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DEVELOPMENT OF SEISMIC ISOLATION TABLE SUPPORTED BY BALL TRANSFER UNITS AND CIRCULAR SPRINGS WITH MAGNETIC DAMPING

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SUMMARY

In the present paper, we deal with a new type of isolation table supported by ball transfer units and circular springs with magnetic damping. The ball transfer units are widely used as integral parts of conveyor systems, feed devices, and machining and packaging equipment. Smooth motion of the ball transfer unit is produced by a multitude of small balls between a large load ball and a hardened ball cup. Damping and stiffness of the isolation table are given by rare earth magnets and a conductor, and by the circular springs respectively. The isolation table is simple in construction, and has about the same stiffness and damping in any direction on the horizontal plane. Resisting force characteristics of the isolation table are measured. The seismic responses of isolation objects placed on the isolation table are also measured employing an electro-hydraulic type shaking table, and the experimental results are compared with the calculated results.

INTRODUCTION

Several types of isolation tables have been developed to isolate electronic equipments, precision instruments, artistic handicrafts, etc. from earthquake or external vibration [Takagami, 1986], [Kashiwazaki, 1989], [Iwata, 1990], [Fujita, 1992]. In order to develop the isolation table, which is simple in construction and low in cost, the authors have devised the isolation tables composed of circular arc beams and magnetic damping, and confirmed their effects of isolation theoretically and experimentally [Furuya, 1992], [Watanabe, 1996]. The isolation tables developed by the authors, however, are not suitable for an object which is heavy in weight and high in centre of gravity since it can not carry large overturning moment. In this study, a new type of seismic isolation table composed of ball transfer units, circular springs and magnetic damping is proposed. It is designed with maintenance free, low height and high load capacity to overcome the disadvantage mentioned above. The resisting force characteristics of the isolation table are examined experimentally. The seismic responses of a weight or a tower like structure placed on the isolation table are also measured employing an electro-hydraulic type shaking table, and the experimental results are compared with the calculated results.

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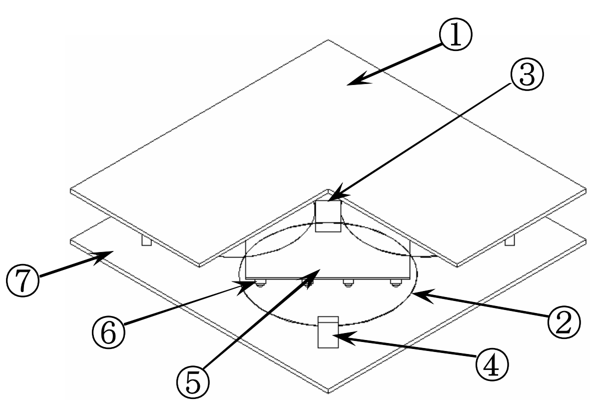
CONSTRUCTION OF ISOLATION TABLE

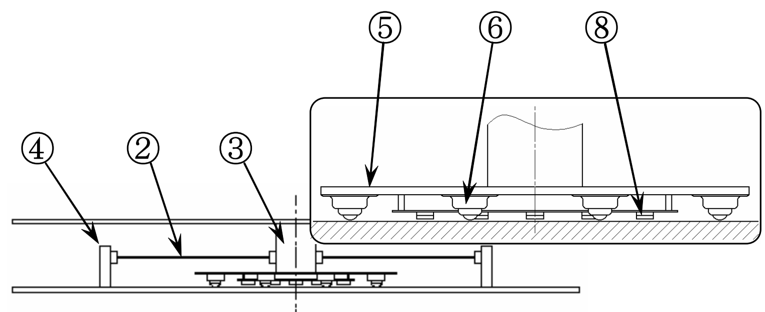
Cross-eyed view and front view of the isolation table are shown in **Fig. 1 (a)** and **(b)** respectively. The internal construction under the 1m square table board (1) is also shown in **Fig. 2**. The isolation table consists of the table board, 5 struts (3) and middle board (5). The isolation table is supported by 12 ball transfer units (6) and 4 pair of circular springs (2) composed of a couple of semi circular springs. The ball transfer units are attached to the middle board, and the circular springs are placed between the central strut on the middle board and the 4 spring holders (4) on the base board (7). Therefore the vertical load can be carried by the ball transfer units and both the horizontal load and the overturning moment can be carried by the circular springs when the object on the table is subjected to horizontal acceleration.

Two types of ball transfer unit and their construction and dimension are shown in **Figs. 3 and 4** respectively. The ball transfer units are widely used as integral parts of conveyor systems, feed devices, and machining and packaging equipment. Smooth motion of the ball transfer unit is produced by a multitude of small balls between a large load ball and a hardened ball cup. Rolling contact of the ball transfer unit with the base board is shown in **Fig. 5**. An elastomer sheet is put between the ball transfer unit and the base plate to avoid the shock load worked on the table board.

Magnetic damping is produced by the relative velocity between the rare-earth magnets (8) and the conductor (base board). 12 rare-earth magnets are attached to the middle board and small gaps are kept between the magnets and the baseboard.



(a) Cross-eyed view



(b) Front view

(1) Table board (2) Circular spring (3) Strut (4) Spring holder (5) Middle board
(6) Ball transfer unit (7) Base board (8) Rare-earth magnet

Fig. 1 Construction of the isolation table

Fig. 2 Internal construction of the isolation table

Fig. 3 Two types of the ball transfer unit

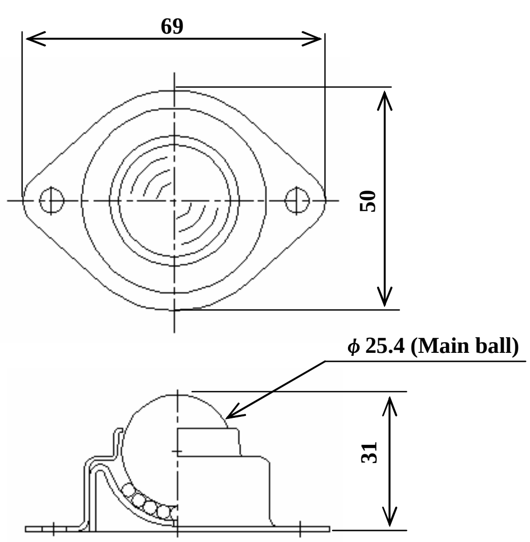


Fig.4 Dimension of the ball transfer unit

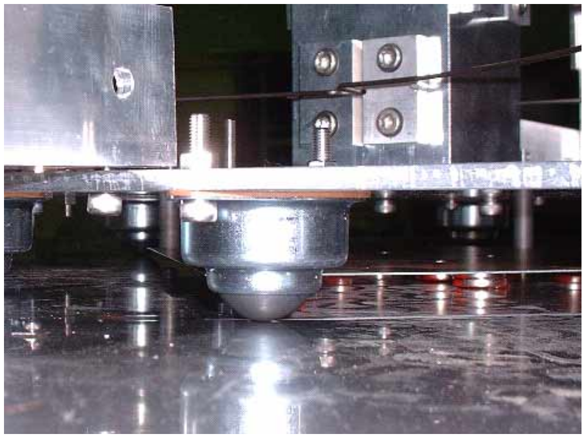


Fig. 5 Rolling contact of the ball transfer unit with the base board

CHARACTERISTICS OF ISOLATION TABLE

Resisting force of the circular springs

Relation between the resisting force and the displacement of the semi circular spring of which both ends are constrained is examined. The diametrical stiffness is 3 times as large as the tangential stiffness, both the stiffness is linear and the experimental results are agree well with the theoretical results derived from curved beam theory.

Resisting force characteristics of the magnetic damper

Relation between the resisting force and number of magnetic fluxes is examined when sinusoidal displacement of frequency 3Hz between the rare-earth magnets and the conductor. In generally, magnetic damping force produced between rare-earth magnets and a conductor changes according to arrangement of magnetic polarity of the magnets. The alternative arrangement of the magnetic polarities is 1.18 times as large as the same arrangement for the isolation table developed by the authors.

Friction coefficient of the ball transfer unit

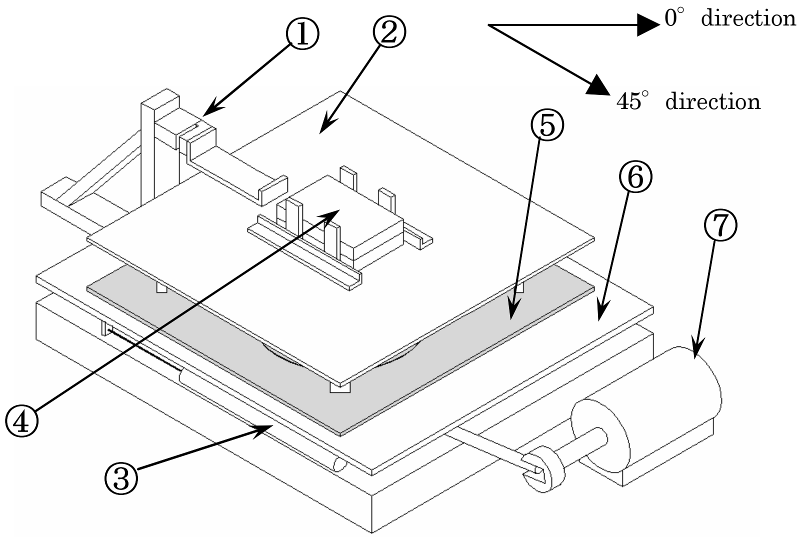
Resisting force becomes minimum value in the contact of C-8Y type ball transfer unit is placed on the base board made by stainless steel. Friction coefficient of the ball transfer unit on the base board made by several kinds of material is shown in **Table 1**.

Table 1 Friction coefficient of the ball transfer unit

Base board	Ball transfer unit	Friction coefficient μ
Stainless	C-8Y	0.014
Stainless	P-8Y	0.024
Duralumin	C-8Y	0.030
Copper	C-8Y	0.041

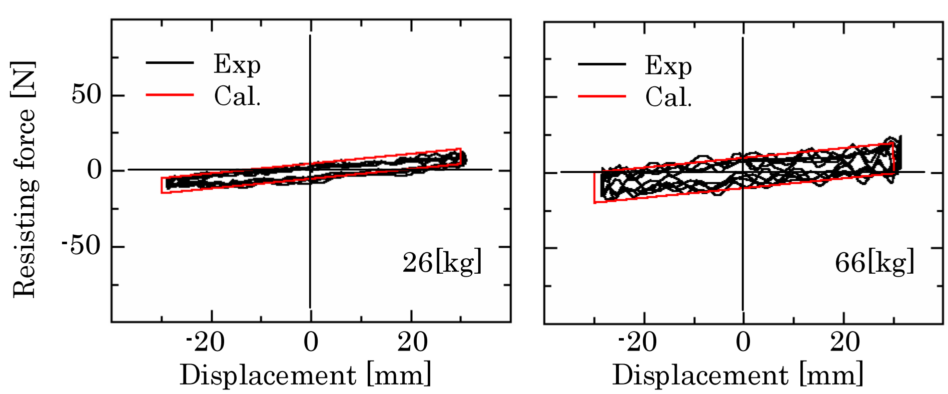
Resisting force characteristics of the isolation table

In order to clarify the force-displacement characteristics of the isolation table, the displacement and the resisting force between the base board installed on a vibrator and the table board attached to a rigid wall are examined. Experimental apparatus is shown in Fig. 6. The displacement and the resisting force are measured by an inductance type displacement transducer, and a load cell respectively. Figure 7 shows the resisting force characteristics of the isolation table under sinusoidal displacement 30mm of frequency 1Hz. 0˚ and 45˚ are exciting force directions which are diagonal and parallel to a side of the table board respectively. These results show that the isolation table has the stiffness is 290.9 N/m for 0˚ direction and 290.4 N/m for 45˚ direction regardless of the weight.

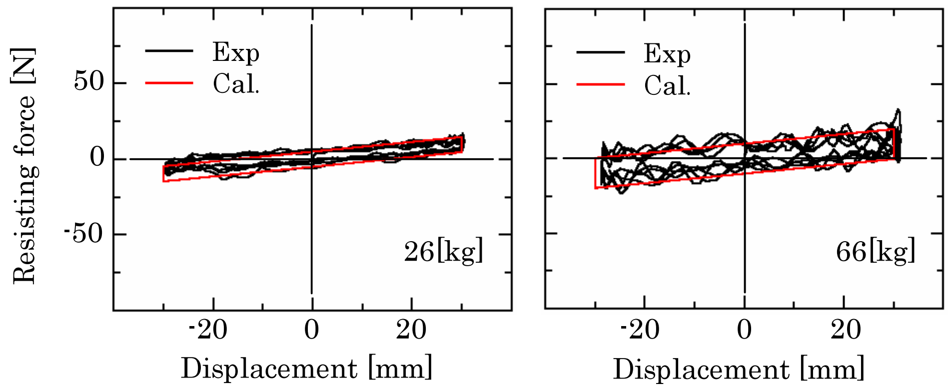


(1) Load cell (2) Isolation table (3) Displacement transducer
(4) Weight (5) Base board (6) Shaking table (7) Motor

Fig. 6 Experimental apparatus



(a) 0˚ direction



(b) 45˚ direction

Fig. 7 Resisting force of the isolation table

SEISMIC RESPONSE ANALYSYS

Analytical model and equation of motion

For concentrated mass

Figure 8 shows the one-degree-of freedom model having a concentrated mass on the isolation table. Temporary stay of the isolation table, which is produced by the friction force of the ball transfer unit, must be taken into account in this analysis. If the concentrated mass on the isolation table is subjected to a horizontal acceleration input $\ddot{z}$ in x direction, the equations of motion of the analytical model are given by the following expressions:

(1) Case of stay

$$u_0 = const., \dot{u}_0 = 0, \ddot{u}_0 = 0 \tag{1}$$

(2) Case of movement

$$m_0 \ddot{u}_0 + c_m \dot{u}_0 + k_t u_0 + f_f sign(\dot{u}_0) = -m_0 \ddot{z} \tag{2}$$

(3) Switching condition from stay to movement

$$|m_0 \ddot{z} - k_t u_0| \geq f_f \tag{3}$$

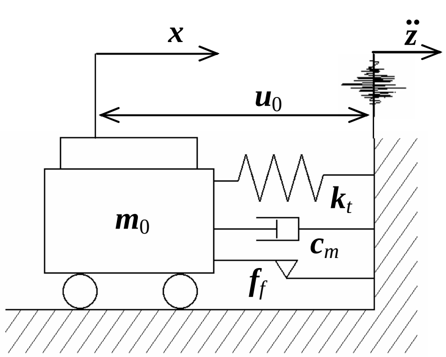


Fig.8 Analytical model of concentrated mass on the isolation table

(4) Switching condition from movement to stay

$$\dot{u}_0 = 0 \text{, and } \left|m_0(\ddot{u}_0 + \ddot{z}) + k_t u_0\right| \le f_f \qquad (4)$$

in which $sign(\dot{u}_1)$ is signum which is 1, 0 or –1 according to sign of $\dot{u}_0$, and m_0 is the mass of the weight including the base board, the struts and the middle board, u_0 is the relative displacement of the mass, c_m is the equivalent viscous damping coefficient of rare-earth magnet, f_f is the friction force of the ball transfer unit, and k_t is the stiffness of the isolation table.

For tower like structure

(1) Case of stay

$$u_0 = const.,\ \dot{u}_0 = 0,\ \ddot{u}_0 = 0$$

$$\begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \\ \ddot{u}_3 \end{Bmatrix} = -\begin{bmatrix} 1/m_1 & 0 & 0 \\ 0 & 1/m_2 & 0 \\ 0 & 0 & 1/m_3 \end{bmatrix} \begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{bmatrix}^{-1} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} - \begin{Bmatrix} \ddot{z} \\ \ddot{z} \\ \ddot{z} \end{Bmatrix} \qquad (5)$$

(2) Case of movement

$$\ddot{u}_0 = -\lfloor m_1\ddot{u}_1 + m_2\ddot{u}_2 + m_3\ddot{u}_3 + c_m\dot{u}_0 + k_t u_0 + f_f \cdot sign(\dot{u}_0) \rfloor / (m_0 + m_1 + m_2 + m_3) - \ddot{z}$$

$$\begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \\ \ddot{u}_3 \end{Bmatrix} = -\begin{bmatrix} 1/m_1 & 0 & 0 \\ 0 & 1/m_2 & 0 \\ 0 & 0 & 1/m_3 \end{bmatrix} \begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{bmatrix}^{-1} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} - \begin{Bmatrix} \ddot{u}_0 \\ \ddot{u}_0 \\ \ddot{u}_0 \end{Bmatrix} - \begin{Bmatrix} \ddot{z} \\ \ddot{z} \\ \ddot{z} \end{Bmatrix} \qquad (6)$$

(3) Switching condition from stay to movement

$$\left|(m_0 + m_1 + m_2 + m_3)\ddot{z} + m_1\ddot{u}_1 + m_2\ddot{u}_2 + m_3\ddot{u}_3 + k_t u_0\right| > f_f \qquad (7)$$

(4) Switching condition from movement to stay

$$\left|(m_0 + m_1 + m_2 + m_3)(\ddot{u}_0 + \ddot{z}) + m_1\ddot{u}_1 + m_2\ddot{u}_2 + m_3\ddot{u}_3 + k_t u_0\right| \le f_f,\ \dot{u}_0 = 0 \qquad (8)$$

(5) Overturning moment on the isolation table

$$M_0 = \frac{L}{3}\{3m_3(\ddot{u}_3 + \ddot{u}_0 + \ddot{z}) + 2m_2(\ddot{u}_2 + \ddot{u}_0 + \ddot{z}) + m_1(\ddot{u}_1 + \ddot{u}_0 + \ddot{z})\} \qquad (9)$$

where

m_0 : lowest mass of tower like structure including the table board

u_0 : relative displacement of m_0 to the ground

c_m : equivalent viscous damping coefficient of the isolation table

k_t : horizontal stiffness of the isolation table

f_f : friction force of the ball transfer unit

m_1 - m_3 : masses of tower like structure

u_1 - u_3 : relative displacement of m_1 - m_3 to the ground

α_{ij} : influence coefficient (deflection of *i* when the load is applied on j)

$\ddot{z}$: input acceleration

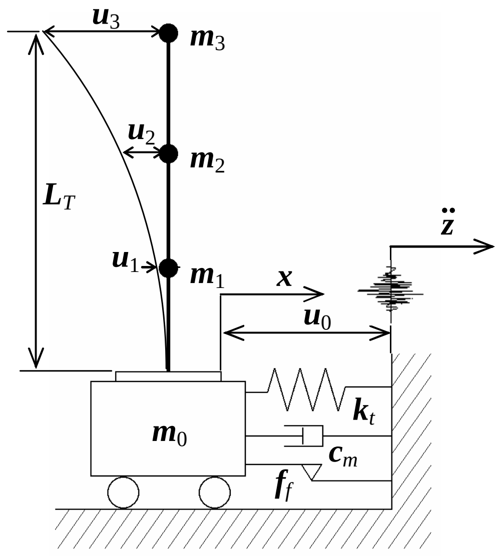


Fig.9 Analytical model of the tower like structure on the isolation table

Table 2 Numerical condition

Isolation table	Mass	m_0	26 [kg]
	Stiffness	$(k_t)_{\alpha=0^\circ}$	290.9 [N/m]
		$(k_t)_{\alpha=45^\circ}$	290.4 [N/m]
	Damping coefficient	c_m	18.4 [Ns/m]
	Friction force	f_f	8.2 [N]
Tower-like structure	Mass	m_1, m_2, m_3	5,5,5 [kg]
	Young's modulus	E_T	206 [Gpa]
	Diameter	d	30 [mm]
	Height	L	1800 [mm]

SHAKING TABLE TEST

Case of concentrated mass

Figure 10 shows the concentrated mass of 66 kg on the isolation table installed on an electro-hydraulic type shaking table. The acceleration of the table board $\ddot{x}_0$ and the relative displacement u_0 are measured by an accelerometer and displacement transducer respectively. Seismic waves are inputted in the direction 0˚ or 45˚ which are diagonal or parallel to a side of the table board respectively.

Table 3 shows the experimental and calculated maxima of the responses for the input seismic waves of El Centro (1940) N-S normalized to be 4.0 m/s ^{2} and JMA Kobe (1995) N-S to be 3.0 m/s ^{2} at the maximum acceleration. Figure 11 and 12 show relation of the output and the input acceleration, and the experimental and calculated response waves for El Centro (1940) N-S normalized to be 4.0 m/s ^{2} at the maximum acceleration respectively. Table 3, Fig. 11 and 12 lead to the following: (1) The effect of the isolation table becomes larger as the acceleration increases. (2) The maximum acceleration of the isolation table decreases to about 1/6 for El Centro (1940) N-S and JMA Kobe (1995) N-S when input acceleration is 1.5 m/s ^{2} and to about 1/10 when 4.0 m/s ^{2}. (3) The isolation effect is not so dependent on the direction of the seismic input. (4) The experimental results are in approximate agreement with the calculated results.

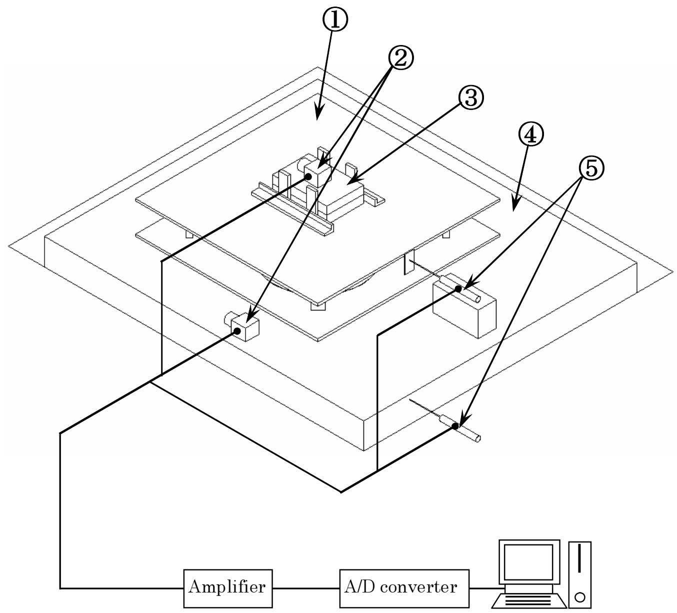


Fig.10 Experimental apparatus

Table 3 Maximum response of the isolation table

Input wave / Direction	El Centro NS ($|\dot{z}|_{max}$= 4.0 [m/s ^{2}])			
	$|\ddot{x}_0|_{max}$ [m/s ^{2}]		$|u_0|_{max}$ [mm]	
	Exp.	Cal.	Exp.	Cal.
0°	0.27	0.23	59.1	61.0
45°	0.22	0.23	55.7	61.0
Input wave / Direction	**JMA Kobe NS ($|\dot{z}|_{max}$= 3.0 [m/s ^{2}])**			
	$|\ddot{x}_0|_{max}$ [m/s ^{2}]		$|u_0|_{max}$ [mm]	
	Exp.	Cal.	Exp.	Cal.
0°	0.22	0.28	57.8	51.5
45°	0.27	0.28	53.5	51.5

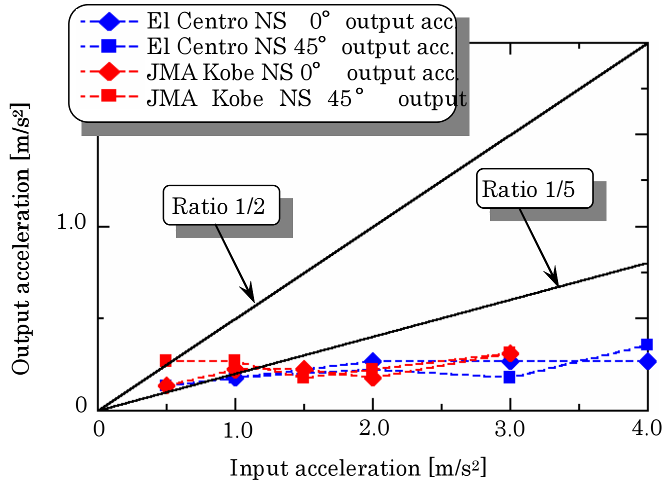


Fig. 11 Maximum acceleration of the isolation table

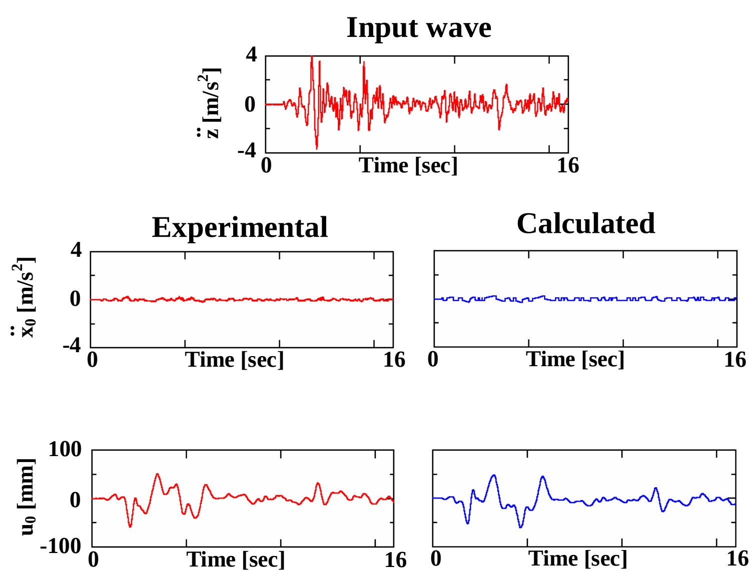


Fig.12 Response waves (El Centro N-S 4.0 [m/s^2], 0˚ direction)

Case of tower like structure

Figure 13 shows the tower like structure installed on an electro-hydraulic type shaking table. Table 3 shows the experimental and calculated maxima of the acceleration responses $\ddot{x}_3$ and $\ddot{x}_0$, the maximum displacement responses u_0, and maximum overturning moment M for the input seismic waves of El Centro (1940) N-S normalized to be 4.0 m/s^2 and JMA Kobe (1995) N-S to be 3.0 m/s^2 at the maximum acceleration. Figure 14 (a) and (b) show the experimental and calculated response waves for El Centro (1940) N-S normalized to be 4.0 m/s^2 at the maximum acceleration. Table 3 and Fig. 14 lead to the following: (1) The effect of the isolation table for El Centro N-S is larger than that of JMA Kobe (1995) N-S. (2) The effect of the isolation table becomes larger as the input acceleration increases. (3) The maximum acceleration of the isolation object decreases to about 1/20 for El Centro N-S and to about 1/10 for JMA Kobe. It can be seen from Fig. 14 that the experimental waves are in approximate agreement with the calculated waves.

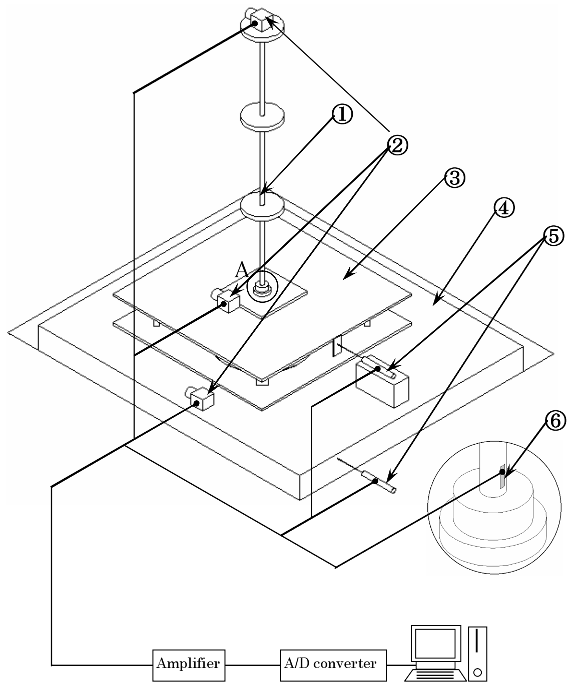
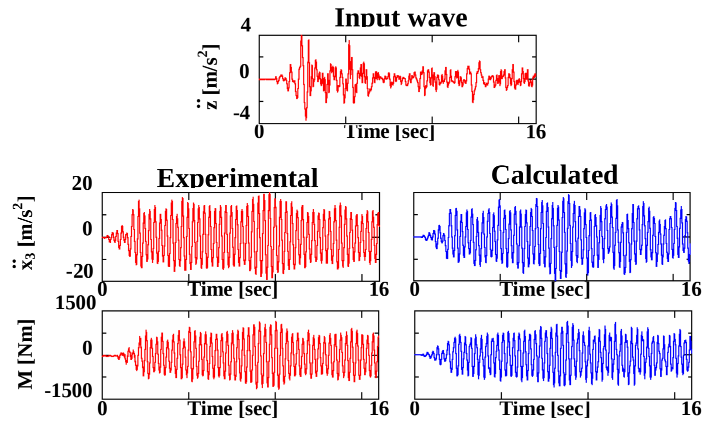


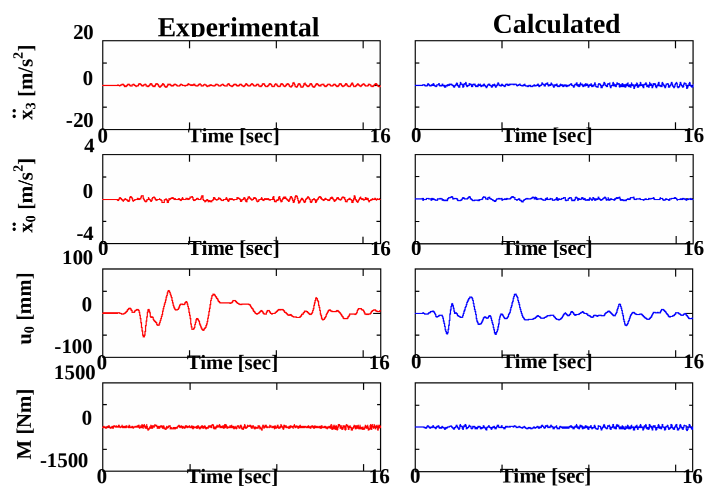
Fig.13 Experimental apparatus

Table 4 Maximum response of the isolation table and the top mass of the tower like structure

Input wave	El Centro NS ($\|\ddot{z}\|_{max}$= 4.0 [m/s^2])							
	$\|\ddot{x}_3\|_{max}$ [m/s^2]		$\|\ddot{x}_0\|_{max}$ [m/s^2]		$\|u_0\|_{max}$ [mm]		$\|M\|_{max}$ [Nm]	
	Exp.	Cal.	Exp.	Cal.	Exp.	Cal.	Exp.	Cal.
Without Isolation	20.42	20.27	—	—	—	—	1164	1134
With Isolation	1.13	1.26	0.35	0.27	54.1	47.7	69	71
Input wave	JMA Kobe NS ($\|\ddot{z}\|_{max}$= 3.0 [m/s^2])							
	$\|\ddot{x}_3\|_{max}$ [m/s^2]		$\|\ddot{x}_0\|_{max}$ [m/s^2]		$\|u_0\|_{max}$ [mm]		$\|M\|_{max}$ [Nm]	
	Exp.	Cal.	Exp.	Cal.	Exp.	Cal.	Exp.	Cal.
Without Isolation	14.60	13.16	—	—	—	—	934	896
With Isolation	1.54	1.58	0.36	0.32	61.0	52.2	92	91



(a) Without isolation



(b) With isolation

Fig.14 Reponse waves

CONCLUSION

Conclusions drawn from the present research are summarized in the following.

(1) The isolation table has the effect of lowering the acceleration response of the object regardless the direction of seismic excitation in the horizontal plane.

(2) The maximum acceleration response of the concentrated mass installed on the isolation table decreases to 1/6 -1/10 and tower like structure to about 1/20 for El Centro N-S and to about 1/10 for JMA Kobe to that of the input seismic acceleration.

(3) The isolation table has a feature that makes the isolation effect better for larger seismic excitation over the range of the maximum input acceleration from 0.5 to 4.0m/s^2.
(4) The isolation table is applicable to the object of which the centre of gravity is in a higher position.
(5) The experimental results of the acceleration and displacement responses approximately agree with the calculated results.

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