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Earthquake Damage and Design Method of Piles

Dommage Séismique et Plan Méthode de Pieux

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SYNOPSIS Reevaluation of earthquake load to pile foundation and it's design method is strongly suggested from the evidence of damage caused by Off-Miyagi Prefecture earthquake in 1978. Several examples of the damaged piles and response analysis of an example of damaged pile foundation are introduced. And then, participation factor of horizontal force applied to piles is discussed for the purpose of rational seismic design of structures supported on pile foundations based on vibrational tests for model ground-pile-building system. A fundamental idea of design of pile foundation is proposed lastly as an appropriate statical method in which seismic effects are introduced.

INTRODUCTION

Since the earthquake on 12 June in 1978 (Off-Miyagi Prefecture), several examples of damaged piles, especially prestressed concrete piles, have been discovered in Sendai City. This is the first experience in Japan that the piles used as building foundations placed in horizontal soil deposits being damaged by vibrational effects of earthquake ground motion. And the aspect of the damage suggests strongly reevaluation of earthquake load to piles and the very design method.

Of course, a few similar examples of damaged piles are already reported by Kishida (1966) and Fukuoka (1966) for the Niigata earthquake in 1964, and Tamura et al. (1973) for the Tokachi-oki earthquake in 1968. But these are, more or less, owing to particular causes such as liquefaction of sandy soil deposits or slope failure of artificial fill ground.

On this opportunity, a systematic research is planned and carried out including the studies such as observation research on earthquake damage of piles, earthquake response analysis of the building with damaged piles, and shaking table tests of model ground-pile-building system. The present paper introduces the findings so far achieved from these works.

EARTHQUAKE DAMAGE OF PILES

The actual conditions of the pile foundations investigated by observation are summarized in TABLE I, and the typical examples of damaged piles are shown in Fig. 1. All the cases excluding case 9 are located at the sites in plain condition. The typical failure mode is estimated as bending or bending-shear failure at the pile top under changing axial load with and without final crush, as shown in Fig. 1a to 1d. Two cases are followed by complete collapses of superstructures, but others are followed by slight or no damage of superstructures. These facts suggest the existence of a general tendency that the heavier the damage of piles, the slighter the damage of superstructures.

Following factors should be considered at least as the causes of the damage of pile foundations.

TABLE I Damaged Piles by 1978 Off-Miyagi Prefecture Earthquake

Case	Type of Building	Pile	Length (m)	Diameter (cm)	Ra (tf)	CRP	Failure Type	Damage of Structure	Geographical Condition	Main Soil Type	Name of Building
1	SRC 11FL	AC	12	60	150	Yes	CR	SY	Plain	Silt, Sand	Kohriyama
2	Box-RC 5FL	AC	16	40	60	Yes	BB	NN	Plain	Silt, Sand	Kohriyama
3	SRC 14FL	AC	24	60	160	?	CR	SY	Plain	Peat, Sand	Sunny Heights
4	Box-RC 4FL	PC	5	35	70	?	CR	NY	Plain	Clay, Sand	Chuo Shintaku Bank Sendai Hostel
5	Box-RC 5FL	AC	7	40	60	Yes	NN	NN	Plain	Clay, Sand	Nishi Nakata
6	RC 4FL	PC	9	30	25	Yes	NN	NN	Plain	Peat, Sand	Nakano Sakae Elementary Shool
7	RC 3FL	RC	6	25	15	?	NN	CO	Plain	Peat, Clay	Taiyo Gyogyo
8	RC 3FL	RC	5	25	20	?	BB	CO	Plain	Peat, Clay	Maruyoshi
9	RC 4FL	PC	10	30	30	?	BS	SY	Slope	Loam	Korean High School

Notation:
AC = Autoclaved prestressed concrete pile
PC = Prestressed concrete pile
RC = Reinforced concrete pile
R_a = Design bearing capacity per pile
CRP= Cracks during pile driving and cutting-off
NN = No damage
CR = Crush with bending-shear cracks
BB = Bending cracks without crush
BS = Bending-shear cracks without crush
CO = Collapse
SY = Slight damage with differential settlement
NY = No damage with differential settlement

a) Case 1 b) Case 1 c) Case 3 d) Case 4

Fig. 1 Typical Examples of Damaged Piles

(1) All of the piles shown in TABLE I are the concrete piles or the prestressed concrete piles, so that, the decrement of strength of pile members would be produced by small cracks during pile driving or cutting-off of pile top. Therefore, particular care should be taken into this effect in design process.

(2) Safety factor of piles might be smaller, because bearing capacity of a pile is designed considerably larger than usual design capacity, especially in case 1 and case 3. Besides, combined stresses of piles due to vertical and horizontal forces are not considered because design of horizontal resistance of piles is not sufficient in almost all cases.

(3) According to the strong motion records in Sendai City, the maximum accelerations at the ground surface are within the range of 250 to 300 gals. From this fact, those buildings in TABLE I are supposed to be vibrated by the larger earthquake ground motion than the design earthquake load of the standing code in Japan.

(4) Piles are supposed to be vibrated as if they were small shear-span columns between both ends of pile caps and lower sand or sand gravel layer, because thickness of surface soft clayey soil layer is very small.

ANALYTICAL EXAMPLE OF DAMAGED PILE FOUNDATION

An earthquake response analysis by the method shown by the author (1973, 1976) was performed for the building of case 1 in TABLE I. One frame section in the span direction (N-S direction) of the building including the heavily damaged piles was selected as an analytical example and simulated by lumped mass model of 25 degrees of freedom. It is necessary to divide the piles into two groups because the extent of damage is clearly different between heavily damaged south side and slightly damaged north side causing inclination of the building about 1/100.

All parameters of analytical model are assumed to be linear elastic, in order to check only the place where the stress of failure is firstly produced. Details of model and preliminary calculation results are reported by the author et al. (1980). After some improvement of model and input ground motion, calculation was repeated. Figure 2 shows an example of those results, time history of the bending moment and the shear force at the pile top of the south side group, which shows the response of bending moment agrees firstly with the value of the failure bending moment of the pile member.

From this fact, it may be possible to suppose that progressive failure would be produced at the earliest failure part by concentration of energy, and finally, crush of the piles would appear around that place, while other parts, where responses reach the failure stresses of piles later, would be damaged only slightly and escape from final crush.

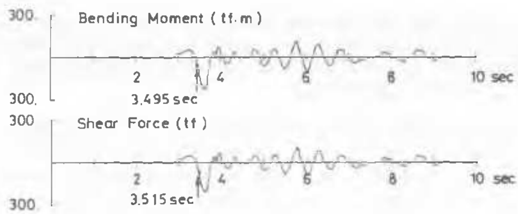

Fig. 2 Example of Analytical Results

VIBRATIONAL TESTS OF MODEL SYSTEM

Vibrational tests of model system by shaking table were performed by the Committee of Horizontal Reaction of Piles (1979) including the author. The main purpose of the tests is to check participation factor of horizontal force of footing and piles in dynamic condition. All parameters of model excluding damping ratio are adjusted by similitude law to the equivalent coefficients of the first vibrational mode of a certain typical residential building in Tokyo. The scale of length is selected as 1/30.

The size and material of each model are as follows: (1) ground (3.7m×1.8m×0.8m, chemical materials with bentnite), (2) pile (2 plates of 5cm×0.57cm×71.7cm, steel), (3) footing (box of 27.8cm×17.3cm×8.3cm with 7.5kgf weight, steel) and (4) structure (2 columns of 5cm×0.3cm×17cm with 12.4kgf weight, steel). Observation system of the tests is summarized in Fig. 3.

Figure 4 shows an example of the test results.

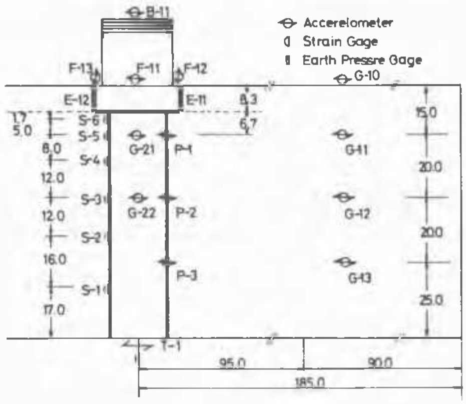

Fig. 3 Layout of Model and Observation System

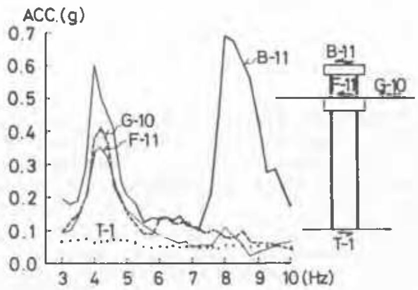

Fig. 4 Response Spectra of Acceleration

Two peaks observed at the top of structure (B-11) are corresponding to the natural frequencies of ground around 4 Hz and of structure around 8 Hz, respectively. The location (G-10) is free surface of ground which is not affected by the model structure. The difference of responses between footing (F-11) and ground (G-10) shows the sway of the building so that it may be possible to divide the total base shear force into two categories as follows:

$$V_T = V_G + V_B \tag{1}$$

in which,

$$V_T = \sum_{i=0}^{nn} \{m_i \ddot{X}_i\} \tag{2}$$

$$V_G = \sum_{i=0}^{nn} \{m_i \ddot{X}_G\} \tag{3}$$

$$V_B = \sum_{i=0}^{nn} \{m_i (\ddot{X}_i - \ddot{X}_G)\} \tag{4}$$

in which,

- V_T : total base shear force
- V_G : base shear component corresponding to response of ground surface
- V_B : base shear component corresponding to relative response to ground
- m_i : mass of each floor including foundation (i=0)
- $\ddot{X}_i$: acceleration response of each floor of building
- $\ddot{X}_G$: acceleration response of free ground surface
- nn : numbers of floor of building

Component V_B can be regarded as inertia force of superstructure due to excitation $\ddot{X}_G$. Component V_G is assumed to be approximately corresponding to the total result of interaction between ground and piles at each level. Results of this procedure and ratio of each component to the total base shear force are shown in Fig. 5a and 5b, respectively. These figures lead to the conclusion that the ratio of inertia component of superstructure V_B becomes on the whole about 0.8 and 0.2 in the range of natural frequencies of superstructure (8 Hz) and ground (4 Hz), respectively, and vice versa for the ratio of V_G. Figure 5c shows the ratio of horizontal reaction at footing denoted by E to base shear component V_B and vice versa for the shear force of piles denoted by P because the friction on the sides and bottom of footing is neglected. Horizontal reaction at footing is determined by the following algebraical difference equation, based on the measurement of earth pressure gages as shown in Fig. 3.

$$E = P_1 - P_2 \tag{5}$$

in which,

- P_1 : earth pressure increment at front of footing with positive sign
- P_2 : earth pressure decrement at back of footing with negative sign

It is necessary to note the possibility that earth pressure at footing is acting as a kind of input force rather than reaction in the range of about 6 to 7 Hz in Fig. 5b or 5c.

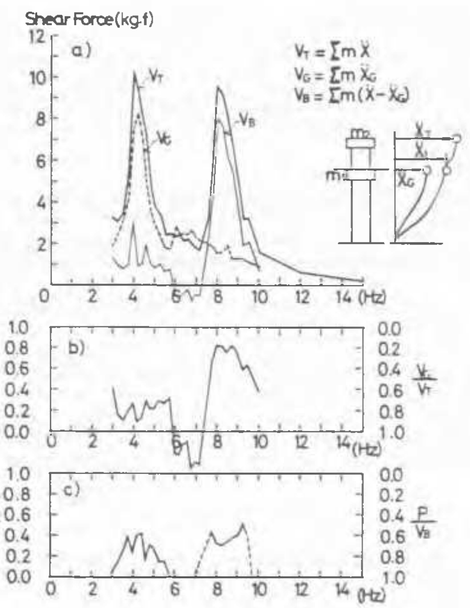

Fig. 5 Base Shear Force Component and Participation Factor

TENTATIVE DESIGN OF PILE FOUNDATION

From discussions above, a tentative draft of simplified procedure of design of pile foundation to horizontal force is proposed as shown in Fig. 6. The principle of this procedure consists in dividing external design force into two categories, i.e., (1) usual concentrated horizontal force at pile cap which is determined by inertia force of superstructure minus reaction at foundation, (2) distributed horizontal force over the total length of pile, for instance, triangle shape.

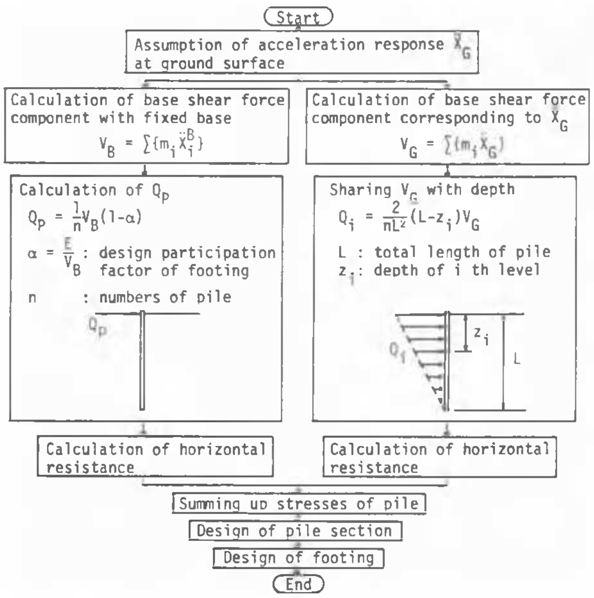

Fig. 6 Tentative Draft of Design of Piles

Inertia force of superstructure can be determined by assuming some available distribution shape of horizontal force at each floor and, of course, including sway component at foundation, if necessary. Design participation factor of foundation reaction should be taken as an appropriate value from such a relation shown in Fig. 5c, and the value not more than 0.3 is recommended here.

Regarding distributed force, the most fitting shape out of not only triangle but also other shapes should be used for representing effects of the natural vibration modes of ground.

Effects of pile grouping should be also taken into account to requirement. Finally, it is necessary to take summing up stresses of pile from both branches and to design pile section and footing. Two cases at least must be checked, i.e., at the first natural frequencies of superstructure and ground, respectively, and design will be made for the disadvantageous case.

CONCLUSION

Reevaluation of the current statical design method to horizontal force concentrated at pile cap is strongly suggested by the aspects of earthquake damage of piles and results from model vibration tests mentioned in this paper.

The most desirable method is, needless to say, the dynamic response analysis of total system of ground, piles and superstructure to some design earthquake ground motion. But it will be very convenient in earthquake-proof design of building supported on piles, if an appropriate statical design method of piles is prepared with due regard to seismic behavior of ground.

A tentative draft of such method is proposed in this paper as well as participation factor of horizontal force of piles. More detailed research on design method of piles will be continued, however, because the problem of how to deal with distribution of external force over the pile length, effects of earth pressure in input force state, effects of pile grouping and so on hereafter still remains.

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