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SEISMIC RESPONSE OF STRUCTURE WHICH SLIDES DURING EARTHQUAKES

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SUMMARY

This paper reports experimental and analytical studies on a structure which slides during earthquakes. From the shaking table test of elastic soil-structure model, soil-structure interaction and the effect of sliding on the interaction is studied. From the shaking table test of elasto-plastic soil-structure model, the effect of non-linearity of soil on the dynamic response of soil-structure system is examined. Simple analytical procedures to simulate the dynamic response of these models are also presented.

INTRODUCTION

An offshore power plant structure is planned: large prestressed concrete caissons mounting plant facilities are constructed in a dry dock, towed to the site, and installed on a sea bottom of 20 m below the sea level (Ref. 1). The design feature of this structure is that the sliding of the structure during strong earthquakes is allowed, while it is designed not to slide against wave forces. This design concept allows the reduction of ballast weight, and the reduction of the seismic force to the structure.

The outline of dynamic response of this structure is illustrated in Fig. 1. To identify the seismic response of this structure, the dynamic behavior of soil-structure model including the effect of the sliding and the effect of non-linearity of soil have to be studied (Ref. 2).

Two series of shaking table tests of soil-structure models including sliding were carried out; one with elastic soil model and the other with sand as the soil model. From these shaking table tests, soil-structure interaction, the effect of sliding on the interaction, and the effect of non-linearity of the soil on the foundation input motion were studied. Simulation of the dynamic response of the soil-structure system were conducted, and the results were compared with the test results.

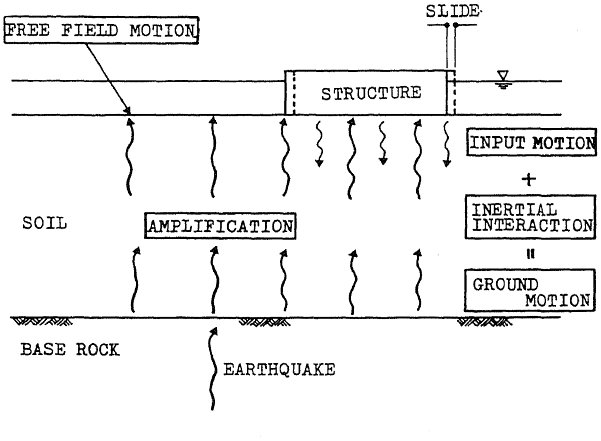

Fig.1 Outline of Dynamic Response

SHAKING TABLE TEST AND ANALYSIS OF ELASTIC SOIL-STRUCTURE MODEL

Experimental Procedure

Shaking table test was conducted using elastic soil-structure model as shown in Fig. 2. The model soil is made of silicone rubber(Specific Gravity: 0.975, Shear Modulus: 0.298 kgf/cm^2). A steel plate of 31.6 kgf in weight was used as a model structure. A teflon sheet of 2mm thick was placed between the soil model and the structure model to cause sliding. The sliding occurred between the teflon sheet and the structure model. The coefficient of friction was measured about 0.15, but showed some increase as the sliding speed increased.

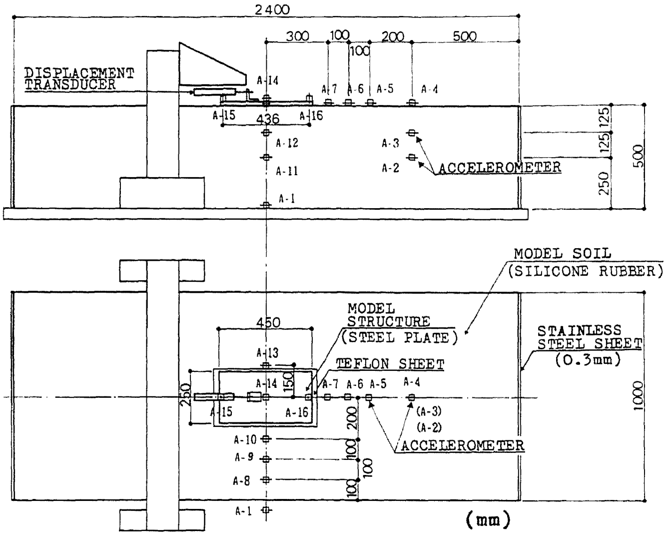

Figure 2 Model and Location of Transducers

Shaking table test was conducted at three different model conditions: 1) Soil model, 2) Soil-structure model without sliding, 3) Soil-structure model with sliding. The model was subjected to one directional horizontal motion of harmonic wave of 1 to 25 Hz, and seismic waves, the time scale of which was scaled to 1/2. The location of accelerometers and a displacement transducer is described in Fig. 2. A forced vibration test of the soil surface was conducted to obtain the impedance of the soil model.

Numerical Model

While the analysis of soil-structure model with sliding could be conducted by non-linear finite element analysis with joint elements(Ref. 3), a simpler procedure as described below was employed :

1) Calculation of foundation input motion by the superposition of 1 st-3rd modes. In an elastic model without foundation embedment like this model, the foundation input motion is equal to the free field motion.

2) Calculation of the response of soil-structure system subjected to the foundation input motion. Figure 3 shows the numerical model. The structure which slides, was modelled by a mass and a bi-linear spring with a large initial stiffness of K_1 and small secondary stiffness of K_2 as shown in Fig. 4 . The load at yielding is 0.15 x (Weight of Structure), which correspondes to the friction coefficient of 0.15.

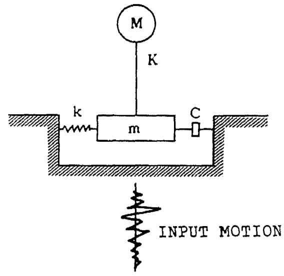

Fig.3 Numerical Model

This modelling is based on the results of static sliding test of concrete block and soil materials described below (Ref.2):

1) There are no differences between static and dynamic friction resistance. 2) The friction resistance is not dependent on the sliding speed.

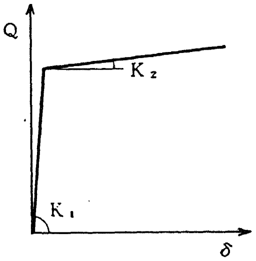

Fig.4 Bi-Linear Spring

The movement of the ground underneath the structure was idealized by a sway member with a mass m , a damper c , and a spring k. The real and imaginary part of the impedance of the ground by this model are k-m ω^2 and c ω respectively. These parameters were computed by the linear regression of the measured impedance in the forced vibration test. The impedance defined by this sway model is compared with the test results in Fig. 5 .

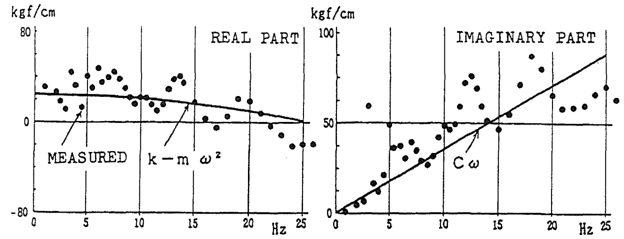

Figure 5 Impedance

Experimental and Analytical Result

The experimental and analytical results of the soil-structure model subjected to El Centro 1940 wave is presented in this section. Fourier spectrum of acceleration at free field (A-4) and at base of structure (A-13) are shown in Fig. 6. The difference of the spectrum of these two points, which correspondes to the inertial interaction, is observed at relatively high frequency zone. The time history of acceleration by the inertial interaction which was computed by (A-13)-(A-4), is also plotted in Fig. 6. Compared with the acceleration by the non-sliding structure, the acceleration by the sliding structure is relatively constant in amplitude, and the response is more impulsive. This impulsive response occurs when the structure starts and stops sliding and this is a special feature of the inertial interaction by a sliding structure.

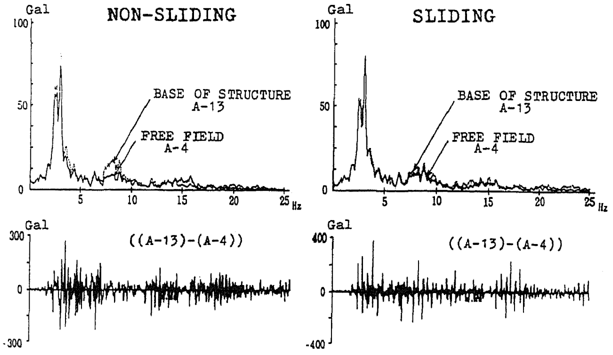

Figure 6 Response of Ground

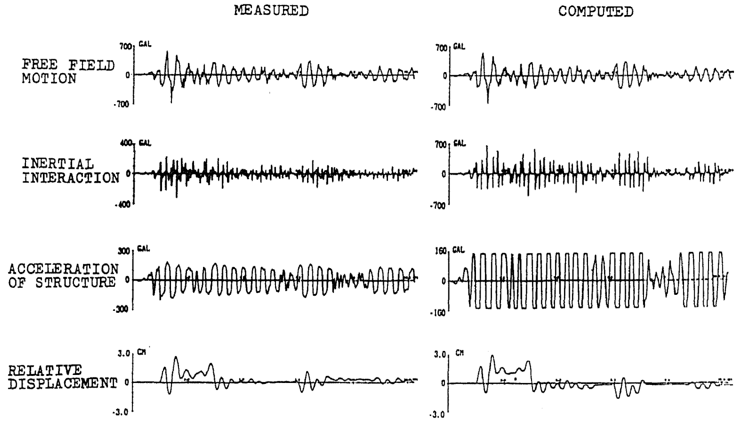

Figure 7 Experiment and Analysis

Analytical result for the soil-structure model is compared with the test result in Fig.7. The computed free field motion shows good agreement with the test result. The acceleration by the inertial interaction observed in the test shows high frequency characteristics compared with the free field motion, and this is clearly reproduced in the simulation. The acceleration of the strucure during sliding is not uniform in the test because of the dependency of the friction resistance on the sliding speed, while the acceleration during sliding is assumed constant in the simulation. In spite of this inaccurate modelling of the maximum structural acceleration, the computed slide displacement of the structure offers very good prediction of the test result.

SHAKING TABLE TEST AND ANALYSIS OF ELASTO-PLASTIC SOIL-STRUCTURE MODEL

Experimental Procedure

The soil model was made by filling artificial silica sand into a cylindrical container of 1.4 m in diameter and 1.2 m in height as shown in Fig. 8. The container allows the horizontal shearing motion of the soil model. The soil model was subjected to a strong shaking on a shaking table to introduce a liquefaction and settlement to consolidate the soil. Major properties of the soil model are listed in Table 1.

Table 1 Properties of Model

Water Content	31.6 %
Unit Weight	1.90 tf/m³
Void Ratio	0.838
Relative Density	70.9 %

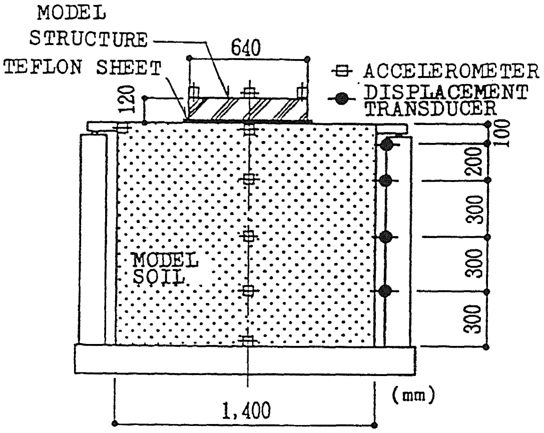

Fig. 8 Model and Location of Transducers

The structure model was a steel box. The normal stress at interface was adjusted to $0.12 \mathrm{kgf/cm^2}$ by installing weight on the structure model. A teflon sheet of 2 mm thick was placed between the soil and the structure model, and the sliding occurred between the teflon sheet and the structure model. The model was subjected to one directional horizontal motion on the shaking table. Both harmonic and seismic waves were used for shaking. Accelerations and displacements were measured at the locations described in Fig. 8 .

Analytical Procedure

Analytical models for one dimensional amplification theory and axi-symmetric finite element analysis (FEM , Ref. 4) are shown in Fig. 9. In the FEM the structure model was replaced by a cylinder with the same cross sectional area.

The initial shear modulus was assumed by the following equation where the shear modulus G_0 is proportional to the square root of the confining stress σ_m (Ref. 5).

$$G_0 = k (\sigma_m)^{0.5} \qquad (1)$$

The constant k was decided so that the 1 st resonant frequency fits the observed value in the shaking table test. The degradation of shear modulus G and the increase of damping coefficient h with respect to the shear strain was considered by an equivalent linear method.

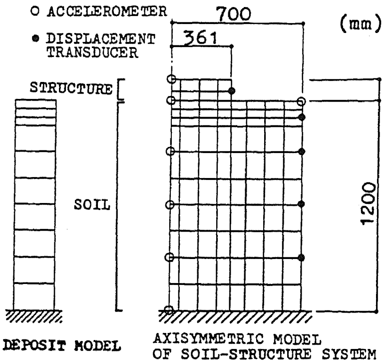

Fig. 9 Analytical Model

Experimental and Analytical Results

The measured and the computed transfer function of the soil model, subjected to 5 Gal and 20 Gal input motion are compared in Fig. 10.
The observed resonant frequency and the amplitude at the peak frequency for 20 Gal motion, were considerably smaller than those values for 5 Gal motion. Analytical result clearly reproduced the effect of non-linearity of soil on the frequency response of the soil model, and showed good agreement with the test results.

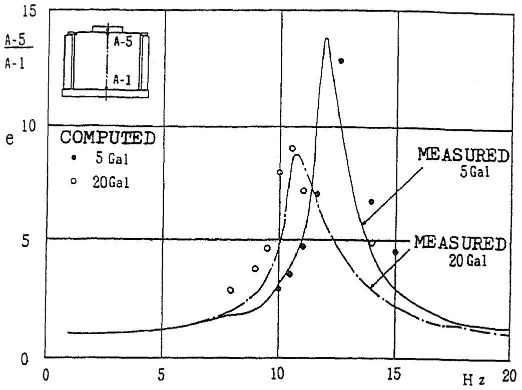

Fig. 10 Frequency Response

Table 2 Modelling of Non-linearity

Case	G	h
1	Strain Dependent	Strain Dependent
2	Constant	Strain Dependent
3	Constant	Constant (4%)

The observed acceleration at the soil model subjected to El Centro 1940 seismic wave is compared with analytical results. In the analysis, the strain dependent nature of the non-linear soil condition was evaluated by three different ways as described in Table 2. The comparison of the measured and computed acceleration time history at the soil surface and the Fourier spectrum ratio of surface/bottom are shown in Figs. 11 and 12. Frequency at the peak of the spectrum ratio in Case 1 was 9 Hz, while it was 12 Hz in Cases 2 and 3 where no degradation of shear modulus was considered. The observed peak frequency was 10 Hz and proves that there was considerable degradation of shear modulus, yet the estimation in Case 1 was a little over-estimation. The amplitude at peak of Cases 1 and 2 showed good agreement with the observation, while the value in Case 3 was more than double the observed value. Therefore the consideration of strain dependency of shear modulus and damping is necessary in the simulation.

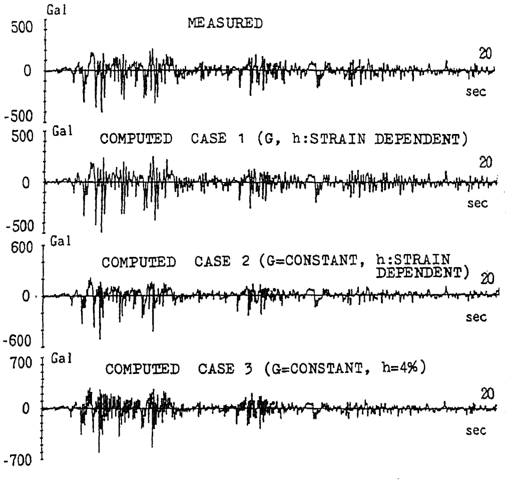

Fig. 11 Acceleration Time History

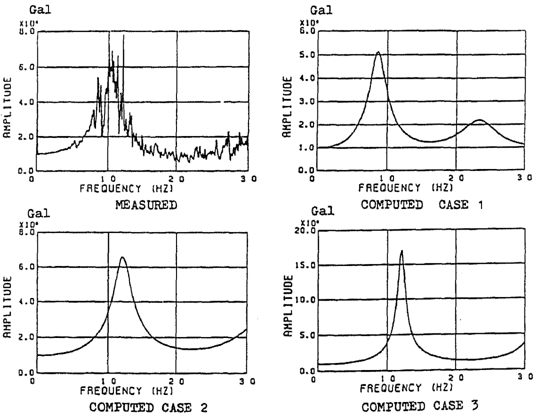

Fig. 12 Fourier Spectrum Ratio

Sliding analysis of the structure was carried out using the analytical program for a rigid body. (Ref. 6) The ground motion underneath the structure was computed by the axi-symmetric FEM of soil-structure model described in Fig. 9, in which the distribution of initial stiffness was decided by Equation (1) including the effect of the structure. The non-linearity of soil properties were evaluated by an equivalent linear method. The analytical result is compared with the test result in Fig 13. The computed slide displacement time history shows reasonably good agreement with the test result.

Though the difference of inertial interaction for non-sliding and sliding structure was not considered in this analysis, the effect of sliding on the inertial interaction has to be considered to compute the the ground motion under the structure, when the effect is considered to be significant.

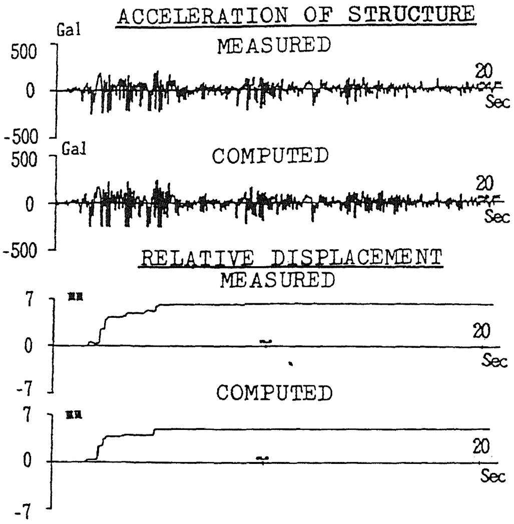

Fig. 13 Sliding Analysis and Test Result

CONCLUDING REMARKS

From the experiments and analyses, the following conclusions have been drawn.

1) The response analysis of the soil-structure model including the effect of sliding may be condcted with a two degree of freedom model: the sliding is modelled by a bi-linear spring and the compliance of the ground is idealized by a sway member.

2) To compute the foundation input motion, non-linearity of the soil has to be considered, and it could be approximated by the equivalent linear method.

3) If the ground motion under the structure is known, the response of structure which slides, can be computed by an sliding analysis of a rigid body.

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