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# A NUMERICAL SIMULATION AND VIBRATION GENERATOR TESTS OF FRAME-FOOTING MODELS WITH SURROUNDING SOILS

Gi HONG , Koichi TAKANASHI AND Kenichi OHI

Institute of Industrial Science, University of Tokyo

## SUMMARY

The purpose of this paper is to clarify the dynamical characteristics the of the soil and to evaluate quantitatively the input energy to a frame during excitations due to earthquake ground motions. Both theoretical and experimental approaches are carried out, where interactions between a frame with a R/C footing and the surrounding soil are taken into account. An evaluation method of the input energy to the frame is proposed

## INTRODUCTION

It has been recognized that the dynamical behavior of a structure subjected to an earthquake excitation is remarkably affected by dynamical characteristics of the structure and soil ground. In particular, on investigation of structural damages by earthquakes, it is very important to clear the soil-structure interaction aspect. Recognizing that structural damages seem to depend on the effective input wave to a frame structure and the dynamic characteristies of the soil ground, the generator tests of a footing have been done.

Most of studies in the literatures were concerned with the dynamic characteristics of the soil ground, but there are not so many researches paid attentions to the frame response of the soil-structure system and also, not many studies for estimations of effective input energy to the frame structure in the soil-structure systems.

The purpose of this paper is to clarify the effects of surrounding soils on the frame response of the soil-structure system subjected to earthquake excitation and to evaluate quantitatively the input energy to the frame under the effects of the surrounding soil vibration.

## ANALYTICAL METHOD

In the analysis, a simple mathematical model is presented. The model comprises a frame with three degrees of freedom and the footing on the soil.

The transfer function of the footing was calculated according to the Dynamical Compliance Theory(Ref.2), in which the surface layer is assumed to have a constant hysteretic type viscoelastic damping without effects of a multi-layer of the soil. The exciting force under the footing is assumed to uniformly distribute for the horizontal excitation and linearly distribute for the rotational excitation.

## INPUT ENERGY TO THE STEEL FRAME

The input energy to the frame structure and the total input energy to the frame-footing system by a vibration generator at the tests and by a natural earthquake are described.

AKIYAMA and TAKAYAMA(Ref.5) presented studies where the input energy to the superstructure is evaluated by using a analytical model with a two lumped mass system which consists of a mat slab with a spring and a dashpot and a superstructure reduced into a simple-mass system, and carried out a numerical analysis in a time domain. A simple empirical formula to evaluate the input energy was proposed.

In this paper, under consideration with the effects of the frequency dependence of the surrounding soil, a relationship equation to express a input energy to the frame structure in a frequency domain is presented. The following analyses were done associated with the types in Fig.1 which are described later.

<u>In case of test(II)</u>

Total input energy to the frame-footing system is

$$E_T = \int_{-\infty}^{\infty} Q_0(t)\,[\dot{u}_B(t) + e\,\dot{\theta}(t)]\,dt \tag{1}$$

in which $Q_0$: vibrating force, $U_B$, $\theta$ : horizontal displacement and rotation of the center of footing , e : height of vibrating point above center of footing.

Input energy to the frame-structure is

$$E_I = -\int_{-\infty}^{\infty} m\,[\ddot{u}_B(t) + h\,\ddot{\theta}(t)]\,\dot{u}_1(t)\,dt \tag{2}$$

in which m : mass of a frame structure $u_1$: horizontal displacement of the top mass, h : height of top mass above center of footing.

Expressing the above equation in the frequency domain, the ratio $R_B$ to the input energy to a frame structure to the total input energy in the frame-footing system is written by

$$R_B = \frac{m\,\mathrm{Real}\,\{i\,\omega^3 H_1(\omega)\,[\overline{H_B}(\omega) + h\overline{H_\theta}(\omega)]\}}{\mathrm{Real}\,\{i\,\omega\,[H_B(\omega) + eH_\theta(\omega)]\}} \tag{3}$$

in which $H_B(\omega)$ , $H_\theta(\omega)$: transfer function of horizontal displacement and rotation in the center of footing. $H_1(\omega)$: transfer function of horizontal displacement of the top mass, $\overline{H_B}(\omega)$ , $\overline{H_\theta}(\omega)$: conjugate complex of $H_B(\omega)$ , $H_\theta(\omega)$ , $i = \sqrt{-1}$

<u>In case of test(III)</u>

In the similar manner, the ratio $R_F$ of input energy to the frame structure to a total input energy in the frame-footing structure systems is given by

$$R_F = \frac{\mathrm{Real}\,\{i\,\omega H_1(\omega)\,[1 + m\omega^2(\overline{H_B}(\omega) + h\overline{H_\theta}(\omega))]\}}{\mathrm{Real}\,\{i\,\omega\,[H_1(\omega) + H_B(\omega) + eH_\theta(\omega)]\}} \tag{4}$$

and in case of a natural earthquake

$$R_E = \frac{\tilde{m}\int_{-\infty}^{\infty}\text{Real}\,[\,i\,\omega H_1(\omega)\ \{1-\omega^2\,(\overline{H}_\theta(\omega)+h\overline{H}_\theta\ (\omega))\ \}\ ]\ |\ \ddot{U}_g(\omega)\,|^2\,d\omega}{\int_{-\infty}^{\infty}\text{Real}\,[\tilde{m}\,i\,\omega\ \{H_1(\omega)+H_\theta(\omega)+h H_\theta\ (\omega)\}\ +i\,\omega H_\theta(\omega)]\,|\ \ddot{U}_g(\omega)\,|^2\,d\omega} \tag{5}$$

in which $\tilde{m} = \frac{m}{M}$ , M : mass of the footing , $|\ddot{U}_g(\omega)|$ : fourier amplitude of a natural earthquake

## VIBRATION GENERATOR TESTS

Test structures Test models consist of a reinforced concrete footing and a steel frame. They were directly installed on the surface of KANTO loam covered by crushed stones and revelling concrete after 50 centimeter top soil removed.

This model was supposed as an independent footing in an actual steel structural system. The two types of structural steel models were constructed on the footing as shown in Fig.1. Each model is described in Tabel 1.

Test program Four kinds of vibration generator tests were carried out:

(I) The vibration test of a footing by the vibrator installed on the footing.

(II) The vibration test of a steel frame with the footing by the vibration installed on the footing.

(III) The vibration test of a steel frame with the footing by the vibrator installed on the floor of the frame.

(IV) The vibration test of a braced frame with the footing by the vibrator installed on the footing (brace : Plate 0.6 x 1.0 cm ).

## COMPARISON OF TEST RESULTS WITH NUMERICAL SIMULATIONS

Four kinds of test results were compared with the numerical results of input energy to the steel frame was described. In the calculation, the following value were used. The phase velocity of shear waves $V_S$= 110 m/s ,density = 1.35 g/cm$^3$(Ref.6) ,$D_1$: the equivalent viscoelastic coefficients for primary wave ,$D_2$: the equivalent viscoelastics coefficients for shear wave. β : damping coefficient of a structure.

A dynamic stiffness function of the soils for horizontal and rotational motion is shown in Fig 3. The solid curve stands for associated simulation estimates, and the dashed curve shows results obtained from statical loading tests. Based on the simulation results, the quantities of horizontal stiffness were taken as constants. These properties are independent of the excitating frequency. As mentioned in the previous studies(Ref.3), there are not so large difference between the simulation results and the test results at the stiffness estimation of the soil ground.

Fig.4 to Fig.10 are plots of the acceleration resonance curve. The solid curves represent the analytical results and the symbol * stands for the test results.

The test results shown in Fig.4 have more sharp peaks in comparing with those in the test results. An alytical model is based on an elastic half-spaced with only a surface layer, neglecting the effects of the lower stiff layer( $V_S$= 320 m/s ) of the soil ground. Thus, analytical results show a little smaller value than the test results.

Agreements between the simulation values and the test values are generally acceptable. (a),(b) in Fig.11 show a ratio of input energy to the frame to the total input in frame-footing structure system at a vibration generator tests, (c) in Fig.11 shows ones in case of a natural earthquake ( observed on December 17,1987 at Chiba city). Therefore, $1-R_F$ ,$1-R_B$ , and $1-R_E$ express a energy ratio dissipated by a damping mechanics in soil ground. These figures show that the ratio of energy input to a frame to the total energy input in the frame-footing model is remarkably influenced by the damping of the frame and the damping mechanics of the soil ground.

## CONCLUSIONS

Acceleration response of the frame-footing systems calculated by the analytical model has a good agreement with that by the test, From the numerical simulation, in case of the perfect elastic ground, it is found that the radiative damping of about 2% for test type(III) is expected , and the radiative damping of about 10% at the natural period for the test type(II) is expected. The ratio of energy input to the frame to the total energy input in the frame-footing model is influenced remarkably by the damping of the frame as shown in Fig.11. So, it is important to evaluate accurately the damping as well as the energy absorption capacity of the frame. Such a numerical simulation provides an important information to estimate the radiative and the dissipative damping of the ground which was not obtained by the experiment.

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TABLE 1 PARAMETERS OF MODEL

| | MODEL A | MODEL B |
|---|---|---|
| $m(t\cdot sec^2/cm)$ | $0.102\times10^{-2}$ | $0.227\times10^{-2}$ |
| $M(t\cdot sec^2/cm)$ | $0.561\times10^{-2}$ | $0.561\times10^{-2}$ |
| $I_M(t\cdot cm\cdot sec^2)$ | 20.39 | 20.39 |
| $K(t/cm)$ | 0.830 | 7.66 |

Height of Top Mass Above Center of Footing:140cm

Height of the Center of Footing Above the Boundary of Ground Surface:30cm

$I_M$ : Mass Moment of Inertia of Footing

K : Stiffness of the frame

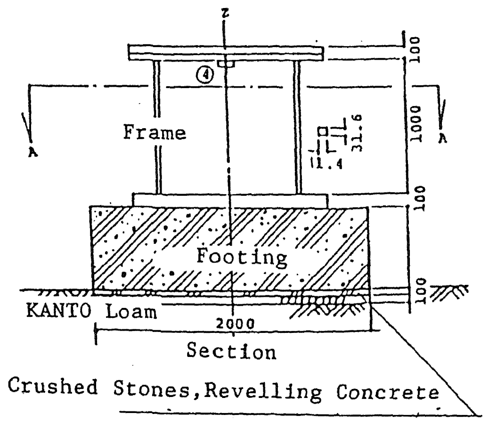



FIG.2 TEST MODEL

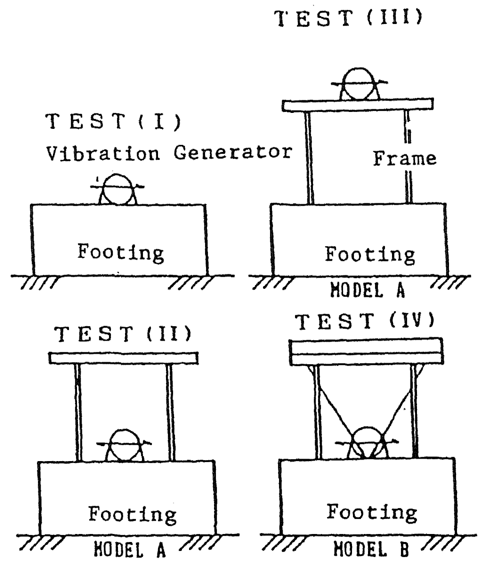



FIG.1 TEST TYPE

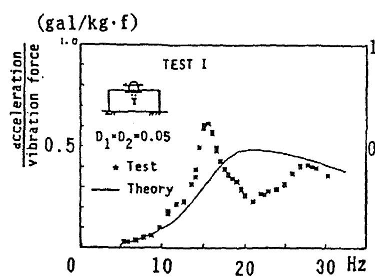



FIG.4 ACCELERATION RESONANCE

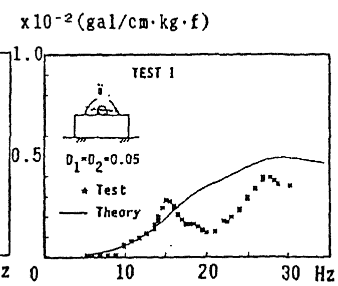



FIG.5 ACCELERATION RESONANCE

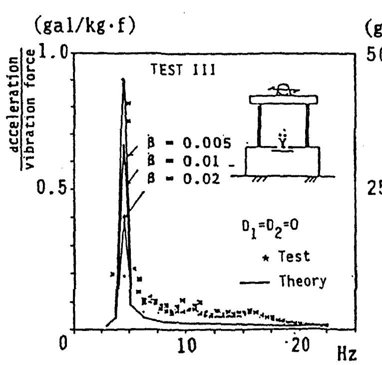



FIG.6 ACCELERATION RESONANCE

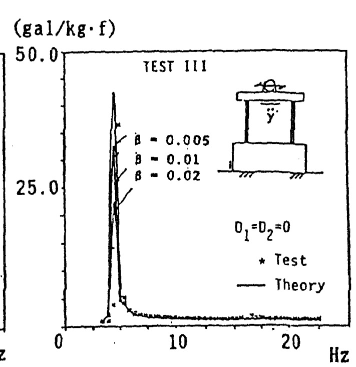



FIG.7 ACCELERATION RESONANCE

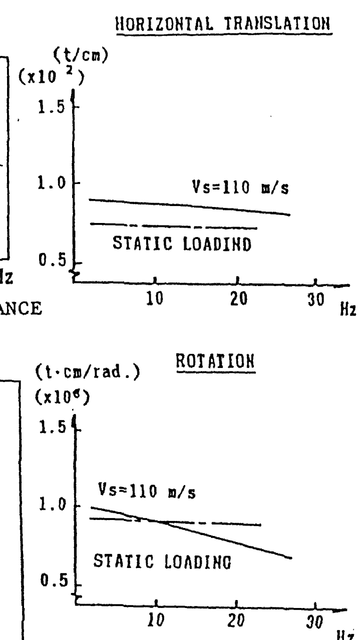



FIG.3 STIFFNESS OF THE SOIL GROUND

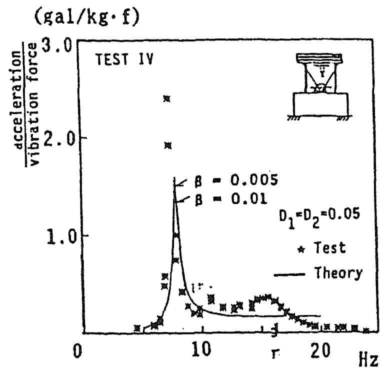


FIG.8 ACCELERATION RESONANCE

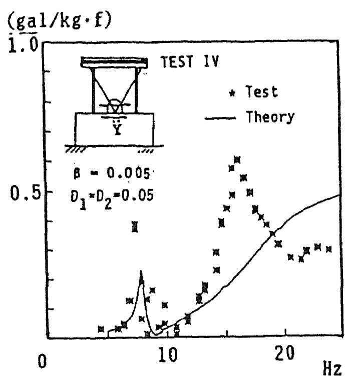


FIG.9 ACCELERATION RESONANCE

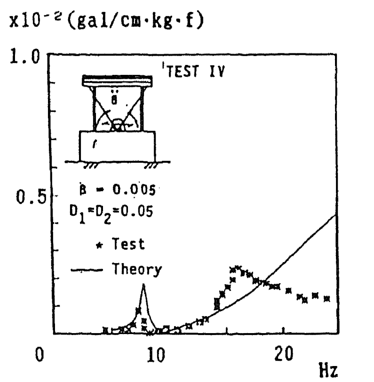
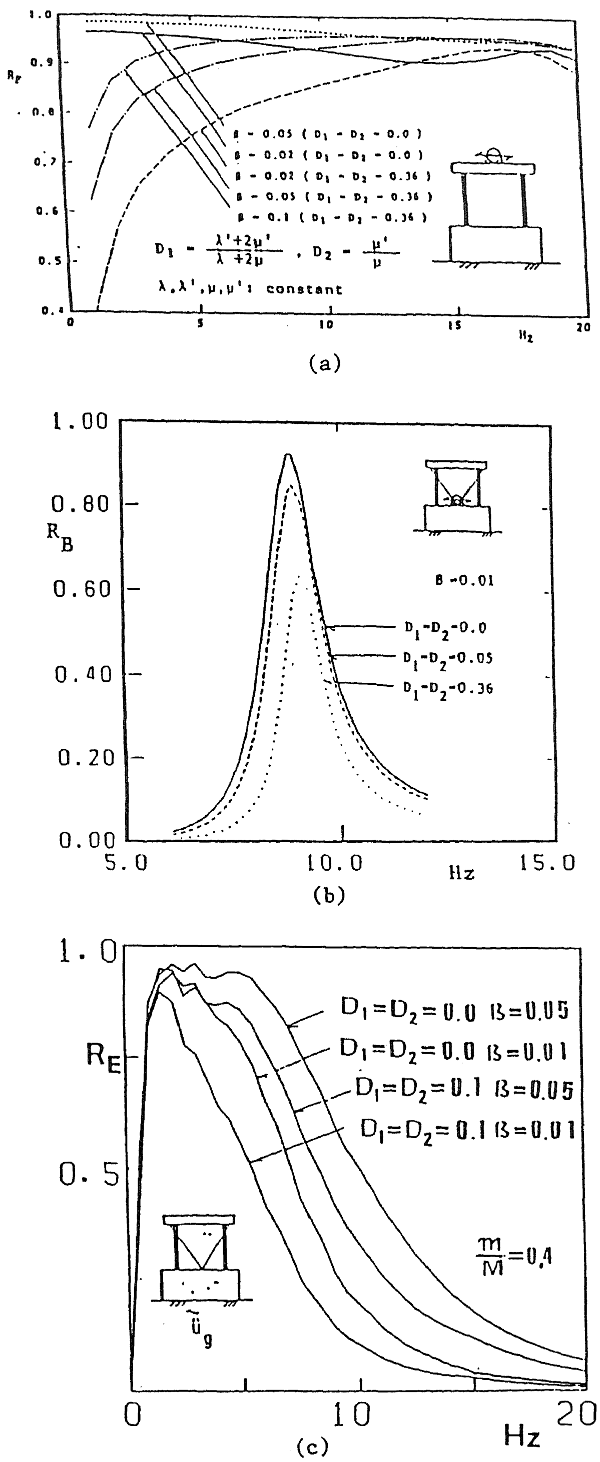


FIG.10 ACCELERATION RESONANCE




$$D_1 = \frac{\lambda' + 2\mu'}{\lambda + 2\mu}, \quad D_2 = \frac{\mu'}{\mu}$$

FIG.11 THE RATIO OF THE ENERGY INPUT TO THE FRAME TO THE TOTAL INPUT IN THE FOOTING-FRAME MODEL