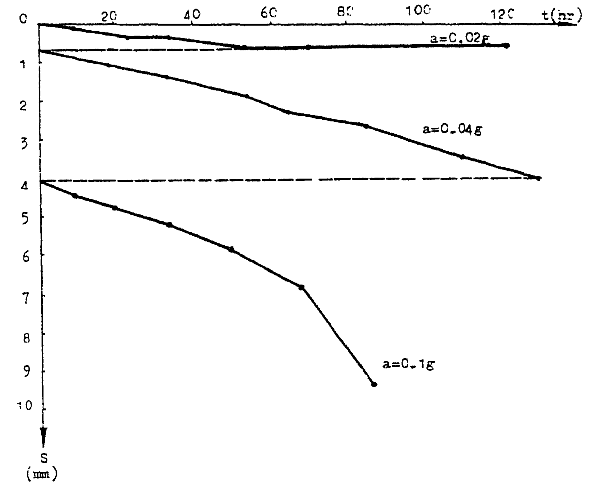

Fig.9. Development of Settlement of RC Pile under Different Accelerations for P_s=42tf

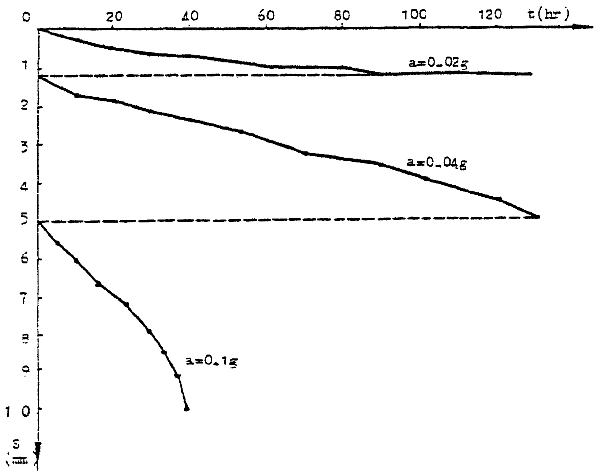

Fig.10. Development of Settlement of RC Pile under Different Accelerations for P_s=63tf

ANALYSIS OF THE EXPERIMENTAL DATA

1. Since the compression set of soil had been completed by a number of static cyclic loading before the vibrator was put into operation, so the additional settlement of pile is mainly due to the plastic deformation in soil directly beneath the pile tip.

2. Development of settlements with time exhibits the vibro-creeping behaviour of soil. As can be seen from Fig.11, the creeping rate may be increased, decreased or kept constant with time depending on the acceleration for a given sustained load P_s or depending on the sustained load P_s for a given acceleration. Consequently, the additional settlements are controlled both by acceleration and sustained load, which agrees with the investigation results.

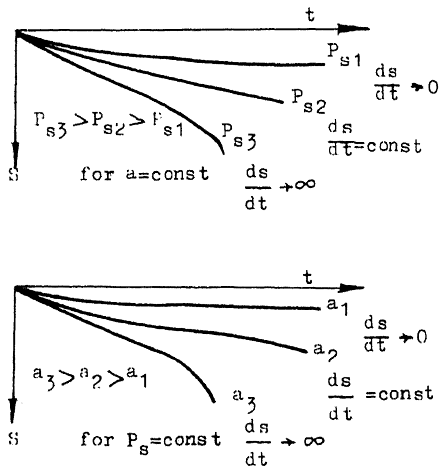

Fig.11. Dependence of Vibrocreeping Rate on Sustained Load and Acceleration

According to the field test results and long-term settlement data collected during investigation, a rheological model consisting of Bingham and Kelvin elements in series has been proposed to account for the vibrocreep behavior of soil (Xu Y. Z. et al 1982).

As shown in Fig.12, if the total stress is σ, then the total strain of the model can be written as

$$\varepsilon = \varepsilon_1 + \varepsilon_2 \tag{1}$$

or
$$\varepsilon = \frac{\sigma}{E}\left(1-e^{\frac{-E}{\eta_1}t}\right) + \frac{\sigma-\sigma_c}{\eta_2}t \tag{2}$$

in which

$$\sigma = \sigma_s + \sigma_d$$

where 'ε_1' is the strain due to the vibrocompaction, 'ε_2' is the strain due to the vibrorceeping, 'σ' is the total stress, 'σ_s' is the stress due to static load 'σ_d' is the stress due to dynamic load, 'E' is the spring constant, 'η_1' and 'η_2' are the viscosity factors of dashpots depending on the acceleration, 'σ_c' is the critical stress for the given level of vibration, 't' is the time interval.

When $\sigma < \sigma_c$ the lower part of the model refuses to act, so the second term on the right drops out. Thus, the creep does not occur and the model predicts essentially vibrocompaction of the soil.

When $\sigma > \sigma_c$, creep continuous indefinitely, its rate is dependent on the η_2 and the stress intensity σ , the greater the σ or the smaller the η_2 , the higher the creep rate.

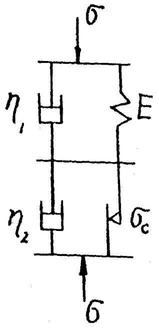

Fig.12. Rheological Model for Characterizing the Vibrocreeping of Soil

3. The skin friction resistence on piles decreases with vibration, and stress concentration is induced in soil directly beneath the pile tip, which has been confirmed by measuring the strains along the pile shaft and the load transferred by pile tip in the test pit. In Fig.13, curve 'a' and curve 'b' show the measured mean vertical stresses along the shaft before and during the vibration, curve 'c' and curve 'd' represent the estimated pressure distribution at the level of pile tip before and during vibration. That is one of the reasons which cause the plastic d formation appearing ahead.

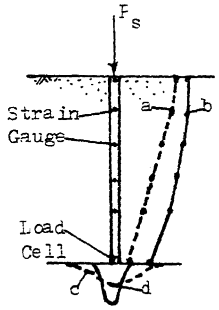

Fig.13. Stress along the Pile Shaft and Pre Distribution at Tip Level

4. On the other hand, soil strength decreases with vibration due to stress variation. If t principal stresses at a given point are σ_1 and under the vibration they will change to $\sigma_1 \pm \Delta$ and $\sigma_3 \pm \Delta\sigma_3$ respectively ($\Delta\sigma_1$ and $\Delta\sigma_3$ are the cy stresses due to vibration), which may lead to transient plastic equilibrium (Fig.14).

In addition, dynamic triaxial test results in cate that angle of dynamic friction is usuall smaller than that of static friction. Fig.15 shows the dynamic shear strength envelopes of dry sand samples for different ratios of init consolidation pressure 'K_c'' in comparison wit static one, where ϕ_d and ϕ are dynamic and sta friction angles respectively.

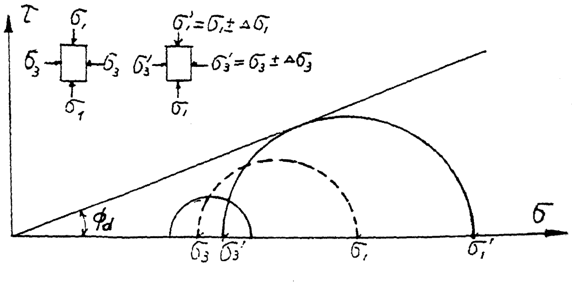

Fig.14. Stress Vaniation in Soil Due to Vibration

5. If the bearing soil strata are saturated, t the pore-water pressure may take place, especi ly for the fine sands with low relative densit Because of small magnitude of amplitude the po pressure goes up tremendously slow, but after long period of vibration it may still reach a value equal to the confining pressure or a val causing the failure of soil (Fig.16).

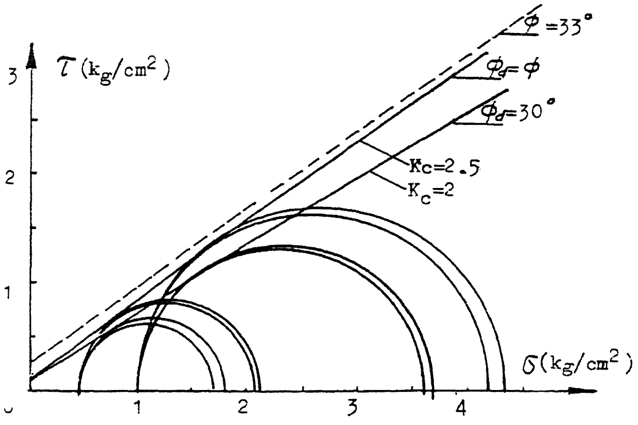

Fig.15. Dynamic Shear Strength Envelopes of Dry Sand

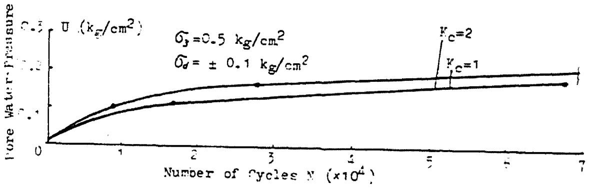

Fig.16. Development of Bore-water Pressure in Long-term Cyclic Triaxial Test on Fine Sand, e=0.60, D_r=72%

LONG-TERM BEARING CAPACITY OF PILE

If an additional settlement of 1mm is taken to be a tolerable value, the corresponding load for a given acceleration (such as a=0.15g for SP pile and a=0.19 for RC pile) can be consisered as the bearing capacity of pile. Then the graphs of development of bearing capacity with time can be obtained (Fig.17 and 18), which show that the bearing capacity of pile under long-term vibration P_t decreases with time and finally approaches to a minimum value P_{al} referred to as long -term bearing capacity expressed as follows:

$$P_t = P_{al} + (P_a - P_{al})e^{\frac{-t}{t_r}} \qquad (3)$$

where 'P_a' is the static bearing capacity of pile determined by load test, 't' is time interval, 't_r' is relaxation time dependent on soil condtions and acceleration.

Plotting the final stable settlements aqainst the corresponding loads for a=0.02g, 0.04g and 0.19g from Fig.8, 9 and 10 as well as that from static load test for a=0, a set of load-settlement curves for reinforced concrete piles can be obtained (Fig.19), and similar curves for steel pipe piles can also be obtained from Fig.5,6, 7 and static load test (Fig.20), whereby bearing capacity of pile for any desirable accelerations can be readily determined by interpolation

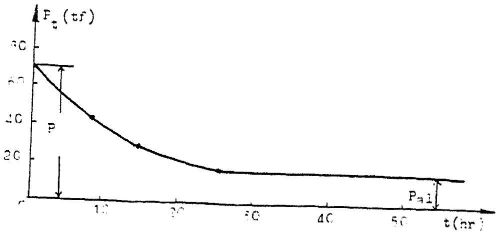

Fig.17. Develoment of Bearing Capacity of SP Pile With Time

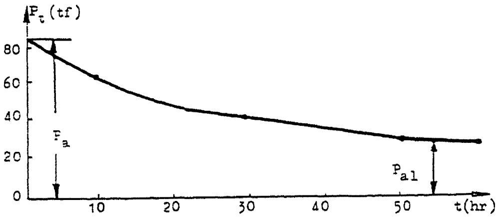

Fig.18. Development of Beating Capacity of RC Pile With Time

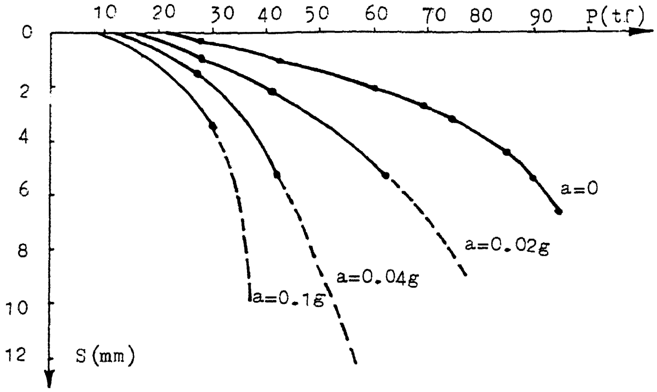

Fig.19. Load-settlement Curves of RC Piles for Different Acceleration

CONCLUSIONS

1. The continuous subsidences of pile foundations under long-term vibration are induced by the plastic deformation of bearing stratum under the pile tip, which is in turn caused by the increase in soil stress and decrease in soil strength.

2. The development of settlements with time has rheological features and its rate depends on vibration level and static load imposed on the pile.

3. Owing to the plastic deformation of soil induced by vibration, the bearing capacity of pile markably decreases with time and reaches a mini-

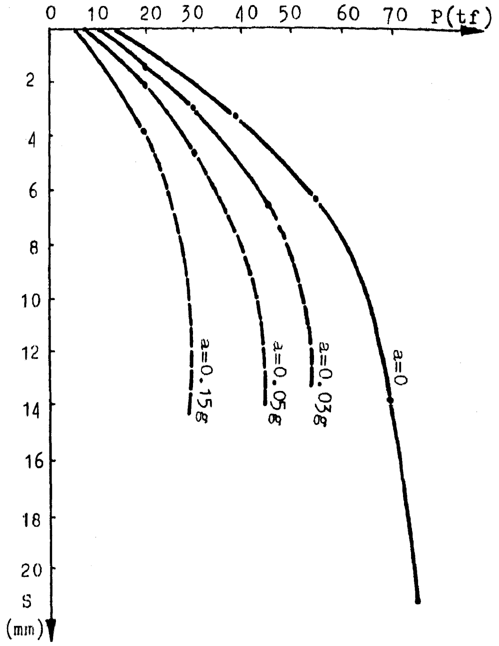

Fig.20. Load-settlement Curves of SP Piles for Different Acceleration

mum value known as loan-term bearing capacity which also depends on the vibration level.

4. Therefore, the permissible load on a pile should not exceed its long-term bearing capacity which can be determined by the dynamic load test described in this paper.

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