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EARTHQUAKE RESPONSE OF A PILE-SUPPORTED 16 STORY BUILDING DURING THE 1995 HYOGO-KEN NANBU EARTHQUAKE

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ABSTRACT

This paper discusses the earthquake response of a pile-supported 16 story S.R.C. structure during the strong ground motions based on the observed acceleration waves recorded during the main shock and aftershocks of the 1995 Hyogo-ken Nanbu earthquake. Response characteristics of the building are greatly influenced by the intensity of earthquake motions. The observation findings are analyzed in terms of earthquake response, with the 16 story building superseded by a spring-mass model mainly considering the non-linearity of the soil-pile system.

KEYWORDS

Earthquake response; Strong ground motion; Soil-pile-structure system; 16 story building; Observed record; Response analysis; Natural period; Damping factor; Hyogo-ken Nanbu earthquake

INTRODUCTION

The Hyogo-ken Nanbu earthquake, measuring 7.2 on the Richter scale, struck southern Hyogo prefecture at 5:46 a.m. on 17th January 1995. We obtained the acceleration records at the ground level and several locations at the building which was a distance of about 50 kms from the epicenter during main shock and aftershocks. According to the records, the maximum acceleration for EW component was 320 Gals on the top floor of the building , and 155 Gals on the ground. This paper discusses the dynamic behavior of the 16 story building during the strong ground motions, giving main consideration to the non-linearity of soil-pile system.(Ohba et al., 1995)

BASIC CHARACTERISTICS OF A BUILDING AND SOIL

The observed building is a 16 story steel frame reinforced concrete structure as shown in Fig. 1. This building is supported by cast-in place concrete piles of 180 cm and 220 cm in diameter and approximately 20 m in length. The building which measured 20 by 40 square meters, has a height of 65.65 m and a foundation depth of 5.2 m.

The soft alluvial layer of soil which measures 21 meters, accumulates above the diluvium which has an N value above 50. The alluvial layer is divided in to two layers, an upper layer of sand and a lower layer of clay. Microtremor measurements and a man-excited vibration test were applied to the building. Fourier spectra which analyzed microtremor records are shown in Fig. 2. Displacement waveforms for EW component during the man-excited vibration test are as shown in Fig. 3. The marks • in the figure indicate man-excited vibration repeated ten times by twenty persons. According to these figures, natural period is 0.88 sec and damping factor is 3.6% for EW component.

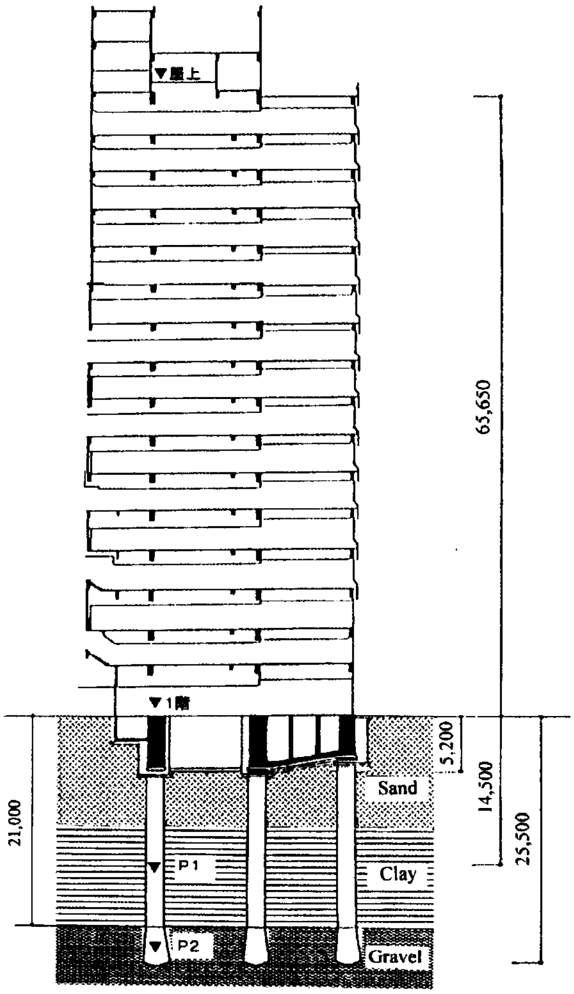


Fig. 1 Outline of building and soil.
Transverse direction (NS)

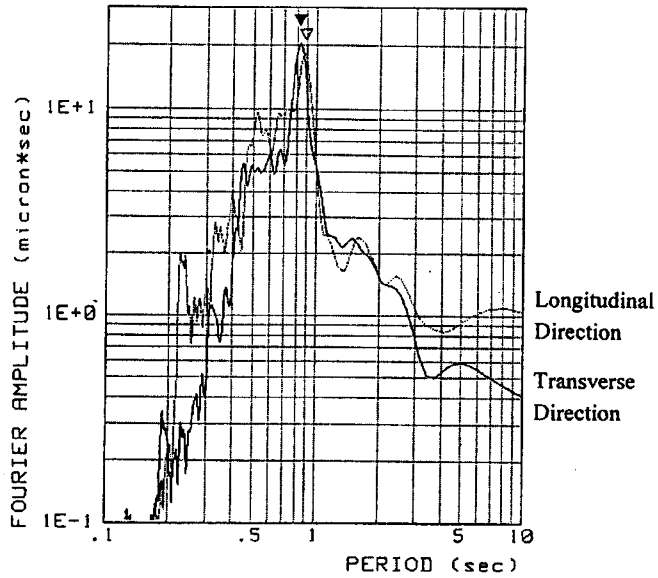


Fig. 2 Fourier spectra for microtremor

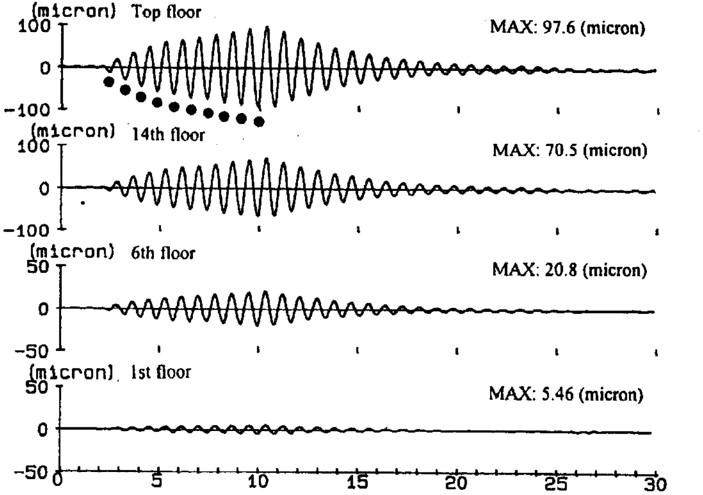
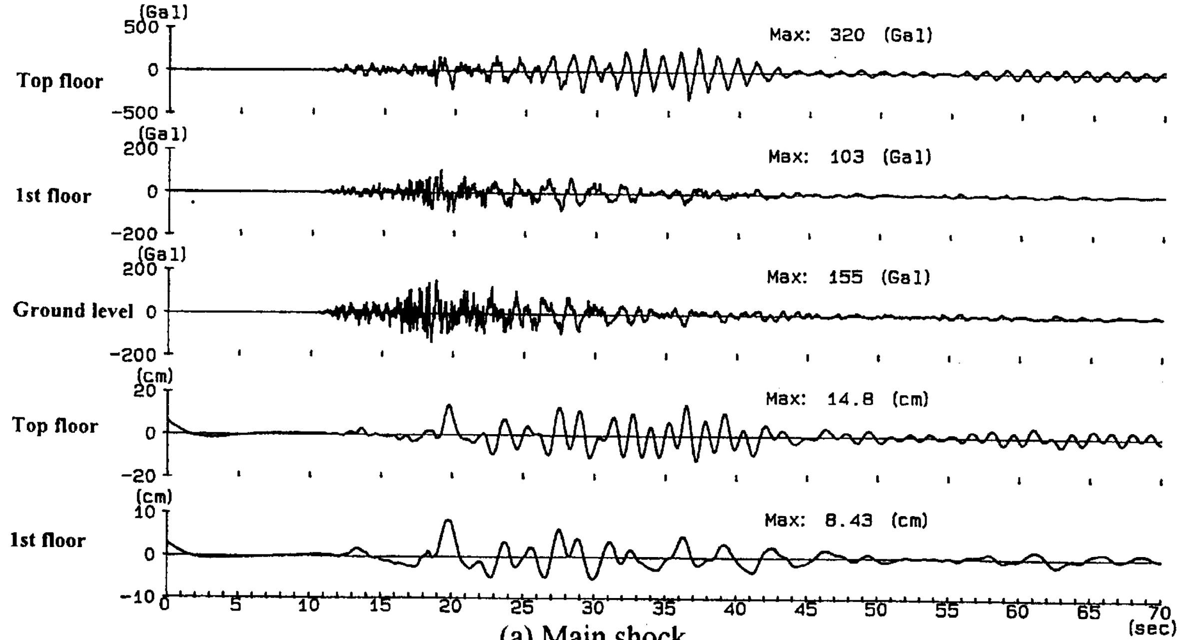


Fig. 3 Man-excited vibration records (EW)

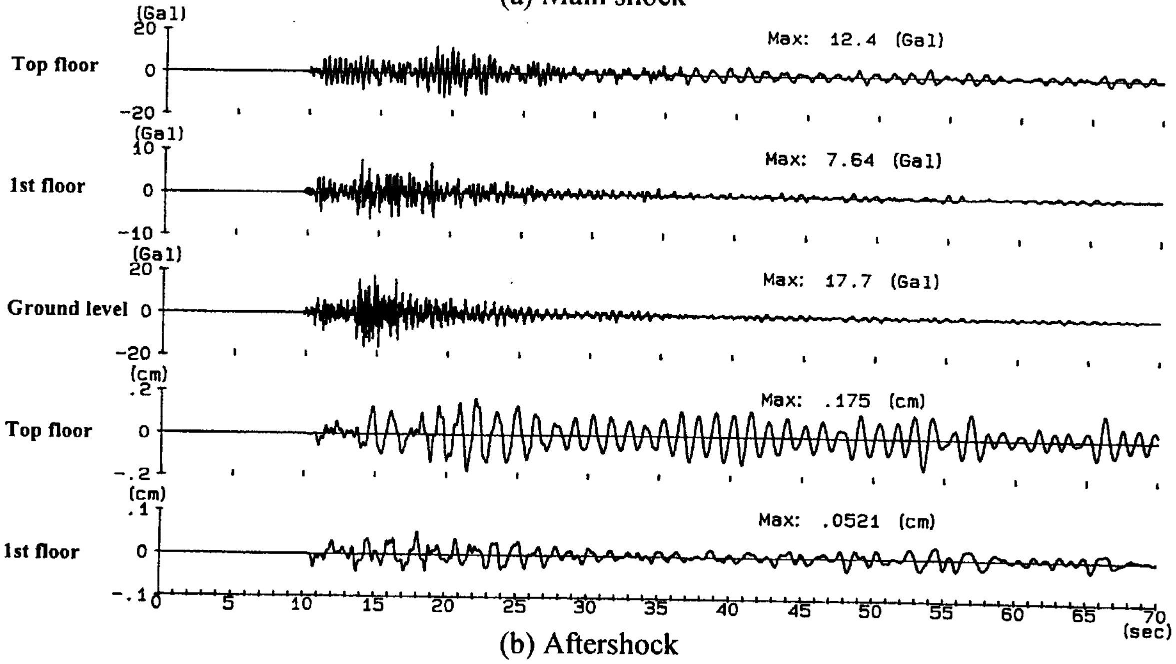
OBSERVATION OF EARTHQUAKE RESPONSE OF THE BUILDING AND GROUND

Earthquake waveforms observed at the top and the first floor of the building and on the ground level are shown in fig. 4. This figure presents the acceleration records and analyzed displacement waveforms during the main and aftershock. Fourier amplitude ratio of the top floor at the building to the ground level during the main and the aftershock are shown in Fig. 5. According to the figure, the natural period during the main shock is 1.3 sec, which is much longer than that during the microtremor.

The natural period is significantly influenced by the intensity of the earthquake response of the building. It can be seen from Fig. 6 that the natural period tends to be longer, as the maximum acceleration at the top floor of the building increases. The natural period during the main shock is approximately 1.5 times that of the microtremor.



(a) Main shock



(b) Aftershock

Fig.4 Earthquake response waveforms during the main and aftershock

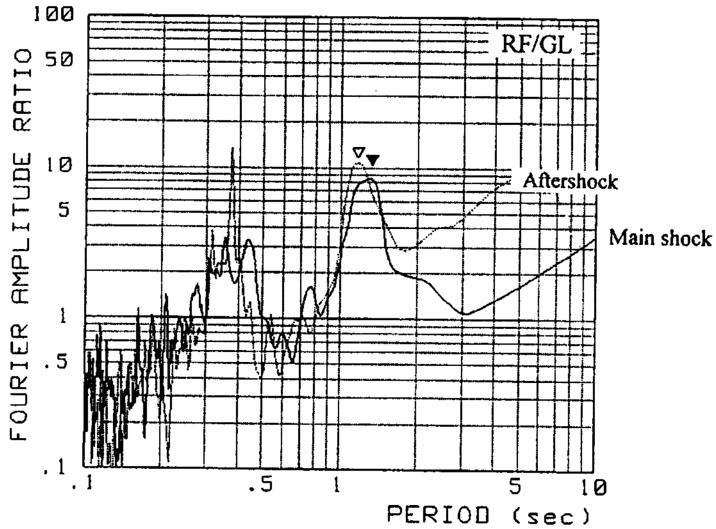


fig. 5 Fourier amplitude ratio of top floor at the building to the ground level

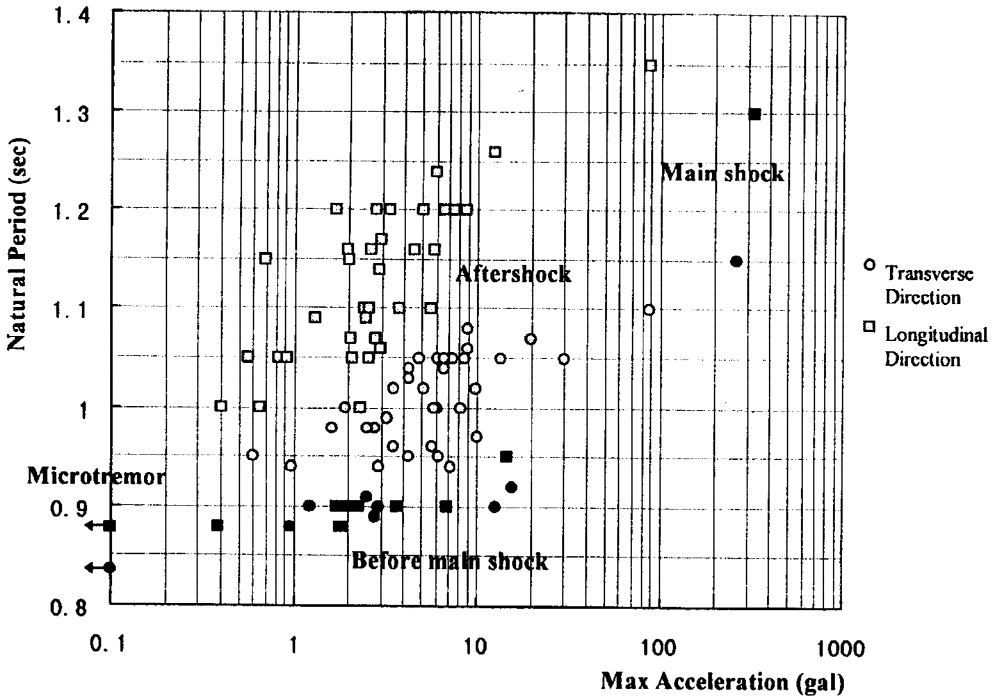


Fig. 6 Relation between the natural period and the maximum acceleration at the top floor of the building

DYNAMIC MODEL AND ANALYSIS OF EARTHQUAKE RESPONSE

The observation findings were analyzed in terms of earthquake response, with the building replaced by an interaction model of spring-mass system as shown in Fig. 7. Spring constants for soil-foundation interaction were evaluated by static calculation at the foundation bottom. In calculating the horizontal spring constants using equation (1), consideration was given to the embedment depth of the foundation (Ohba et al., 1987). Pile head displacement was evaluated by using Chang's formula for a fixed pile head, with proper correction made for coefficient of horizontal subgrade reaction depending on amount of pile-deformation.
Horizontal spring constant (K_H) is shown as follows :

$$K_H = K_{HP} + K_{HW} + K_{HF} \qquad (1)$$

where K_{HP} :Horizontal resistance of piles
K_{HW} :Front passive earth pressure for embedded portion
K_{HF} :Side frictional resistance for embedded portion

$$K_{HP} = n k_h B / \beta \qquad (2)$$

where $\beta = (k_h B / 4 E_p I_p)^{1/4}$
n :number of piles
B :Pile diameter (cm)
E_p :Young's modulus of pile (kg/cm^2)
I_p :Geometrical moment of inertia for pile (cm^4)
k_h :Coefficient of horizontal subgrade reaction corrected with pile head displacement taken into account (kg/cm^3)

$$k_h = k_{h0} y^{-1/2} \qquad (3)$$

where y :Horizontal displacement of pile head (cm)

$$k_{h0} = 5.6 N B^{-3/4} \qquad (4)$$

where N :Average N value obtained in standard penetration tests

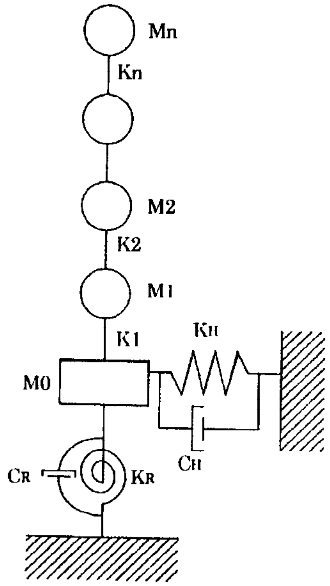


Fig. 7 Analytical model

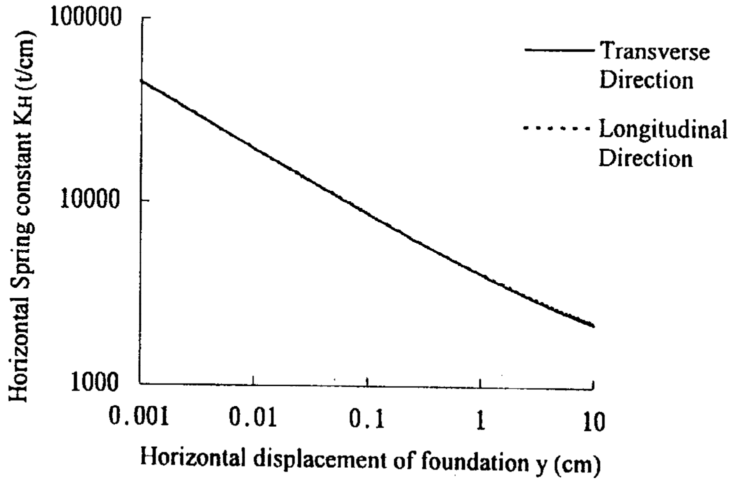


Fig. 8 Relation between horizontal displacement of foundation and horizontal spring constants

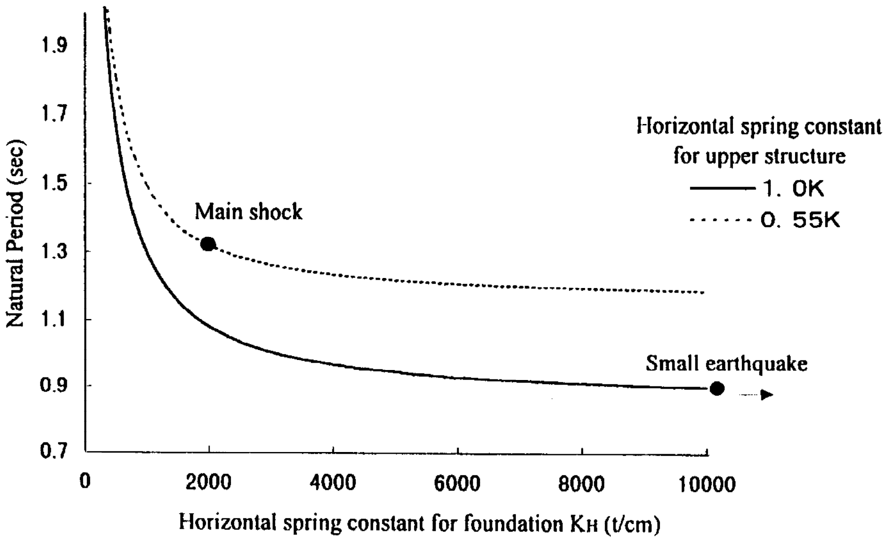


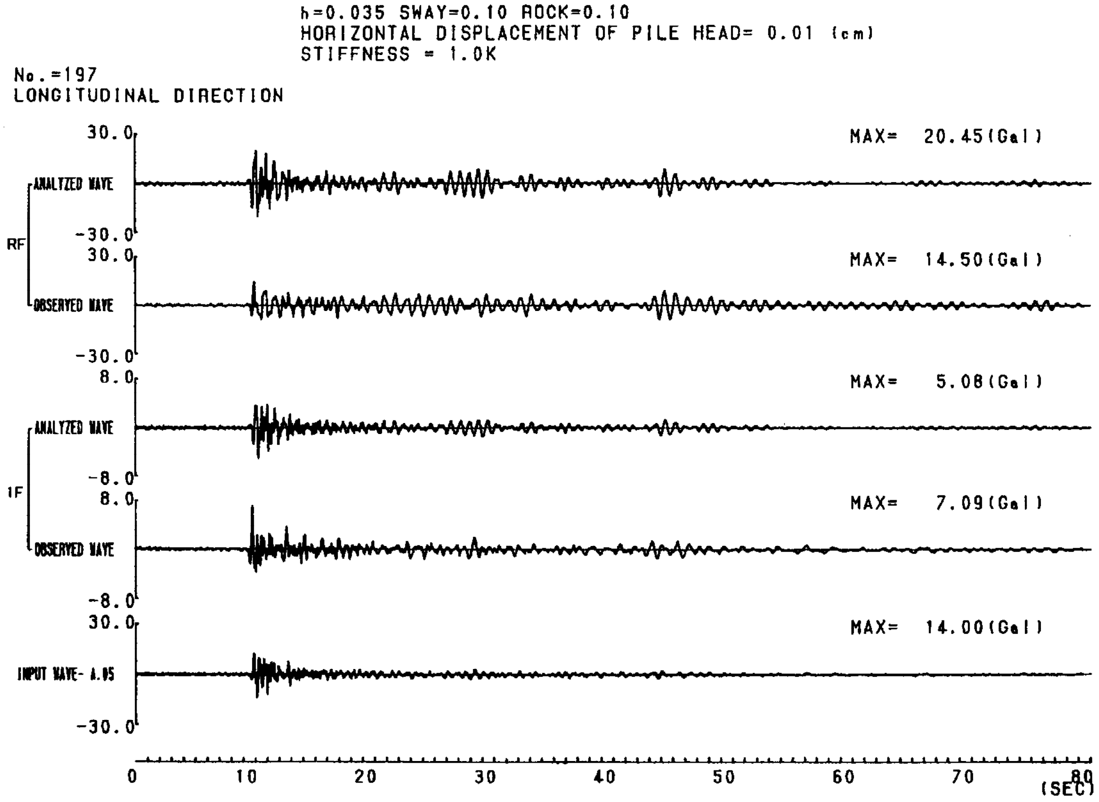
Fig. 9 Effects of soil-foundation spring constants on natural period

Effects of horizontal displacements of foundation on horizontal spring constants are shown in Fig. 8. Horizontal spring constants tend to decrease as horizontal displacements increase.

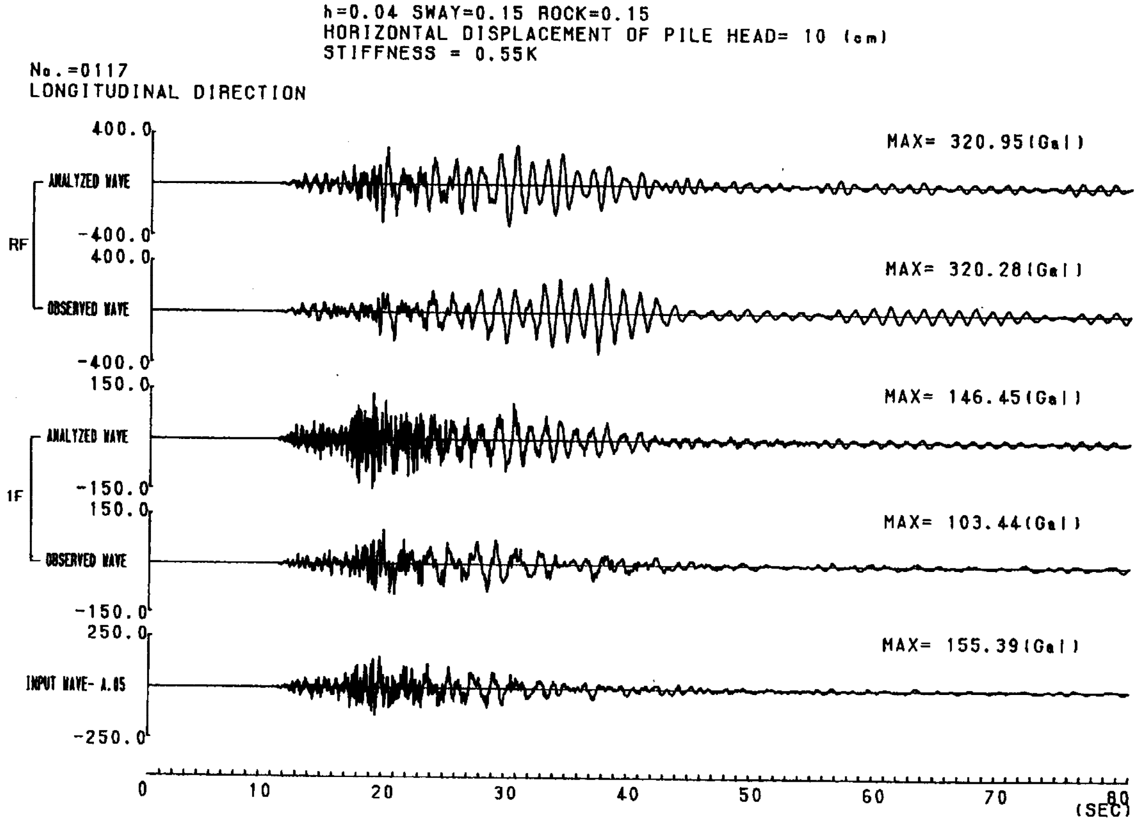
Rocking spring constants were evaluated based on vertical displacement comprised of pile settlement and axial pile deformation, with the rate of axial force reaching the pile end modified depending on ground conditions, and were obtained in accordance with the plane arrangement of piles.

The rigidity for upper structure was evaluated based on horizontal spring constant (K) calculated by elastic displacement of the structure. The horizontal spring constant was decided upon by comparing the natural period obtained from observation records with the natural period of the analytically determined results. Considering the non-elastic behavior of the structure, the horizontal spring constant during main shock was 0.55K. In this case, the natural period of the building obtained by analytical calculation, corresponded to the observation result.

The relation between horizontal spring constants for foundation and natural period of the building is depicted in Fig. 9. As this figure indicates, natural period tends to become longer as horizontal spring constants decrease. Measured values plotted in the figure were obtained from the small earthquake and main shock during the Hyogo-ken Nanbu earthquake.



(a) Acceleration waves during the small earthquake



(b) Acceleration waves during the main shock

Fig. 10 Comparison of observed and calculated waves at the top floor and the 1st floor of the building for longitudinal direction

The damping factor was determined by comparing the results of man-excited vibration tests with the analytical results. The response of the building was analyzed with the damping factor assumed, and calculation was repeated on a trial and error basis until analytical results corresponded to the observed waves obtained by man-excited vibration tests. The damping factors obtained when both waveforms almost agree, are 2% for upper structure, 10% for sway and rocking vibration. According to the observation results during earthquakes, the damping factor increases as the earthquake response of the building increases. When the earthquake response of the structure is analyzed, the damping factor must vary according to the intensity of the earthquake motions.

COMPARISON OF OBSERVED AND CALCULATED WAVES

Fig. 10 (a) shows the acceleration waves during the small earthquake observed on the top floor and the first floor of the building, in comparison with the wave calculated by an analytical model as shown in Fig. 7. In this case, the damping factor was evaluated to be 3.5% for upper structure, 10% for sway and rocking vibration. Fig. 10 (b) shows the observed and calculated acceleration waves during the main shock. In this case, the damping factor was evaluated to be 4.0% for upper structure, 15% for sway and rocking vibration. The analytical model, though simplified, satisfactorily represents the earthquake response of the observed building.

CONCLUSION

Observation and analysis conducted for the earthquake response of the 16 story building during the main and aftershock are summarized below.

(1) Transfer characteristics from ground to structure are significantly influenced by the intensity of the earthquake motions. As the intensity of the earthquake motion increases, the natural period tends to be longer and damping factor tends to be larger.

(2) The natural period of the building during strong ground motion is approximately 1.5 times that of a microtremor. It can be primarily shown that the pile and soil are non-elastically deformed by a force stronger than the substance's elasticity limit.

(3) The behavior of a building during strong ground motion can be estimated from a simplified computer generated model of the spring-mass system, by using the simulated evaluation method for the dynamic spring constants and damping factors.

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