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THE BEHAVIOR OF A PILE FOUNDATION UNDER CYCLIC OVERTURNING MOMENT

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SUMMARY

This paper presents a method to estimate the rocking behavior of a pile foundation subjected to cyclic overturning moment during an earthquake. In this case, the non-linearities of both skin friction and pile tip reaction of the ground are taken into account. Comparing calculated results with pile test results, it is clarified that the effects of the non-linearities of skin friction on the pile behavior should not be disregarded in the estimation. Further, especially in the estimation of the rocking behavior of a pile foundation, the vertical dead load of a structure should be taken into account.

INTRODUCTION

For preventing damages of a building with a pile foundation due to seismic tilts and differential settlements, it is important to study the behavior of the pile foundation under seismic cyclic overturning moment as well as cyclic lateral load. These effects were especially pronounced in the Mexican earthquake of 1985.

To estimate the rocking behavior of a pile foundation, the adequate investigation of the cyclic vertical behavior of a pile is required.

In this paper, the writers examine the calculation method for a pile under cyclic vertical load at first, and then, investigate the effects of vertical dead load of a structure and others on the behavior of pile foundation under cyclic overturning moment.

ANALYSIS METHOD OF BEHAVIOR OF A PILE FOUNDATION UNDER CYCLIC OVERTURNING MOMENT

The rocking spring constant(KR) of a pile foundation as shown in Fig.1 is calculated by the following equation,

$$KR = M/\theta = \Sigma KV_j * L_j^2 \tag{1}$$

in which M is the overturning moment, θ is the rotating angle of a foundation, KV_j is the vertical spring constant of the j-th pile and L_j is the distance from the j-th pile to the rotating center of the pile foundation.

In the calculation of the vertical spring constant of the pile in Eq.1, to approximate precisely the behavior of the model pile, both soil and pile are sliced into multi-thin layers as shown in the same figure. The basic equation in an arbitrary contiguous i-th layer is expressed as,

$$AE(d^2y_i/dx_i^2) - QF_i(y_i) = 0 \qquad (2)$$

where, A is the cross-sectional area of the pile, E is the Young's modulus, x_i is the depth from the upper surface of the i-th layer, y_i is the pile's vertical displacement at depth x_i, $QF_i(y_i)$ is the skin friction and KF_i is the spring constant of the skin friction.

The non-linearities of both the skin friction(QF_i) in Eq.1 and the end bearing reaction(QT) at the pile tip are defined by Eq.3(Fig.2), which are obtained from many pile tests under cyclic vertical load. The values of both QF_i and QT for an arbitrary amplitude of displacement are divided by the value of QF_{i1} and QT_1, respectively, determined for y=1cm under the virgin load applied in each test. In the actual calculation for the pulling up load which becomes larger than the vertical dead load(PL) of a structure, the end bearing reaction of the pile tip is regarded as zero [B - C,in Fig.2(b)].

for virgin load : $QF_i/QF_{i1} = 1/\sqrt{0.35y_i^2 + 0.6y_i + 0.05}$ (3-a)

for repeated load: $QF_i/QF_{i1} = 2/\sqrt{0.35(y_i/2)^2 + 0.6(y_i/2) + 0.05}$ (3-b)

where, the origin of the coordinates of QF_i-y_i curve under the repeated load is set at the reflection point of the repeated load.

Now assuming that $Q(y_i)$ in each layer are constant, the general solution for Eq.1 can be given as follows :

$$y_i = A_i * exp(\alpha_i \cdot x_i) + B_i * exp(\alpha_i \cdot x_i) \qquad (4)$$

in which, α_i is $\sqrt{QF_i/AE/y_i}$, and A_i, B_i are the arbitrary constants. These constants are determined by applying the boundary conditions at the head and tip of the pile, and also from the continuity conditions between each layer.

The actual calculation of the pile as mentioned above is made by applying the convergence calculation with $QF_i(y_i)$ and y_i.

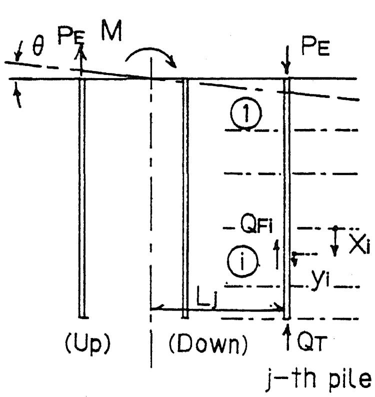
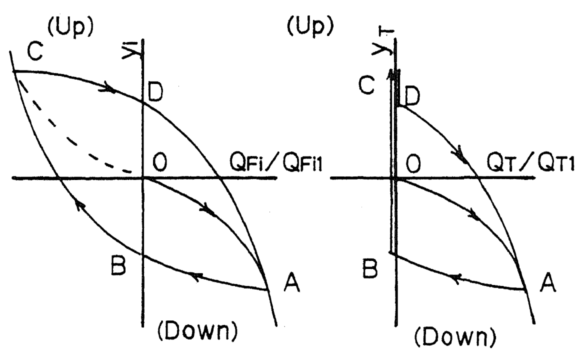


Fig.1 Model pile foundation for analysis



(a) Skin friction

(b) Reaction of pile tip's spring

Fig.2 Reaction-displacement curves for analysis

BEHAVIOR OF TESTED PILES UNDER CYCLIC VERTICAL LOAD

The writers have compared our results of analyses with those of cyclic vertical load tests on piles, and have proved the applicability of our calculation method of the vertical spring of a pile.

Calculations were made for two models of the tested piles which were driven in soft ground as shown in Fig.3, i.e., (i) TEST 1 : a steel pile tested under cyclic pulling up load and (ii) TEST 2 : a PC-pile tested under cyclic pushing down load. The diameter of the pile in TEST 1 is 35.5 cm and that of TEST 2 is 35 cm.

Curves of chain in Fig.4(a) shows the calculated hysteresis loops of the pile, which are the relations between the displacement and the vertical load at the pile head, in comparison with curves of full line obtained from TEST 1. The same figure(b) shows the result for TEST 2. These figures show that the both hysteresis loops calculated for the piles of TEST 1 and TEST 2 agree well with those of test results. It also shows that the bearing capacity of the pile in TEST 2(cyclic pushing down load) becomes greater than that in TEST 1(cyclic pulling up load) where the pile tip separates from the bearing stratum. Further, it will be made clear that the non-linearity of both calculated and measured hysteresis loops becomes larger as the displacement of pile head exceeds about 1 cm.

From the above results, it is said that the non-linearities of skin friction under pulling up load as well as that under pushing down load could be evaluated by Eq.3, and the calculation method proposed in this paper is applicable for estimating rocking spring of a foundation under cyclic overturning moment.

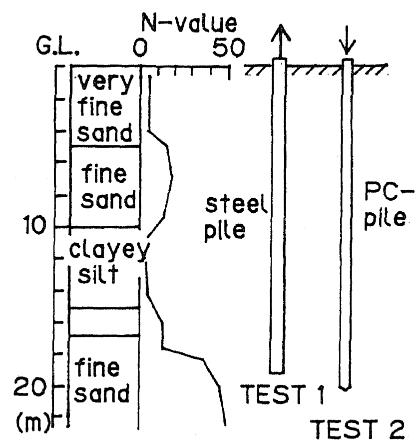
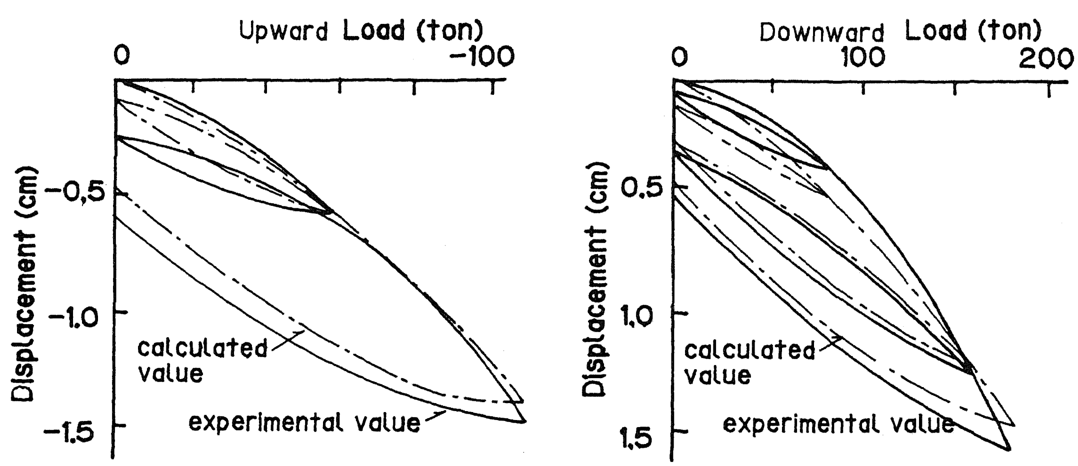


Fig.3 Boring log and tested piles



(a) TEST 1, cyclic pulling up load (b) TEST 2, cyclic pushing-down load

Fig.4 Hysteresis loops obtained from tests and that calculated

BEHAVIOR OF A MODEL PILE FOUNDATION UNDER CYCLIC OVERTURNING MOMENT

To get the accurate estimation of the rocking behavior of a pile foundation, it is important to make clear the behavior of a pile under vertical cyclic load, as mentioned before in Eq.1. From this viewpoint, the effects of the vertical dead load of a structure and others on the behavior of a pile under cyclic vertical load were investigated at first.

(1) Behavior of a pile under cyclic vertical load

Calculations were made for a analysis-model pile shown in Fig.5. In this case, the constants of the pile were varied, i.e., i) pile length(L_1) in the surface layer, ii)embedded depth(L_2) of the pile in bearing stratum and iii) spring constant(KT) of bearing stratum at the pile tip. The value of the KT in CASE I, which is shown in Fig.5, is determined from the test data of driven piles and that in CASE II is estimated by assuming the pile as a bored pile. As for the cyclic vertical load(PE) in this paper, we treat the seismic load which increases or decreases from the vertical dead load(PL) of a structure. The values of PL, PE and L_2 for each pile length(L_1) in this analysis are shown in Table 1.

Fig.6(a) shows the hysteresis loops of the piles, in which the vertical dead load(PL) is considered, as comparing with that of each pile as shown in Table 1. In this case, the spring constant(KT) at the pile tip is equivalent to that of CASE I in Fig.5, and the embedded depth of the pile is 1D(D:pile's diameter). The same figure(b) also shows a similar result of the piles calculated with neglecting PL. In the absence of PL, the non-linearity of a hysteresis loop on the side of the pushing down load becomes larger than that on the side of the pulling up load. On the other hand, in the absence of PL, the opposite tendency is recognized, especially with decreasing of pile length(L_1).

Fig.7(a) compares the hysteresis loops of the piles(L_1=20 m), in which the pile tip's spring of CASE II(Fig.5) is adopted, with those of the piles with different embedded depths(L_2). In the same figure, the loops in CASE I as mentioned above are also shown. In CASE I, the effect of L_2 on the loop behavior of the pile is almost neglected. On the contrary, that effect in CASE II becomes larger as L_2 becomes deeper, because, in CASE I, the tip bearing capacity of the pile is much larger than the skin friction at the part(L_2) of the pile. Further, in CASE II, the non-linearity of the loop becomes smaller as L_2 becomes deeper.

In the Fig.7(a), hysteresis loops are shown, in this case the pushing down load is applied on the pile head at first. On the other hand, the hysteresis loops, in the case the pulling up load is applied at first are shown in Fig.7(b). Comparing both figures, it is admitted that the hysteresis loops under the first cyclic load differ from each other, but those of under the second cyclic load and thereafter coincide each other.

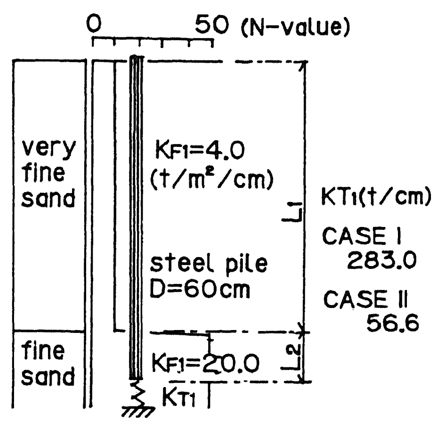


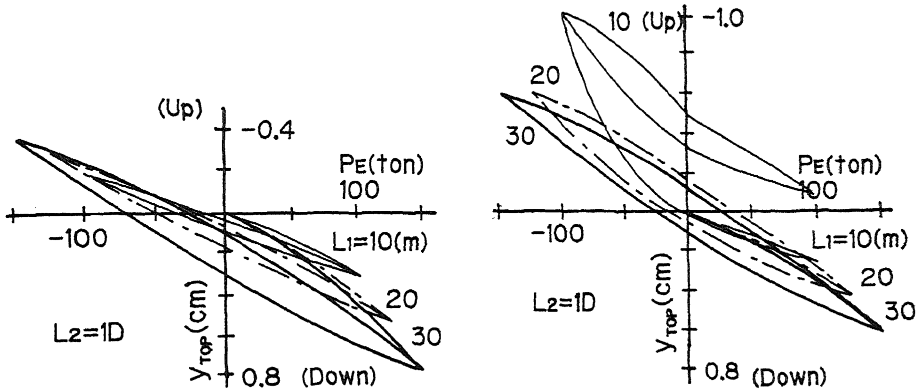
Fig.5 Model pile for analysis

Table 1 Model piles

L_1(m)	PL(ton)	PE(ton)	L_2
10	80	+100	
20	100	+120	0～2D
30	120	+150	

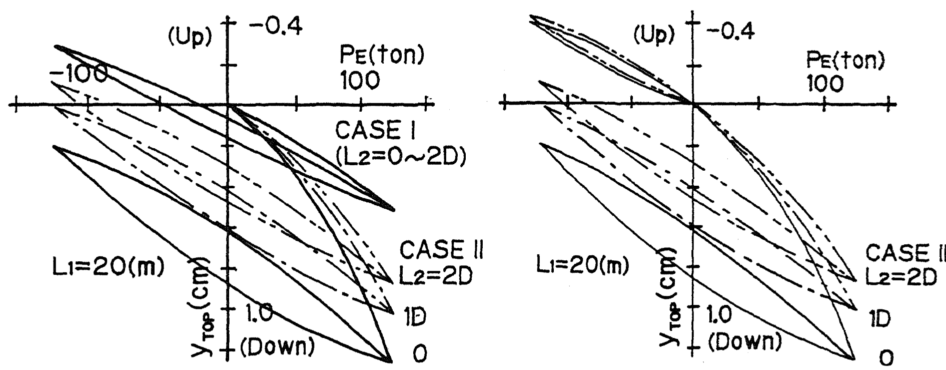
L_1, L_2 : Fig.5
D : pile's diameter
PL : vertical dead load of a structure
PE : seismic load

From above results, it is said that the effect of the vertical dead load of a structure on the vertical behavior of the pile can not be disregarded. Especially when the spring constant at the pile tip is weak, the effect of the embedded depth of the pile should not be neglected.



(a) Considering PL (b) Neglecting PL

Fig.6 Effects of vertical dead load(PL) and pile length(L1)



(a) Started with pushing up load (b) Started with pulling down load

Fig.7 Effects of initial load direction and embedded depth(L2)

(2) Behavior of a pile foundation under cyclic overturning moment

Calculations were made for a model foundation with two piles as shown in Fig.8, where analysis for a single pile had been made previously as mentioned in article (1). The distance between two piles is assumed 6 meters.

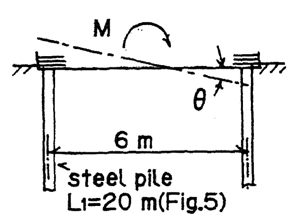


Fig.8 Model foundation for analysis

Fig.9 shows the hysteresis loops of the pile foundations, which are calculated with considering the vertical dead load(PL) of a structure, in comparison with those calculated with neglecting PL. As to the spring constant at the pile tip, the same value with CASE I(Fig.5) is adopted, and the pile length(L1) is assumed 20 meters. The area of hysteresis loop, that is hysteresis damping, becomes smaller with the presence of PL than without PL. Further, the value of resisting overturning moment of the pile foundation becomes larger with the presence of PL than without PL, because the vertical reaction of the pile situated on the side of pulling up load is smaller than that on the side of pushing down load, especially in the case the absence of PL.

Fig.10 compares the hysteresis loops of the pile foundations with two different pile length, L_1=10m and 30m, respectively, which are calculated with considering the vertical dead load(PL) as shown in table 1. From this figure and Fig.9(L_1=20m), it is noticed that the non-linearity of a hysteresis loop becomes greater as L_1 becomes shorter. Especially when L_1 is 10m, the rotating angle of the foundation increases extremely, as it becomes larger than 1*10-3 radian, and the shape of the loop becomes different from those in cases of longer piles.

As to the effect due to the embedded depth(L_2) of a pile on hysteresis loop, Fig.10 shows the comparison between the case of L_2=0 and L_2=2D(D:pile's diameter). In this case, the value of the spring constant at the pile tip is the same value with CASE II(Fig.5). Though the resisting overturning moment becomes greater as the L_2 becomes deeper, the value dose not reach the value of CASE I(Fig. 9). Further, the non-linearity of the loop without L_2 becomes larger than that with L_2. Whereas in CASE I, the effect of L_2 on the loop almost can be neglected by the reasons which was mentioned in the above article (1).

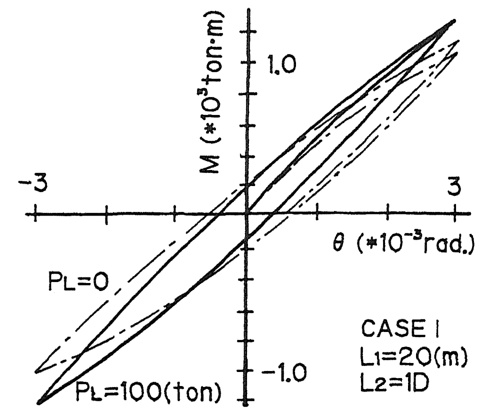


Fig.9 Effect of vertical dead load(PL)

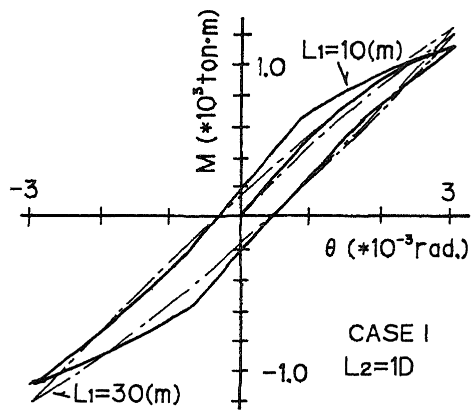


Fig.10 Effect of pile length(L1)

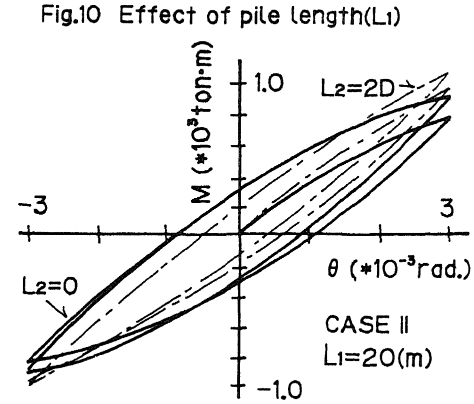


Fig.11 Effect of embedded depth(L2) of pile

CONCLUSION

These studies suggest that the calculation method proposed in this paper can be applicable for the estimation of rocking behavior of a pile foundation due to an earthquake. Further, the effects of vertical dead load of a structure as well as the non-linearity of skin friction on the rocking behavior of a pile foundation should not be disregarded.

REFERENCE

1. Kotoda, K., Kazama, S. and Turuda.K : The Hysteresis Properties of Rocking Spring of Pile Foundation under Cyclic Overturning Moment(Part 1), (Part 2), Summaries of Technical papers of Annual Meeting A.I.J.,1987 Foundation