

# STRESS CHARACTERISTICS OF PILE GROUP DURING EARTHQUAKE BASED ON CENTRIFUGE LARGE SHEAR BOX SHAKING TABLE TESTS

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## SUMMARY

Experimental investigations are performed on the stress characteristics of pile group during earthquake for general building based on centrifuge large shear box shaking table tests (model area:  $100 \times 50 \times 27.5$ m, input motion: above the Kobe Earthquake of 1995). Some interesting results are obtained on the stress characteristics of pile group, and contributions to a reduction of the stress of pile by footing beam of general building without basement floor are indicated. Simulation analyses have a good agreement with experimental results, and applicability for aseismic design of the analysis method is investigated.

## INTRODUCTION

The ordinary aseismic design of the pile foundation is based on the method of modeling a pile into elastic beam and loading inertial force at pile top. The method that also took in the influence of soil displacement [1], the direct method with superstructure [2], the static incremental analysis by the frame model [3], etc. may be used according to the grade of an aseismic design. Here, although the first method is simple, the influence of inertial force and the influence of ground motion are evaluated separately. Although the 2nd method can take a dynamic effect as a direct model with superstructure, it treats pile group as one pile in stress evaluation. The 3rd method is static analysis although the influence of a pile position is evaluated. On the other hand, in a real phenomenon, unknown points are left behind about the pile stress in case of a strong earthquake.

From these, this research investigated the stress of pile group in case of a strong earthquake by experiment. And the applicability as aseismic design of the analysis method was considered. The experiment is centrifuge large shear box shaking table tests about the building of 10 stories. The size of shear box is about 2x1x0.55m (centrifugal force 50G). This is equivalent to a 100x50m actual ground and a depth of 27.5m. The foundation is 3x4 piles. The used earthquake is larger than the Kobe Earthquake of 1995, and simulation analyses were performed.

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### **OUTLINE OF EXPERIMENTS**

#### **Experiment method**

The soil consists of two layers, the surface and bearing stratum. The building was not a part and modeled the whole. The excitation was carried out about the small earthquake, the middle earthquake, the damage limit earthquake, the safe limit earthquake, and the great earthquake. Among those, the result of the small earthquake and the great earthquake were shown here. Measurement was carried out about pile strain, building acceleration, soil acceleration, etc. In addition, the scale is described by 1G gravitational force field in consideration of the law of similitude after that (length, displacement: 50 times, velocity: 1 time, acceleration: 1/50, time, period: 50 times, frequency: 1/50).

## **Outline of test model**

The outline of test model is shown in Fig.1. The plane of the building is 12x18m. The footing beam was also modeled for every span. The footing beam depth is 2.5m. The pile is steel pipe pile (diameter of 500mm, thickness of 20mm). The pile length is 20m. The pile end was embedded to bearing stratum. The frequency and damping of the building at the time of fixing column base were checked by free vibration experiment. The frequency is 1.52Hz (0.66s). The damping is 1%. Free vibration wave is shown in Fig.2. Shear wave velocity (Vs) of the soil was counted backward from the transfer function of an experiment result (Fig. 3). It is 127 m/s (64 - 151 m/s), and density is 1.3 t/m<sup>3</sup>. Vs of the bearing stratum is 533 m/s, and density is 1.7 t/m<sup>3</sup>.



The sizes in this figure are a real scale.

Fig. 1 Outline of Test Model

#### **Input motion**

The input motion is the simulated earthquake ground motion specified by the Japanese Building Standard Law [4]. The maximum acceleration is 20gal in the small earthquake, and is 470gal in the great earthquake. As an example, the input motion and response spectrum of the great earthquake are shown in Fig.4 and Fig.5. The spectrum of the great earthquake shows the very large value of 120 cm/s on the bearing stratum.

### **RESULTS OF EXPERIMENTS**

#### Soil and structure

The response spectrum of the small earthquake is shown in Fig.6 (a). The peak of the natural period of the soil is in 0.7s. The peak of the natural period of the

soil-structure system is in 0.77s. The response spectrum of the great earthquake is shown in Fig.6



Fig. 3 Transfer Function of Free Field



of Input Motion (h=0.05)



Fig. 6 Response Spectrum (Superstructure, Ground Surface) (h=0.05)



Fig. 7 Distribution of Maximum Curvature

Fig. 8 Distribution of Maximum Curvature (Effects of Footing Beam)

## (b). By nonlinearity, both the soil predominant

period and the soil-structure system predominant period appear near 1.4s. The soil surface spectrum is over 300 cm/s. This is larger than the value of the Kobe Marine Meteorological Observatory which is one of the points that the largest record was obtained in case of the Kobe Earthquake of 1995.

#### Pile stress and effects of footing beam

The maximum curvature distribution of pile during earthquake is shown in Fig.7. The maximum ductility factor of piles is 1.63 in case of the great earthquake. Next, the same excitation was performed except for the sand of the footing beam circumference. Comparison of those results is shown in Fig.8. From these, if the footing beam does not share stress, it is shown that the pile maximum curvature of the great earthquake increases 1.5 to 3 times (the small earthquake one to 3 times). Thereby, even if soil stiffness goes down, it is indicated that the footing beam shares remarkable seismic force and it is contributing to reduction of the stress of pile. In addition, the building inertia force in case of the great earthquake when removing the sand of the footing beam circumference did not change so much with the time of not removing. Moreover, the almost same result was obtained about other piles.

## SIMULATION ANALYSES AND APPLICABILITY OF ANALYSIS METHOD

## Analysis method

The lumped mass model was used for the simulation analysis of experiment results. If this model is used, since dynamic analysis can be performed simply, it is promising as a prospective aseismic design method of pile. For this reason, this model was selected in order to examine verification of experiment results, and the applicability to the aseismic design method of pile. Since the soil spring matrix of a rigorous solution is contracted and used for this lumped mass model [5], [6], it can obtain the result simply near a rigorous solution. The outline of this analysis model is



Fig. 9 Analysis Model

shown in Fig.9. The stiffness and the damping factor of the structure were determined from the test (Fig.2). Nonlinearity is the bilinear type. The footing beam is assumed to be a rigid body. The pile was collected to one so that flexural rigidity might become the same. Nonlinearity was modeled in the bilinear type from yield momentcurvature and ultimate moment-curvature. The soil properties were defined from Fig.3. Nonlinearity is the Ramberg-Osgood model. The standard strain and the maximum damping constant were defined in consideration of confining pressure for every soil depth by the triaxial dynamic deformation test results. The nonlinearity of the soil spring and soil dashpot are also the Ramberg-Osgood model, and made the stiffness decreasing rate the same as the soil of the same depth.



Fig. 10 Time History of Acceleration (Arf)

#### Analysis results

Comparisons of time histories are shown in Fig.10. Comparisons of response spectrum (h=5%) are shown in Fig.11, Fig.12. Except the amplification in the short period area of the experiment result by noise



(Small Earthquake)

1500 (cm/ Experiment(Great eq,Arf Analysis(Great eq,Arf) 1000 500 0 0.1 1 (sec.) 10 (a) Superstructure (Arf) 500 (cm/s) Experiment(Great eq,A Analvsis(Great eq.Af1) 400 300 200 100 0 0.1 10 1 (sec.) (b) Ground surface (Af1)







Fig. 14 Response Spectrum

## Fig. 13 Distribution of Maximum Curvature

vibration, the analysis result harmonizes with the experiment result. Comparisons of the pile maximum curvature distribution are shown in Fig.13. The analysis result harmonizes with the experiment result in general. The variance in the curvature of the pile top of the experiment result is caused by the variance in the degree of pile top fixation and the stiffness decreasing.

## Applicability of analysis method

The applicability to the aseismic design of the used analysis model was examined paying attention to the soil constant setting. In a business design, although S wave velocity can be presumed from N value, since a triaxial dynamic deformation test is not performed, it is hard to acquire the information about the soil nonlinearity. Then, the influence of the method of

0.0 (m)

-2.5

-5.0

-7.5

-10.0

-12.5

-15.0

-17.5

-20.0

-22.5

setting up these constants (standard strain  $\gamma_{0.5}$ and maximum damping constant hmax) was considered here. As a method of not testing and obtaining these constants, use of the standard values [7] of the Building Standard Law can be considered in Japan. Then, the influence of applying the standard value to these constants was considered here.

Analyses are the following four cases. In analysis 1, the standard strain and hmax are the test values (the above-mentioned simulation analysis). In analysis 2, the standard strain and hmax are the standard values (standard strain  $=4.0 \times 10^{-04}$ , hmax=0.277). In analysis 3, hmax is the standard value and the standard strain is the test value. In analysis 4, the standard strain is the standard value and hmax is the test value.



Fig. 15 Distribution of Maximum Curvature

Comparison of the analyses 1, 2, and 3 about the superstructure response is shown in Fig.14. Since it hardly changed with the result of analysis 2, the result of analysis 4 was omitted. Since the difference between each analysis result is small, about the superstructure response, it is shown that the standard values are applicable to the soil nonlinearity constant. Next, comparisons of the pile maximum curvature distribution of analyses 2, 3, 4, and the experiment result are shown in Fig.15. Although analyses 2 and 4 differ from the experiment result a little, analysis 3 harmonizes with the experiment result. From these, about pile stress evaluation, although the standard value is applicable to the maximum damping constant hmax, the application to the standard strain requires examination.

## CONCLUSIONS

The centrifuge large shear box shaking table tests that has the following strong points were performed on the stress characteristics of pile group during earthquake for general building.

- 1. Not partial modeling but modeling of the whole of a structure (3x4 piles).
- 2. The wide area soil model (model area:  $100 \times 50 \times 27.5$ m).
- 3. The great earthquake input motion exceeding the Kobe Earthquake of 1995 (soil surface response spectrum: above 300cm/s).

The following results were obtained in the experiments and the simulation analyses.

- 1. The footing beam of a general building without a basement floor shares remarkable seismic load also with the case of a great earthquake. This contributes to reduction of the stress load of a pile.
- 2. The analysis result harmonizes with the experiment result.
- 3. Applying not examination results but the standard values to soil nonlinearity constants (standard strain and maximum damping constant) hardly affects response evaluation of a superstructure. However, about pile stress evaluation, although application to the maximum damping constant is possible, the application to the standard strain has the necessity for examination.

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