AN EXPERIMENTAL STUDY ON STRUCTURE-GROUND INTERACTION

by

M. Shinozuka[I], T. Fukuda[II] and H. Asada[III]

SYNOPSIS

Fundamental nature of dynamic structure-ground interaction is investigated by performing an experiment with the aid of a model of a single-degree-of-freedom structure attached to a shaker table either directly or through a layer of rubber material purporting to represent the ground layer. Unlike most experiments of this type, the shaker table is excited such that the specified free-field motion would be reproduced on the rubber surface regardless of the thickness of the layer if the structure were absent. This permits one to assess the effect of structure-ground interaction when a structure is placed on ground layers with an identical free-field surface motion but of different thickness.

INTRODUCTION

As the sophistication of structural analysis for strong-motion earthquakes increases, the problem of dynamic structure-ground interaction begins to attract more attention among engineers. The present study focuses on the fundamental nature of this interaction problem by performing an experiment which uses a shaker, a (single-degree-of-freedom) structure and a layer of rubber purporting to represent a ground layer as shown in Fig. 1.

The essential feature of this experiment is to excite the shaker table in such a way that, if the structure were absent, the ground surface motion (the horizontal motion of surface of the rubber layer at the point where the footing is to be glued) would be identical to the specified signal regardless of the thickness d of the layer (including the case d = 0). This is accomplished with the aid of an analogue tape recorder recording the motion of the table corresponding to the specified surface motion before the structure

I Professor of Civil Engineering, Columbia University, New York, N. Y., U. S. A.

II Lecturer, Osaka City University, Osaka, Japan.

III Visiting Research Technician, Columbia University, New York, N. Y., U. S. A. On Leave from National Aerospace Laboratory, Science and Technology Agency, Tokyo, Japan.

is glued. This record will be played back to excite the table through MTS servo-control system after the structure is glued to the rubber, and among other quantities, the acceleration of mass M_s is measured and recorded. Different values of natural frequency f_s of structure is obtained by changing the height L of mass M_s. A mechanical viscous damper is added to the structure as shown in Fig. 1 to provide a reasonable amount of damping (approximately 2%).

ANALYTICAL MODEL

The widely accepted analytical model for the layer in terms of equivalent translational mass and rotational moment of inertia with corresponding linear viscous dampings as shown in Fig. 2, is employed in this study. Referring to Figs. 2 and 3 for notations, the equations of motion can be written as

$$\begin{bmatrix} k_{11} & k_{12} & 0 & 0 \\ & k_{22} & k_{23} & k_{24} \\ sym. & & k_{33} & k_{34} \\ & & & k_{44} \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{Bmatrix} = \begin{Bmatrix} f_1 \\ 0 \\ 0 \\ 0 \end{Bmatrix} \quad (1)$$

where

$$k_{11} = M_r\frac{d^2}{dt^2} + M_s\frac{d^2}{dt^2} + C_{rt}\frac{d}{dt} + k_{rt}\ , \quad k_{12} = M_s\frac{d^2}{dt^2}$$

$$k_{22} = M_s\frac{d^2}{dt^2} + C_s\frac{d}{dt} + \frac{12EI}{L^3}\ , \quad k_{23} = k_{24} = -\frac{6EI}{L^2}$$

$$k_{33} = J_r\frac{d^2}{dt^2} + C_{ro}\frac{d}{dt} + k_{ro} + \frac{4EI}{L}\ , \quad k_{34} = \frac{2EI}{L}$$

$$k_{44} = J_s\frac{d^2}{dt^2} + \frac{4EI}{L}\ , \quad f = \left(k_{rt} + C_{rt}\frac{d}{dt}\right) x_0$$

It is noted that in this model M_r and J_r represent combined effect of mass and moment of inertia of the footing and the ground layer respectively.

EXPERIMENTAL RESULT

The frequency response (to sinusoidal excitation of layer surface) of translational acceleration of M_s exhibited four peaks reflecting translational mode of structural mass at the fundamental natural frequency (f_1), rotational mode of M_r at the second natural frequency, rotational mode of M_s at the third and translational mode of M_r at the fourth. All quantities identified in Fig. 2 are either computed or measured directly except for J_r, M_r and c_{rt}. J_r and M_r are estimated from measured values of k_{rt} and k_{ro} and the observed frequencies of the second and the fourth mode. A value is chosen for c_{rt} so that the theoretical and the measured frequency responses agree reasonably well as shown in Fig.4 (for the case f_1 = 3.26 Hz). The values of these quantities are listed in Table 1.

The relationship between the structural response (translational acceleration of M_s) and the table excitation in the frequency domain is indicated in the block diagram (Fig. 5) where $U_0(\omega)$, $V_0(\omega)$, $W_0(\omega)$ and $W(\omega)$ are Fourier transforms of signals as indicated and $G_0(\omega)$, $H_0(\omega)$ and $J(\omega)$ are frequency response functions of assumedly linear systems also as indicated. The interaction ratio $I(\omega)$ as defined in Fig. 5 is the ratio between the response amplitudes with and without interaction. A typical result of $I(\omega)$ for the mass acceleration when d = 1" and 2" is plotted in Fig. 6 where curves (1) - (4) respectively correspond to the structures with f_s = 3.26, 3.76, 4.16 and 4.63 Hz. It is observed that these are roughly the frequencies at which the curves take minimum values whereas the maximum values of the interaction ratio are obtained near the lowest resonance frequencies of the structure-foundation system.

ACKNOWLEDGEMENT

This work was supported by National Science Foundation under NSF GK-24925.

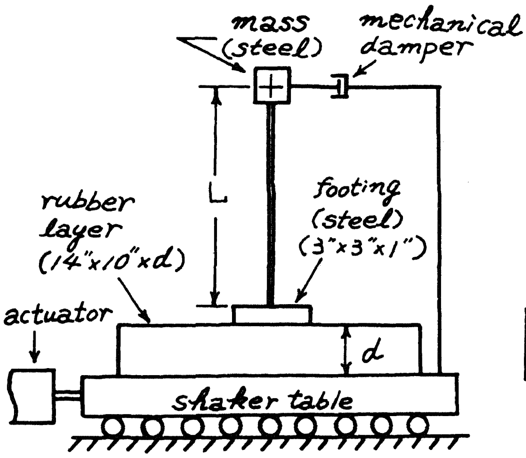

Fig. 1

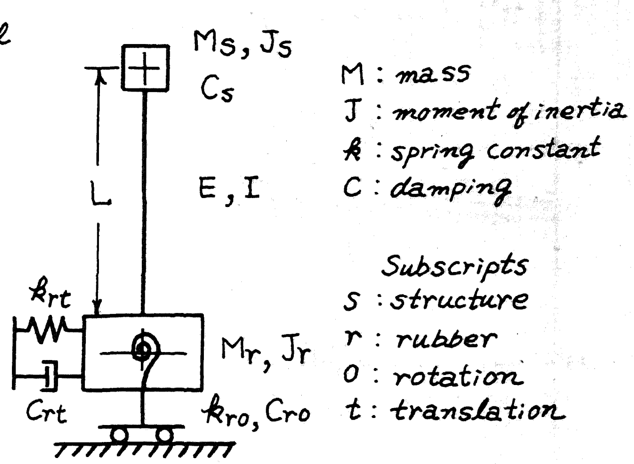

Fig. 2

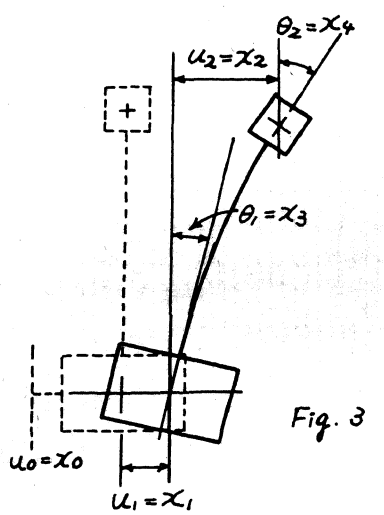

Fig. 3

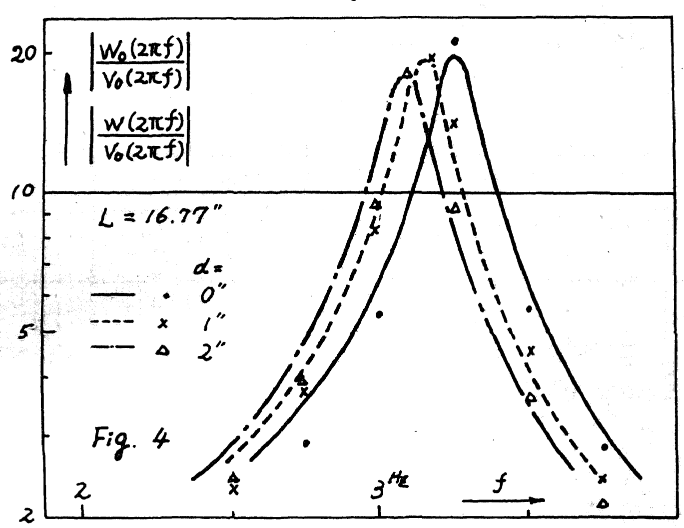

Fig. 4

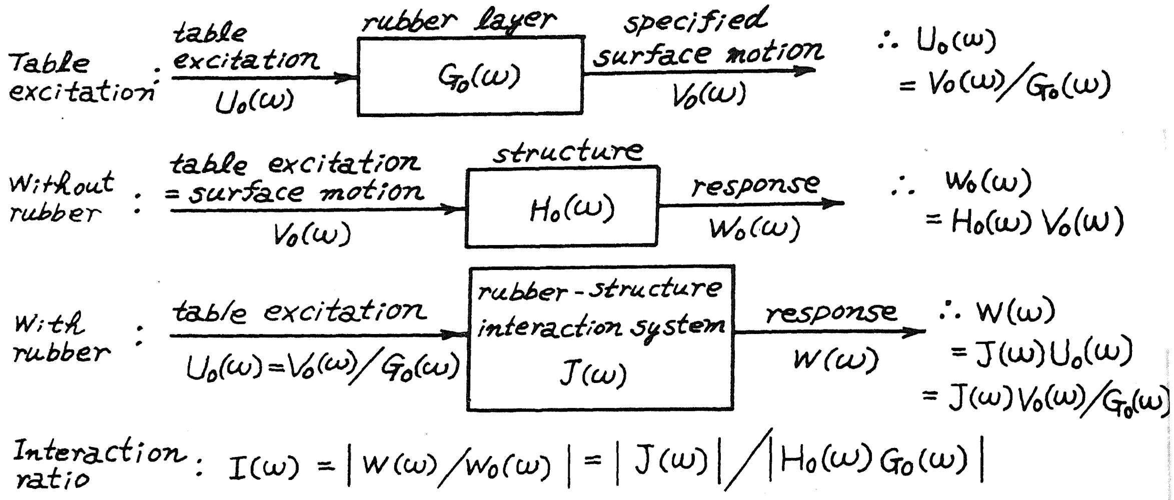

Fig. 5

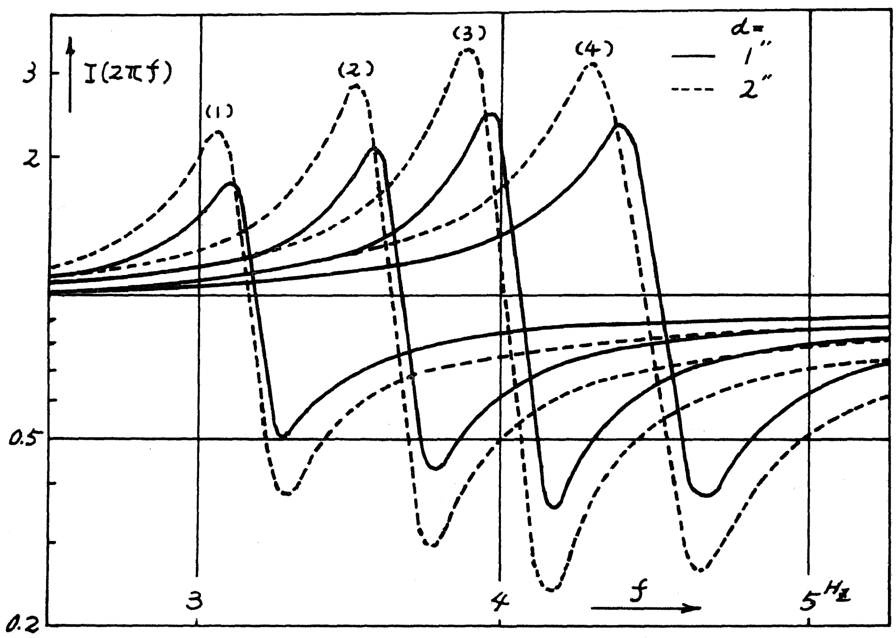

Fig. 6

Table 1 (all units in lb, in and sec)

d	k_{rt}	c_{rt}	k_{ro}	c_{ro}	M_r	J_r
1"	1952	0.200 (5.51%*)	6850	2.82 (7.95%*)	0.00169	0.0459
2"	1366	0.300 (7.24%*)	4120	1.85 (7.61%*)	0.00314	0.0359

M_s = 0.0037, J_s = 0.00199, c_s = 0.00377(0.0208*), EI = 2441.
Elastic constants of rubber: E = 170 (tension), 300 (comp.), G = 60, ν = 0.43.

* Damping ratio using corresponding mass and spring constant