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A Study of Lateral Bearing Capacity of Pile by Dynamic Test

Paper No. 5.16

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SYNOPSIS In order to improve the knowlege of the Lateral Loading behavior of artificially drilled cast-in-place concrete piles, the full-scale lateral static and dynamic loading tests of eleven piles had been carried out by the authors in Louyang, China. In this paper, the principle of laterally dynamic pile test is discussed. The results of the static and dynamic tests performed in the light of different diameter piles are analyzed comparatively. It is found that the critical loads defined by the dynamic testing are almost identical with results of the static testing ones. Thus we come to a conclusion that the lateral critical loading of the single pile in the area can be determined by dynamic testing method.

INTRODUCTION

The pile used for earthquake resistant design will mainly bear the horizontal load over-turning moment. In the majority of aseismic design projects, pile design for super-structure will be carried out with refrence to equivalent static load analysis of the piles. Comparing with the vertically loaded pile, the laterally loaded pile has two remarkable characteristics, first, the soil-pile interaction is so complex that the behavior of the lateral pile and soil system is known very little; second, it is demanded that condition of the lateral soil-pile system must be within the elastic range in normal use. The lateral bearing capacity of the pile depends on the properties of lateral soil and the material of the pile used, namely the section stiffness of pile, embedded depth, the soil condition, horizontial allowable dis-placement and the fixed condition at the pile head and so on. Our on-site works of the dynamic and static tests of the pile showed that the lateral bearing capacity of the pile comes from the comprehensive responses of the various affecting factors described above.

Artificially drilled piles (cast-in-place) have been widely used as foundations in urban areas in China. Generally, their lateral bearing capacity is determined by the static load test. In recent years. the application of the dynamic pile testing has been rapidly enlarged not only in testing pile integrity but also in its capacity. Futhermore, these tests can become a cheaper, more rapid and more reliable pile quality control in com-paring with the static load tests.

The principle of laterally dynamic test is discussed in the paper. The static calculation may be simplified according to the relation between the data of the stiffness of dynamic soil-pile system test and static calculation. The dynamic and static full scale test results of the eleven piles, artifically drilled, are comparatively analyzed in loess-like soil both under the natural and saturated states. It shows that the dynamic pile test values of lateral bearing capacity are in accord with the static test critical loads, and so it comes to a conclusion that in Luoyang area the lateral critical load of a single pile may be determined by means of dynamic testing method, thus the allowable lateral bearing capacity of the pile may be obtained in a simpler way.

PRINCIPLE OF DYNAMIC PILE TEST

Horizontal Stiffness of Dynamic Pile Test

On the basis of vibrating theory, we first ex-cited the pile head horizontally as shown in Fig.1. and at the same time measuring the free vibration frequency of the lateral soil-pile system, and finally calculating the lateral pile capacity according to the horizontal stiffness of the dynamic test. Assuming the horizontal movement is X when the lateral force H acts on the pile head, then, $H=-K_x X$, inertia force $I=-m(d^2x/dt^2)$, on condition that there is not any other force,

$$d^2x/dt^2+\omega^2 x=0 \qquad (1)$$

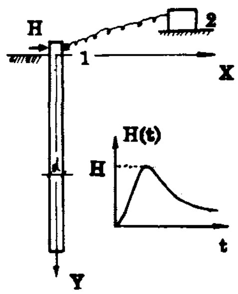
the solution to the Eq.(1) may be written as: $X=A_1\cos\omega t+A_2\sin\omega t$, in which ω =controlling parameter, $\omega=2\pi f_x=(K_x/m)^{0.5}$,

$$f_x=(1/2\pi)[(K_x g)/W]^{0.5} \qquad (2)$$

then,the dynamic horizontal stiffness of a pile:

$$K_x=[(2\pi f_x)^2 W]/g \qquad (3)$$

where W=weight of the soil-pile system participating in vibrating, calculated according to vibrating theory or the designing method of the vibrating footing (Y.Z.Xu, 1989).



1.Transducer
2.Dynamic Pile Tester

Fig.1 Sketch of the lateral dynamic pile test

Ralation between Dynamic Stiffness and Static Calculating

Generally speaking, linear elastic foundation reaction method is used for calculating the internal force and movement of the laterally loaded pile (横山幸满,1977, H.G.Poulos and E. H.Davis, 1980), that is, E. Winkler model, m method is one of it, recommended in China Foundation Design Code. According to the primary parameter equation in static calculation, the internal force and movement of the pile can be calculated on the basis of the ground surface and any depth below the ground level, and the maximum bending moment of the pile and its position can be calculated as well. If the piles are divided into high-rise and low pile caps or free and fixed-head piles, etc., then the calculation will be more complicated. This calculation may be simplified according to the dynamic testing, only five basic parameters need calculation, the others will be solved in light of these parameters. According to the half-space model, calculation of dynamic stiffness of piles may be found in papers by M.Novak (1974), X. Y.Yang (1982) and others.

It is demanded that the lateral soil-pile system must be within the elastic range in normal use, thus, both the lateral movement of the subsoil surrounding the shaft and deflection of the pile shaft are very much limited, then, this circumstance can be simulated by the low strain dynamic pile test (strain amplitude : 10^{-5}-10^{-4}). Simplifying m method, herein, we assume that the lateral modulus of subgrade reaction E_x is a constant within the depth of determining the lateral capacity. The comparative tests show that when piles occur small lateral movement, this simplification is possible, for the lateral loading behavior of piles is mainly determined by the soil-pile system of the number of times of the pile diameter near the ground surface. According to Y. L. Chang's principle of elastic foundation beam, we get the following: $d^4x/dy^4+4\beta^4 x=0$, then

$$\beta=[E_x/(4EI)]^{0.25} \qquad (4)$$

where EI=bending stiffness of pile shaft; β = characteristic coefficiet of piles deformation, the most fundamental parameters in the static calculating. It is appropriate to relate dynamic result with β. With refrence to Y.Z.Xu (1989), we get $K_x=(3/4)E_x l$, $E_x=(4K_x)/(3l)$, the E_q.(4) is then as follow :

$$\beta'=[E_x/(3EIl)]^{0.25} \qquad (5)$$

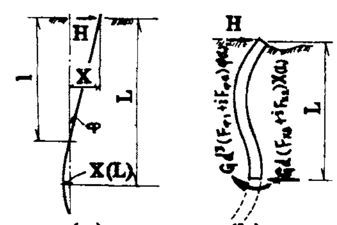
where l=depth of the first unmoved point of pile shaft (m), see Fig.2.

The five basic parameters for dynamic calculating are K_x, E_x, β (or β'), l and L. L is the depth of the first unturned point of pile shaft(m), it has no concerned with frequency, this concept has been confirmed in theoretically, see Fig. 2, in which F_{x1} and F_{x2}= displacement functions (X.Y.Yang, 1982), $F_{\varphi 1}$ and $F_{\varphi 2}$=rotational displacement functions (X. Y.Yang,1982). For free head and low cap piles, l and L are given by using the following:

$$l=\pi/(2\beta) \qquad (6)$$

$$L=(3\pi)/(4\beta) \qquad (7)$$

According to l and L, we may obtain the internal forces and some others (Y.Z.Xu,1989), meanwhile, can determine the critical load of a pile.



(a) (b)

Fig.2 Axial elastic curve of low free head pile

$$\text{low pile:} \quad H_{cr}=(\Delta E_x)/(2\beta) \qquad (8)$$

$$\text{high-rise pile:} \quad H_{cr}=[\Delta 3EI(\beta h)^3] / \{h^3[(1+\beta)^3+0.5]\} \qquad (9)$$

where h=height of pile head above the ground surface (m); Δ =pile shaft static horizontal movement at the ground level (mm), corresponding to H_{cr}, governed by the soil conditions and the material of the pile used, specially affected much by bending strength of pile shaft. Generally, we require of Δ < 6 mm when we calculate the critical load in terms of the dynammic pile test. The Δ value should be a constant for the same soil-pile system. The static designing parameters can be obtained from the dynamic testing ones. however, the dynamic ones must be divided by the dynamic modification factor.

Calculating the critical load from Eq.(8) or (9), then, the lateral allowable capacity can be determined by [China Cast-in-Place Piles Code of Designing and Construction JGJ4-80], which will be simplified as Code of JGJ4-80 in the following.

ANALYSIS OF TESTING RESULTS

Comparative Test One

In a project, Luoyang, the lateral dynamic and static tests were performed on two hand dug well piles (displacement pile). From the site investigation, the upper soil layers (3.5m thickness) are fill and neo-loess-like silty clay, the lower layer is the homogeneous loess-like silty clay (17.5m thickness). There is no groundwater in the depth of exploration.

In order to increase the lateral resistance, the two test pile shafts are designed as oral cross section, the equivalent circular diameter 1.15 m, pile length 15.6m (the embedded length 14.5m). To verify the effects of the enlarged base to the lateral deflection and capacity, the pile No.2 is dug out as the enlarged base, namely belled pier (the pile No.1 is not). The test pile have the same shaft section and steel reinforcing cage. The concrete strength is 24 MPa. The static load tests are conducted in the light of the Code of JGJ4-80, using the cyclic loading and unloading testing method. The test equipments include a horizontal jack, a transducer, a static resistance strainometer, a dial and a spherical hinged bearing and so on. The test result, H_o-$\Delta X_o/\Delta H_o$ curve for the pile No.2, is shown in Fig. 3 and hence the lateral critical load is 270 kN.

The dynamic testing is performed first. The testing equipments are illustrated briefly in Fig.1. The pile caps are installed on the pile head to meet the needs of the static load test. The subsoil around the pile head is all removed away before the tests, the tests are conducted in the test pit. The exciting point and transducer are all installed on the shaft below the pile cap. The dynamic test results of the pile No.2 are as follows: E_x=59000 kPa, l=5.52829m, L=8.72791m, K_x=317140 kN/m, β =0.29191(1/m), from Eq.(9), EI=2031400kN.m, h=1.0m, Δ =0.00482m, thus, H_{cr} =275kN. On the same principle, we may get the dynamic testing results of the pile No.1. The internal force and the others may be calculated on the basis of the dynamic pile test (Y. Z.Xu,1989), the calculation of others is omited.

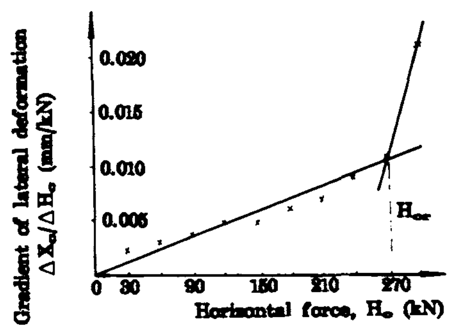


Fig.3. H_o-$\Delta X_o/\Delta H_o$ curve (pile No.2)

The dynamic and static results are listed for comparison Tab.1. We can see that the dynamic pile test values are in accord with the critical loads of the static test. The belled pier(pile No.2) does not either significantly decrease the lateral deflection or increase the lateral resistance. This conclusion coincides with thus appeared in the paper L. C. Reese et al. (F.G.Bell,1985).

Tab.1. Results of the Dynamic and Static Pile Tests (Test One)

Pile No.	Critical Load and Displacement		Contract Value of Critical Load, H_{cr} (kN)	
	H_{cr}(kN)	X_o(mm)	Static Test	Dynamic Test
1	315	1.76	315	320
2	270	1.66	270	275

Comparative Test Two

The test-site lies on both allluvial and diluvial soil layers, two grade self-weight non-collapse loess. The upper layer is the loess-like silty clay (15.0 m thickness), the lower layers are silty clay and cobble. There is no groundwater in the depth of exploration. The dynamic and static comparative tests of nine piles have been performed in loess-like soil both under the natural and saturated states. The test pile are artificially drilled (displacement pile).

The concrete strength of the piles is 23.5 MPa. The static load tests are carried out in terms of the Code of JGJ4-80, the test equipment are the same as the aforementioned tests (Test One). Taking the immersion test of the pile No.4 as example, H_o- ΔX_o / ΔH_o curve is given in Fig.4, the subsoil surrounding the shaft is in saturated state, then the lateral critical load is 40 kN. The length and diameter of the pile No.4 are 18 m and 0.4 m.

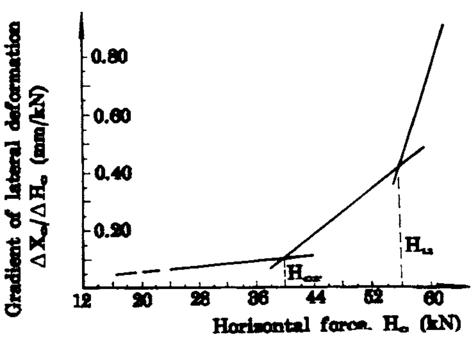


Fig.4. H_o- $\Delta X_o/\Delta H_o$ curve (pile No.4)

Tab.2. Results of the Dynamic and Static Pile Load Test (Test Two)

Soil State	Pile No.	Pile Diam. (mm)	Pile Length (m)	Contrast Value of Critical Load, H_{cr} (kN)	
				Static Test	Dynamic Test
Natural State	5	600	16	77(2.30mm)*	
	6	600	16	77(2.42mm)*	
	7	400	16	56(3.95mm)*	60
	8	400	16	56(5.39mm)*	62
Ponding, Saturated State	1	600	18	66(1.90mm)*	70
	2	600	18	66(7.14mm)*	71
	3	400	18	40(4.73mm)*	36
	4	400	18	40(2.56mm)*	
	5	600	16	70(5.74mm)*	74
	6	600	16	70(3.68mm)*	79
	7	400	16	45(10.87mm)*	35
	8	400	16	45(10.13mm)*	34

*Note—Figures in brackets are lateral displacement, X_o, corresponding to H_{cr}

The dynamic pile test is conducted before the static load test, the dynamic testing is performed in the way as being done before. The results of the dynamic and static testing which are for comparison were listed in Tab.2. From Tab. 2 conclusions can be drawn as follows: (i)the bigger pile shaft, the smaller lateral deflection and the higher lateral resistance. It is the same the other way round. (ii)the lateral movement increased under the saturated states of the subsoil surrounding the shaft and the lateral pile capacity decreased and (iii) regardless of the natural or saturated states, the critical loads defined by the dynamic testing almost identical with that of the static testing ones.

CONCLUSION AND DISCUSSION

The comparison of the results of the dynamic and static tests of the eleven piles (cast-in-place) in self-weight non-collapse loess under the natural and saturated states, shows that the calculated values defined by the dynamic testing almost identical with that of the static tests. The pile dynamic testing gives you both accuracy and stability. The static load test may be progressively substituted by pile dynamic testing in determining the lateral allowable capacity of the piles in Luoyang area including similar subsoil, where a large number of dynamic and static comparative tests had been done successfully.

From our experienes, the lateral bearing capacity determined by the pile dynamic testing is more accurate than the vertical one. There are many experimental formulas to calculate the vertical bearing capacity of the pile, e.g., the formulas based on static cone penetration test, SPT and soil parameter, etc. However, there is no similar practical calculating formula concerning the lateral bearing capacity of the pile, from this point of view, a formula for calculating the lateral capacity from the pile dynamic testing is of definite significance.

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