Nonlinear Dynamic Experiments and Analyses of Embedded Building Model

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ABSTRACT

Shaking table tests on a simplified model were conducted to confirm the dynamic response of an embedded structure resulting from the plasticity of the surrounding soil and the nonlinear dynamic earth pressure acting on the embedded walls of the structure. A new analytical method of finding the dynamic nonlinear response of an embedded structure was developed. In this method, the plasticity of the surrounding soil and the geometrical nonlinearity at the interface of the structure and the soil are simultaneously considered. This method can simulate the nonlinear dynamic earth pressure on the underground walls of the structure model observed in the shaking table tests.

INTRODUCTION

When the effect of severe earthquakes on structures is considered, geometrical nonlinearity such as friction at the soil-structure interface and the asymmetric character of the dynamic earth pressure must be taken into account, because these factors greatly affect the response of the structure.

To confirm the nonlinear phenomena mentioned above, shaking table tests were carried out on a simplified building model, and a new analytical method was developed.

MODEL SHAKING TABLE TESTS

Shaking table tests were performed on a model as shown in Fig. 1. The building model, which can be regarded as a rigid body, was placed on the center of the supporting ground and then the surroundings of the building were backfilled with Toyoura Sand (specific gravity of solids = 2.65, 10-percent grain size = 0.16mm, uniformity coeficient = 1.35, the maximum and minimum unit weight = 1.645 gf/cm^2 and 1.335 gf/cm^2, respectively). In addition, to simplify the test conditions, silicone rubber, which can be regarded as an elastic body, was used for the supporting ground so that nonlinearity was only generated in the backfilled soil.

Horizontal excitation was supplied by 20 cm/sec^2, 50 cm/sec^2 and 100 cm/sec^2 sweep waves to the building model for backfilled depths of 20 cm and 30 cm. The frequency range was 2.8 Hz to 42.0 Hz.

Fig. 2 shows the transfer functions of the horizontal acceleration of the top of the building model to the shaking table. The first peak in each transfer function represents the natural frequency of the building model for rocking, while the second peak represents the first natural frequency due to shear deformation of the soil. For each input acceleration, the deeper the backfilling, the higher the natural frequency of the building model for rocking tends to be. Moreover, for each backfilled depth, the natural frequency of the building model for rocking decreased when the input acceleration increased. This is considered to be due to the nonlinearity of the backfilled soil and the dynamic earth pressure on the underground walls.

Fig. 3 shows the relationship between earth pressure and the relative displacement of the building model to the backfilled soil. The figure suggests that the dynamic earth pressure yields in the active region.

METHOD OF NONLINEAR ANALYSIS

The method of nonlinear analysis proposed in this paper is characterized as follows:

a) A Finite Element Method is utilized to make models of the soil and the Building.
b) The geometrical nonlinearity of slide, separation and uplift between the building and the soil is represented using nonlinear connecting elements (Hara, 1987).
c) Plasticization of the soil, namely its material nonlinearity, is handled using equivalent-linear analysis.
d) Reliability of the analytical method has been confirmed by comparing the results with those from shaking table tests on uplift for a building without backfilled soil (Hara, 1987).

A flow chart of the analytical method is given in Fig. 4. As geometrical nonlinearity which substantially affects the response of the building only occurs when the input acceleration exceeds a certain limit, it is sufficient to take account of plasticization of only the surrounding soil for cases where the input acceleration is small (Fig. 4 *1). On the contrary, when the effect of geometrical nonlinearity is large, the value of plasticization of the surrounding soil from the nonlinear analysis differs greatly from the value assumed by equivalent-linear analysis. Therefore, further nonlinear analysis is necessary to obtain the value of plasticization of the surrounding soil (Fig. 4 *2).

An analytical model for a backfilled depth of 20 cm is shown in Fig. 5. The building and two kinds of soil are divided into two-dimensional FEM elements. Nonlinear connecting elements, which consist of axial springs and friction springs as shown in Fig. 6, are put between the building and the soil. The initial stress due to the model's weight was taken into account when judging conditions for slide and separation of the nonlinear connecting elements. In the equivalent-linear analysis as the first step of the method, the nonlinear connecting elements are replaced by linear springs. The constants used in the analyses are given in Table 1.

In the analytical model, the Young's modulus for the building model was fixed, and its weight was distributed so that the moment of inertia and the center of gravity of the building agree with those of the test model. The Toyoura Sand has the initial shear modulus, Go, given by,

$$Go=1650\sigma v^{0.5}\ (\mathrm{kgf/cm^2})\ ....(1)$$

where

σv=vertical stress (kgf/cm^2)

Shear modulus and damping ratio with shear strain as shown in Fig. 7 was obtained from simple shear tests carried out on Toyoura Sand. In this figure the value for the abscissa is normalized with the shear strain $\gamma_{0.5}$, which is the shear strain when the shear modulus is half of the initial shear modulus.

$$\gamma_{0.5} = 0.0569 \sigma_v^{0.5} (\%) \ldots\ldots\ldots\ldots (2)$$

The value of the tensile stress at which separation begins to occur for the nonlinear connecting element was obtained from the test results shown in Fig. 8. Also, the friction coefficient between a steel building and Toyoura sand was assumed to be 0.1.

RESULTS OF SIMULATION ANALYSIS

Equivalent-linear analysis and nonlinear analysis were performed according to the flow chart shown in Fig. 4. Fig. 9 shows the transfer functions of the acceleration of the top of the building model to the shaking table. Waveforms of the response acceleration of the top of the building model and the dynamic earth pressure on the underground walls are shown in Fig. 10 and Fig. 11. These figures give the results from the model tests, equivalent-linear analysis and nonlinear analysis for backfilled depths of 30 cm and 20 cm under 50 cm/sec^2 excitation.

The natural frequency for rocking obtained from the equivalent-linear analysis for both backfilled depths are higher than those from the tests, because in the equivalent-linear analysis the dynamic earth pressure on the underground walls acts in both compression and tension. However, the use of nonlinear connecting elements gave results which agreed well with those from the tests. In addition, with regard to the waveforms of dynamic earth pressure, it is proved that such a phenomenon as asymmetry of dynamic earth pressure on the active region is favorably reproduced by analysis using nonlinear connecting elements.

EFFECT OF SLIDE AND SEPARATION

To examine the effect of slide and separation, the model with a backfilled depth of 20 cm shown in Fig. 5 was used. The analysis was done for two cases, one being a linear case and the other a nonlinear case. For both cases, constants for the above-mentioned equivalent-linear analysis for a backfilled depth of 20 cm under 50 cm/sec^2 excitation were used. As an external force(moment), a couple consisting of a sinusoidal waves of frequency 5 Hz was made to act on the top and the base of the building. The equivalent rocking rigidity and the equivalent rocking damping ratio were calculated from the hysteresis loop of the overturning moment around the base of the building and the angle of inclination of the building. To compare the linear and nonlinear cases, the ratios of the nonlinear case to the linear case for the rigidity and the damping ratio were calculated.

The results are shown in Fig. 12. From this figure, the following points were confirmed concerning the geometrical nonlinearity of slide and separation.

a) Even when only slide occurs between the underground walls and the backfilled soil, its geometrical nonlinearity can greatly affect the response of the building.
b) The equivalent rigidity of rocking decreases due to slide and separation.
c) The equivalent damping of rocking first increases due to slide but then decreases due to separation.

CONCLUSIONS

The following conclusions were obtained from this study.

a) The effects of the material nonlinearity of the surrounding soil and the geometrical nonlinearity of the dynamic earth pressure which acts on the underground walls were confirmed by the results of the shaking table tests on the model.
b) The nonlinear phenomenon of dynamic earth pressure on the undergound walls found by the tests could be reproduced with analysis using nonlinear connecting elements.

c) The effect of the geometrical nonlinearity of slide and separation on the underground walls was analyticaly confirmed.
d) Based on the above conclusions, the accuracy and the reliability of this analytical method was proved.

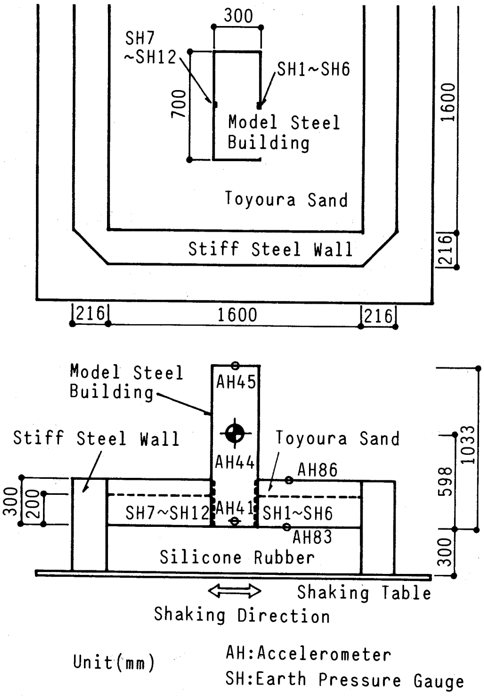


Fig. 1 Outline of Test Specimen

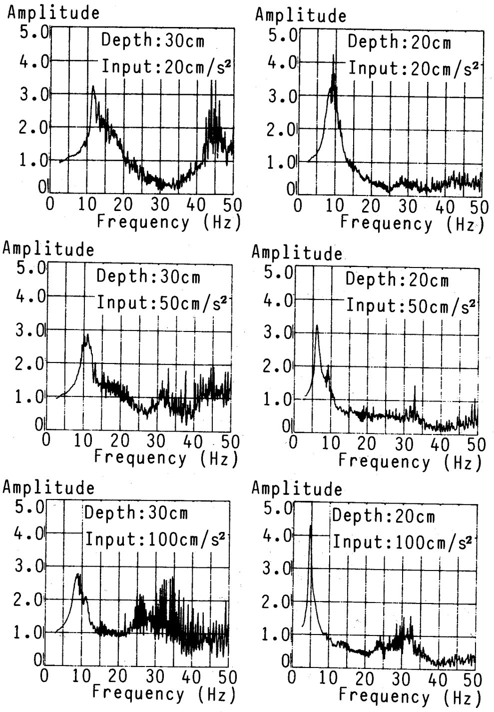


Fig. 2 Transfer Functions of Acceleration of the Top of the Building to the Shaking Table

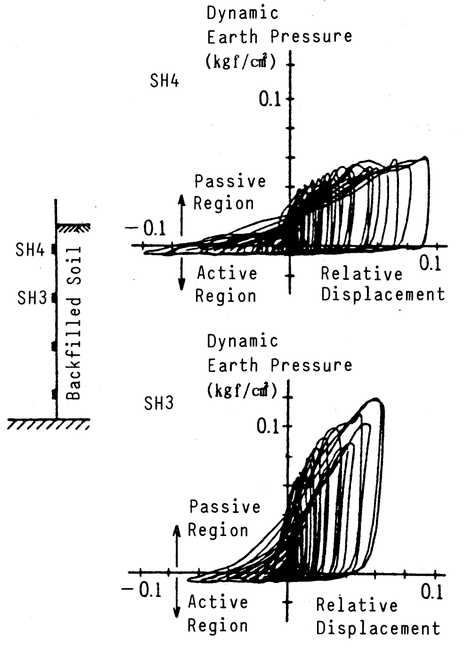


Fig. 3 Hysteresis Loops of Dynamic Earth Pressure versus Relative Displacement

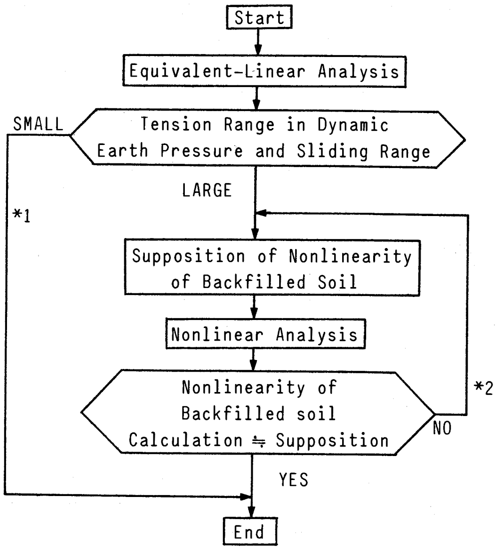


Fig. 4 Flow Chart of the Analysis

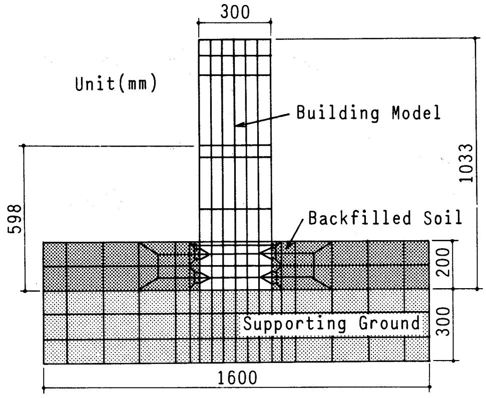


Fig. 5 Analytical Model

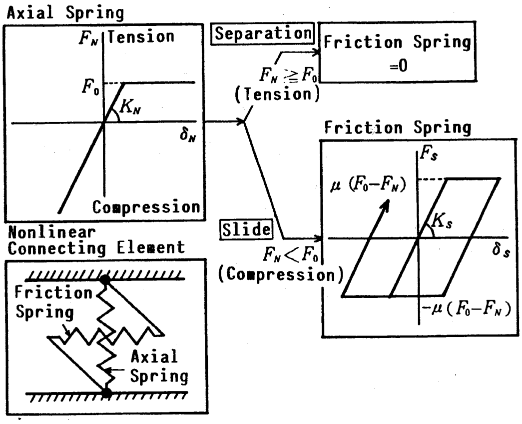


Fig. 6 Mechanism of Nonlinear Connecting Element

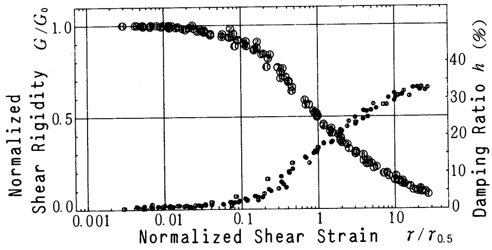


Fig. 7 Relationship between G/Go, h and $\gamma/\gamma_{0.5}$

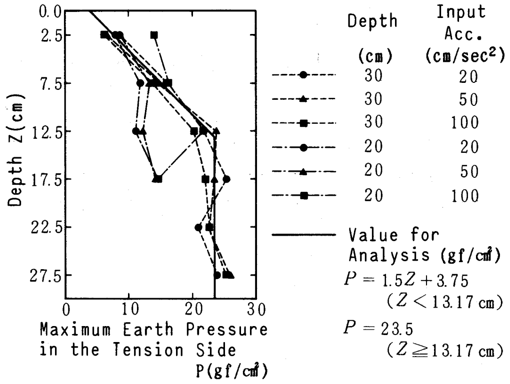
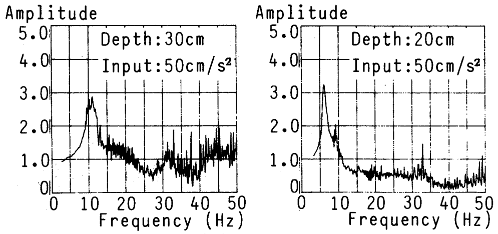
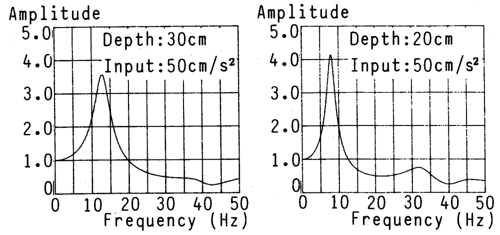


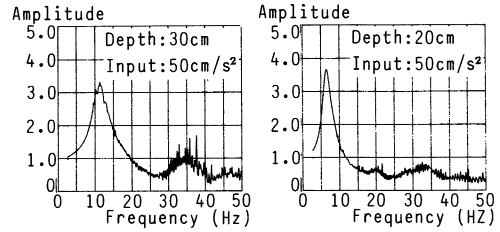
Fig. 8 Yield Point of Dynamic Earth Pressure on Active Region



(a)Experiment



(b)Equivalent-linear Analysis



(c)Nonlinear Analysis

Fig. 9 Transfer Functions of Acceleration of the Top of the Building to the Shaking Table

Table 1 Properties of Building Model and Soils

	Building Model	Supporting Ground	Backfilled Soil
Unit Weight γ(gf/cm^2)	——	1.555	1.60
Young's Modulus E(kgf/cm^2)	2.10 x 10^6	47.0	Equation(1) and Fig. 7
Poisson's Ratio ν	0.30	0.48	0.325
Damping Ratio h	0.05	0.025	Fig. 7
Total Weight W(kgf)	247.6	——	——
Moment of Inertia Ig(kg cm^2)	1.30 x 10^6	——	——

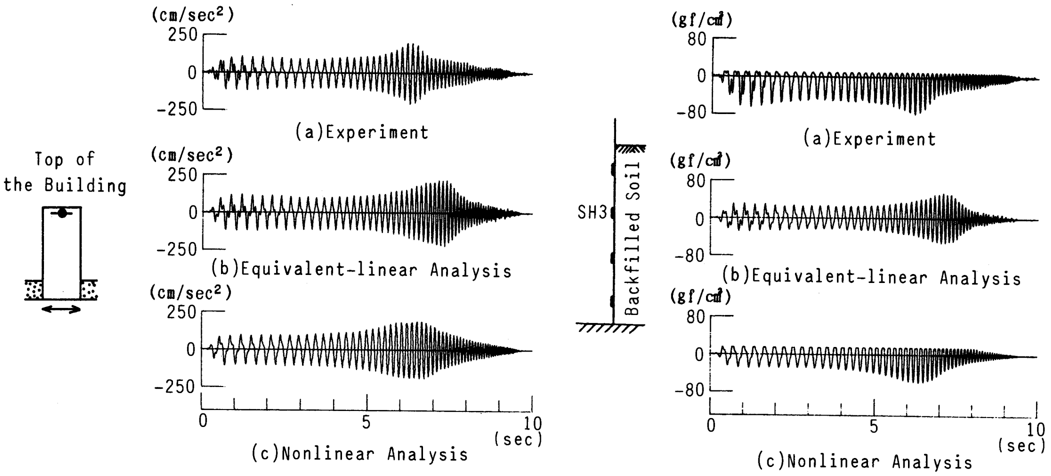


Fig. 10 Response Acceleration and Dynamic Earth Pressure for a Backfilled Depth of 20 cm under 50 cm/sec^2 Excitation

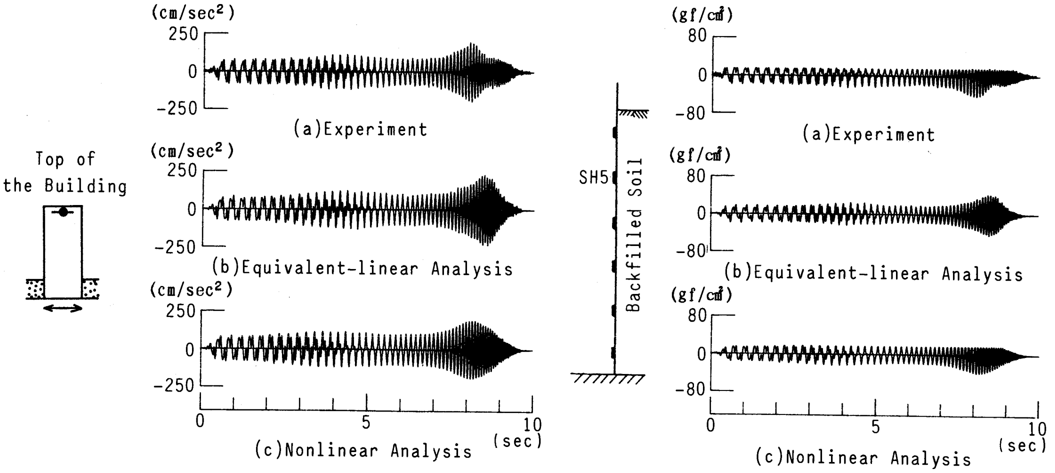


Fig. 11 Response Acceleration and Dynamic Earth Pressure for a Backfilled Depth of 30 cm under 50 cm/sec^2 Excitation

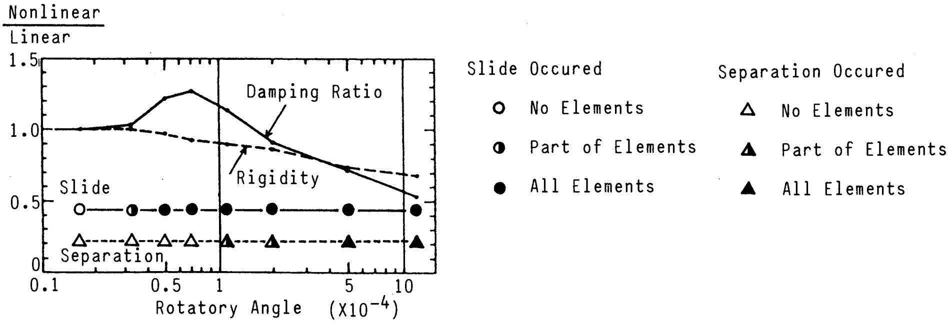


Fig. 12 Spring Constant and Damping Ratio of Rocking Vibration

REFERENCE

1) Hara, A. et al.(1987), "Dynamic tests and analyses on uplift of reacter buildings," Transactions of the 9th SMiRT, Vol. K1, PP.207-212.