SHAKE TABLE TESTS ON THREE-DIMENSIONAL VIBRATION ISOLATION SYSTEM COMPRISING RUBBER BEARING AND COIL SPRINGS

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ABSTRACT

In these days of the high cost of land and the concentration of activities, the most direct benefit from the vibration isolation technologies is the release of land directly over or adjacent to railways, for building and structure uses. This technique had been pioneered in the UK and has been introduced into the USA and especially in Japan as the extension of the technologies for protecting buildings against damage from earthquakes (Grootenhuis, 1989). The application of the technology for traffic vibration isolation of entire buildings has been becoming increasingly necessary in Japan. Vertical component of vibration is considered to be more essential for this technique than lateral one. On the other hand, seismic isolation technology is required for reducing the responses in horizontal direction. So, if the vibration isolation technology for both traffic vibration and earthquake is realised, this will become a desirable vibration isolator for three-dimensional disturbances. In this study, a new type of three-dimensional vibration isolation system for entire buildings has been proposed to have its lateral first natural frequency of 0.5 Hz and a vertical one of less than 3.5 Hz and to prevent the dangerous rocking motion of the supported building by applying additional side-support bearings to restrain the rotation. The performance of isolation was investigated by the shake table tests and by the response analysis.

KEYWORDS

Three-dimensional vibration isolation system; Rubber bearings; Traffic induced vibration; Earthquake isolation

INTRODUCTION

Isolation of buildings or structures on rubber bearings from ground-borne vibration has been in practice for over 30 years. The technique of isolation of entire buildings or structures against traffic induced vibration has been pioneered in the United Kingdom where there are lots of buildings, mainly in London, mounted on laminated rubber bearings (Fujita, 1996), which are usually designed to give the superstructures the vertical first natural frequency of 7 to 10 Hz. In these days of the high cost of land and the concentration of activities, the most direct benefit from the vibration isolation technologies is the release of land directly over or adjacent to railways, for building and structure uses. In Japan, as well, the application of the technology for traffic vibration isolation of entire buildings has been becoming increasingly necessary. However almost no attempts have been made so far, because the vertical component of vibration is considered to be more essential for this technique than lateral one and it is considered to be difficult to suppress excessive rotational motion of the vertically isolated buildings or structures during strong earthquakes.

On the other hand, seismic isolation technology is required for reducing the responses in horizontal direction. In this case, the vertical natural frequency is designed to be as higher as possible in order to avoid the vertical or rotational resonance in the superstructures. However, in this field, the three-dimensional seismic isolation is becoming desirable for the buildings in which vertical seismic responses are crucial to structural design of the internal components as well as the horizontal ones. Fast Breeder Reactor power plant, Nuclear Fusion power plant and semi-conductor manufacturing factory are considered to be in this category.

In this study, a new type of three-dimensional vibration isolation system for entire buildings has been proposed to have its lateral first natural frequency of 0.5 Hz and a vertical one of less than 3.5 Hz and to prevent the dangerous rocking motion of the supported building by applying additional side-support bearings to restrain the rotation. The performance of isolation was investigated by the shake table tests and by the response analysis.

PROPOSED VIBRATION ISOLATION SYSTEM

Three-dimensional vibration isolation systems can be classified into following groups depending on the requirement of performance.

In the case of isolation of traffic vibration is only required:

Figure 1 shows a conventional isolation system for entire buildings or structures from ground-borne vibration using laminated rubber bearings. The vertical 1st natural frequency is normally designed to 5~10 Hz and the horizontal one to about a half of that. High damping rubber bearing or additional damping would be applied if required. When located in a high seismicity area, a seismic safety of the building must be obtained by the superstructure itself by using a snubber to suppress an excessive deflexion due to its rocking motion.

In the case of two-dimensional seismic isolation is only required:

This type, as shown in the Fig. 1, is the most conventional seismic isolation system which having its horizontal natural period of 2~3 s and the vertical natural frequency of 15~20 Hz. Usually an additional hysteretic or viscous damper is laterally applied to the system to avoid a resonance at its natural frequency. Nowadays the rubber bearings having higher damping functions such as lead-plug filled rubber bearings or high-damping rubber bearings are becoming more popular in Japan. Although this system has relatively higher vertical natural frequency, isolation effect against the traffic induced vibration is still expected because the major dominant frequency range of the disturbance is usually in the range of around 60 Hz and the propagation of the vibration energy is restricted to the points in which the bearings are located.

In the case of three-dimensional isolation is required (the vertical natural frequency is higher than 5 Hz):

By designing seismic rubber bearing to give the super structure its vertical 1st natural frequency of 5~10 Hz and its horizontal 1st natural period of 2~3 s, both horizontal seismic isolation effect and vertical isolation effect against traffic induced vibration will be obtained (Figure 1). When utilising vertically soft system to building, the vertical deflexion and the rocking motion will be amplified during severe earthquakes, so that energy absorption system of large capacity will be needed. In addition, considering long term durability of the system, it seems to be difficult to design the base-isolated buildings having their vertical first natural frequencies lower than 5 Hz by supported by nothing but the rubber bearings.

In the case of three-dimensional isolation is required (the vertical natural frequency is lower than 5 Hz):

Figure 2 shows the concept of the three-dimensional isolation system proposed in this study. The isolation system consists of rubber bearings for the horizontal isolation and coil spring with energy absorber for the vertical isolation; of course coned-disc sprig sets or air-cushion mount and so on can be also applied in place of the coil spring. The coil spring can provide the superstructure with a lower vertical natural frequency of 1~5 Hz for the vertical isolation. The upper flange of the rubber bearing is restrained by the vertically placed rubber bearings attached to the floor slab of the superstructure or the additional outer flange. In this system, excessive rotational motion of the building accompanying the vertical isolation can be geometrically suppressed sufficiently. The vertically installed dampers also function to reduce the excessive vertical deflexions. Figure 3 shows the proto-type of the system based on this concept.

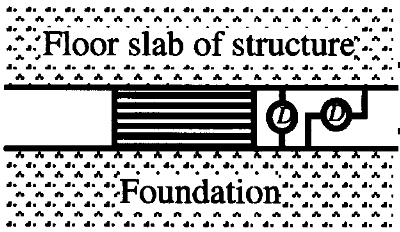

Fig. 1. Conventional vibration isolation system

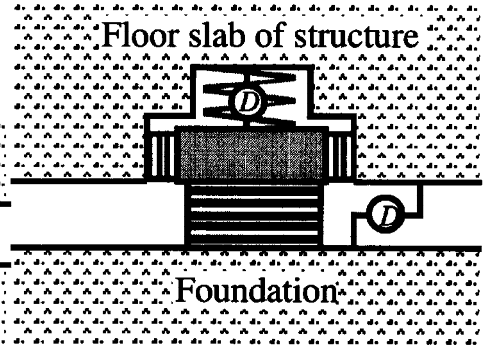

Fig. 2. Concept for rocking-motion restraint vibration isolation system

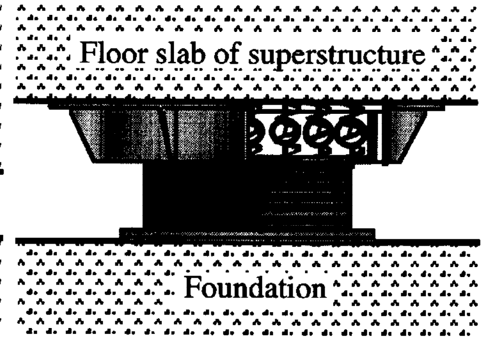

Fig. 3. Proposed three-dimensional isolation system

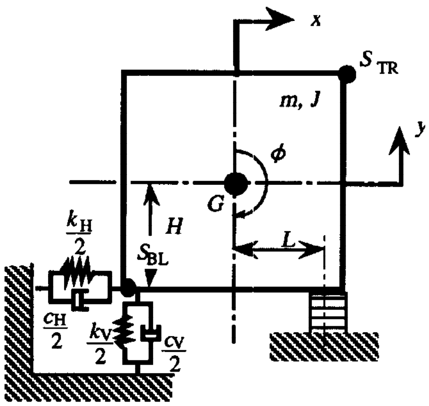

Fig. 4. Analytical model for conventional vibration isolated building with low vertical frequency

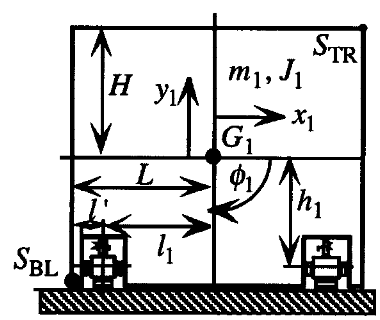

Fig. 5. Analytical model for three-dimensional vibration isolated building

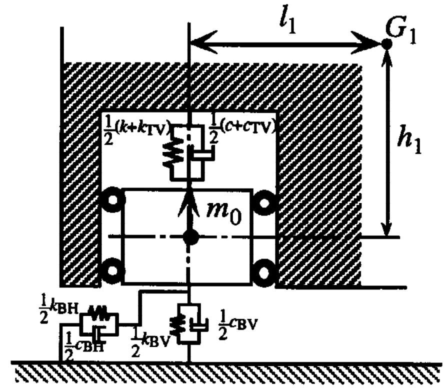

Fig. 6. Close view of model for the rocking motion restraint model

PRE-STUDY ON PERFORMANCE OF PROPOSED SYSTEM

Analytical model for the conventional three-dimensional isolation system

Figure 4 shows the analytical model regarding the conventional base-isolated building. As shown in Fig. 1, this SDOF model represents either vibration isolated building model against traffic induced vibrations or seismic base-isolated building model depending on their horizontal and vertical stiffness of the rubber bearings employed in the systems. In this model, the superstructure is regarded as a rigid body and the horizontal, the vertical and the rotational motion are considered as a 3DOF model. The equations of motions are derived as follows:

$$\ddot{x} + 2\zeta_H\omega_H(\dot{x} - H\dot{\phi}) + \omega_H^2(x - H\phi) = -\ddot{z}_H \tag{1}$$

$$\ddot{y} + 2\zeta_V\omega_V\dot{y} + \omega_V^2 y + g = -\ddot{z}_V \tag{2}$$

$$\ddot{\phi} - \{2\zeta_H\omega_H(\dot{x} - H\dot{\phi}) + \omega_H^2(x - H\phi)\}H\frac{m}{J} + (2\zeta_V\omega_V\dot{\phi} + \omega_V^2\phi)L^2\frac{m}{J} = 0 \tag{3}$$

where the variables used in the equations are;

x, y : horizontal and vertical displacement of the centre of gravity of the building relatively to the ground
ϕ : rotational angle of the building model
m, J : mass and moment of inertia for the centre of gravity of the building model
H : elevation of the centre of gravity of the building model
$2L$: length of the distance between the rubber bearings are located
k_H, c_H : horizontal stiffness and damping coefficient of the rubber bearing
k_V, c_V : vertical stiffness and damping coefficient of the rubber bearing

z_H, z_V : horizontal and vertical displacement of the ground
g : acceleration of gravity
and the following expressions are employed into the equations:

$$\omega_H = \sqrt{\frac{k_H}{m}},\ \omega_V = \sqrt{\frac{k_V}{m}},\ \zeta_H = \frac{c_H}{2\sqrt{mk_H}},\ \zeta_V = \frac{c_V}{2\sqrt{mk_V}},\ \alpha = \frac{H}{L}$$

Analytical model for the proposed three-dimensional isolation system

Figure 5 shows the analytical model for the proposed three-dimensional base-isolated building. As previously described regarding Fig. 2 and Fig. 3, this system has a function to restrain an excessive rotational motion of the building. Desirable restraint-system or material is now in consideration, but the perfect-restraint assumption is employed into the model to evaluate the performance in this study. Figure 6 shows a schematic close-view of the system in which the vertical motion of the coil spring attached to the top of the upper flange of the rubber bearing is only allowed. The equations of motions are derived as follows:

$$\ddot{x}_1 + \frac{2}{1+2\beta}\zeta_{BH}\omega_{BH}(\dot{x}_1 - \alpha l_1\dot{\phi}) + \frac{1}{1+2\beta}\omega_{BH}^2(x_1 - \alpha l_1\phi) = -\ddot{z}_H \tag{4}$$

$$\ddot{y}_1 + 2\zeta_{TV}\omega_{TV}(\dot{y}_1 - \dot{y}_0) + \omega_{TV}^2(y_1 - y_0) = -\ddot{z}_V \tag{5}$$

$$\ddot{\phi} - \{2\zeta_{BH}\omega_{BH}(\dot{x}_1 - \alpha l_1\dot{\phi}) + \omega_{BH}^2(x_1 - \alpha l_1\phi)\}\frac{3\alpha}{l_1(1+\alpha)} + (2\zeta_{BV}\omega_{BV}\dot{\phi} + \omega_{BV}^2\phi)\frac{3}{1+\alpha} = 0 \tag{6}$$

$$\ddot{y}_0 + \frac{1}{\beta}\zeta_{BV}\omega_{BV}\dot{y}_0 + \frac{1}{2\beta}\omega_{BV}^2 y_0 - \frac{1}{\beta}\zeta_{TV}\omega_{TV}(\dot{y}_1 - \dot{y}_0) - \frac{1}{2\beta}\omega_{TV}^2(y_1 - y_0) = -\ddot{z}_V \tag{7}$$

where the variables used in the equations are;
y_0 : vertical displacement of mass of the upper flange of the three-dimensional isolation system relatively to the ground
x_1, y_1 : horizontal and vertical displacement of the centre of gravity of the building relatively to the ground
ϕ_1 : rotational angle of the building model
m_1, J_1 : mass and moment of inertia for the centre of gravity of the building model
m_0 : mass of the upper flange of the three-dimensional isolation system
k, c : shear stiffness and damping coefficient of the rotation-restraint supports
k_{TV}, c_{TV} : vertical stiffness and damping coefficient of the vertical isolation system comprising coil springs and viscous dampers
h_1 : distance between the centre of gravity of the building model and the mass of the upper flange of the three-dimensional isolation system
$2L$: width of the building
$2l_1$: length of the distance between the rubber bearings are located

Besides, subscript 'B' is added to the parameters used in the conventional isolation system model shown in Fig. 4 and the following expressions are employed into the equations as well:

$$\omega_{TV} = \sqrt{\frac{k + k_{TV}}{m_1}},\ \zeta_{TV} = \frac{c + c_{TV}}{2\sqrt{m_1(k + k_{TV})}},\ \omega_{BH} = \sqrt{\frac{k_{BH}}{m_1}},\ \zeta_{BH} = \frac{c_{BH}}{2\sqrt{m_1 k_{BH}}}$$
$$\omega_{BV} = \sqrt{\frac{k_{BV}}{m_1}},\ \zeta_{BV} = \frac{c_{BV}}{2\sqrt{m_1 k_{BV}}}L^2,\ \alpha = \frac{H}{L},\ \beta = \frac{m_0}{2m_1},\ J_1 = \frac{m_1}{3}(L^2 + H^2) = \frac{m_1}{3}(1 + \alpha^2)L^2$$

Investigation of the performance of isolation

In response analyses to investigate the performance of the system preliminary, a ratio α (=H/L)=1 and a width of the building: $2L$ =10 m were assumed and horizontal and vertical components of actual seismic wave such as El Centro NS-UD(Imperial Valley Earthquake, 1940), Hachinohe EW-UD(Tokachi-Oki Earthquake, 1978) and Akita NS-UD(Nihonnkai-Chubu-Oki Earthquake, 1982) were used. Besides, the first horizontal natural period of the isolated building and the damping ratio was assumed to be 2s and 0.15 respectively.

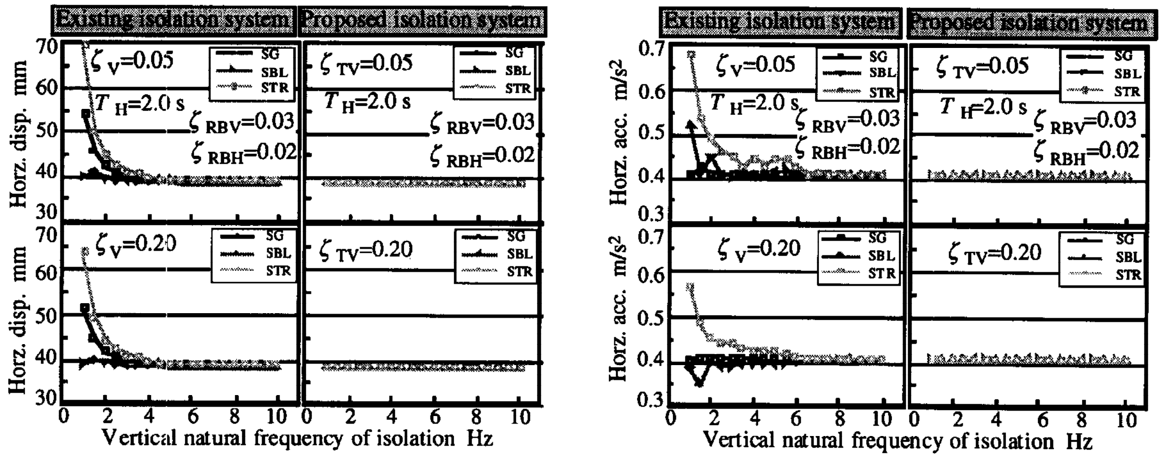

Fig. 7. Dependency of vertically installed damper on performance of isolation in horizontal direction

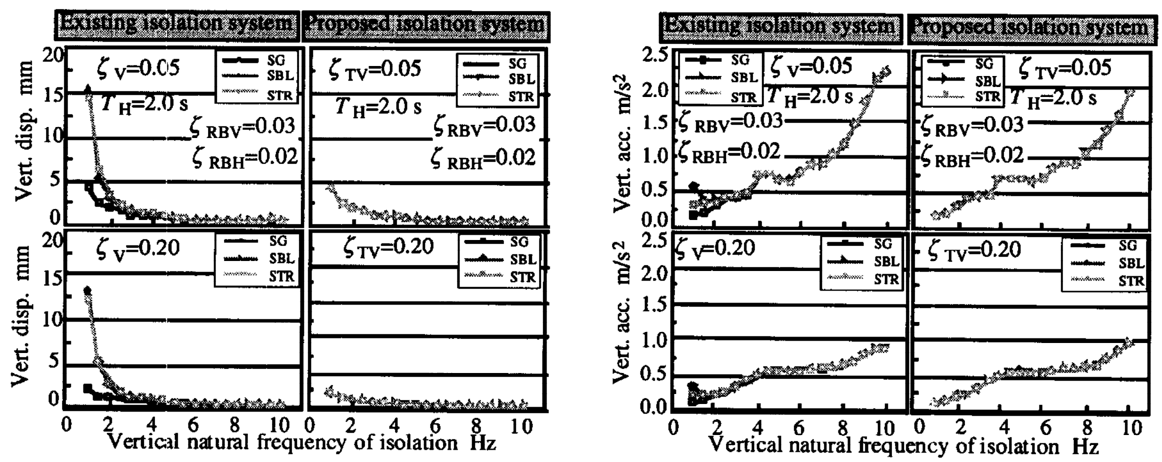

Fig. 8. Dependency of vertically installed damper on performance of isolation in vertical direction

Figure 7 shows dependencies of the vertically installed dampers on the performance of isolation in horizontal direction being compared the conventional-type isolation system with the proposed one each other against the El Centro NS-UD input (NS: 1.0 m/s^2, UD: 0.5 m/s^2).

In the results obtained from the calculations for the conventional isolation system, it is obvious that both response deflexion and acceleration of the superstructure increase significantly due to rocking motion in a vertical frequency range lower than 2~4 Hz although both responses are slightly suppressed when a vertical damping ratio of the device is increased from 0.05 to 0.20. In the case of the proposed system in which the perfect rotational-restraint is assumed in the model, however, the responses are sufficiently suppressed even in the lower vertical frequency range as a matter of course. Moreover the results also indicate a validity of the device being restrained geometrically because the vertical damping ratio of the device does not affect.

Figure 8 shows the results obtained for the vertical responses. It is not clear to say in general but as far as the El Centro NS-UD input is concerned, by choosing a vertical natural frequency of the system lower than 4 Hz, the vertical isolation effect is obtained, so that the basic concept of the system would be applied to a three-dimensional seismic isolation system. It is considered that a first vertical natural frequency should be chosen in the range lower than 1 Hz if a drastic effect of isolation is required as well as the horizontal one produces. In this point of view, a rotation-restraint system or mechanism is considered to be necessary into the three-dimensional isolation system to effectively suppress the dangerous rotational motion of the superstructure.

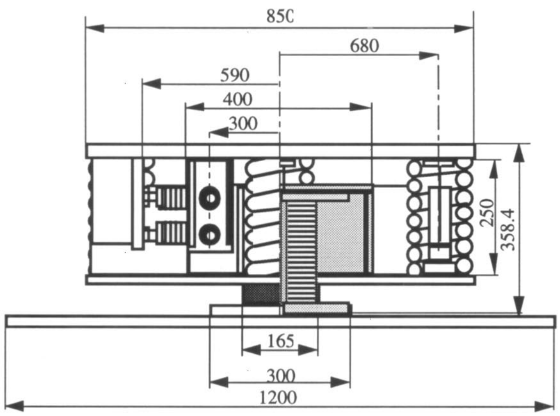

Fig. 9. Three-dimensional isolation system used for the tests

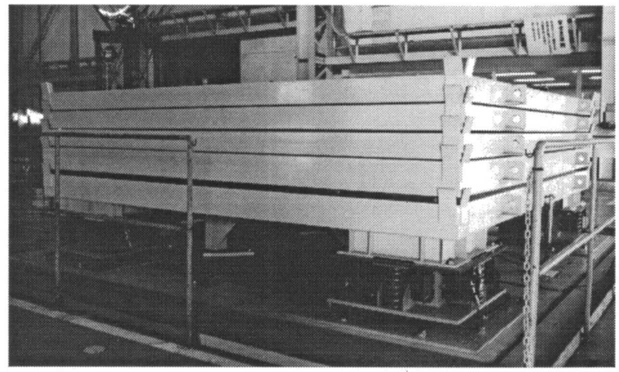

Fig. 10. Three-dimensional base-isolated structure used for the tests

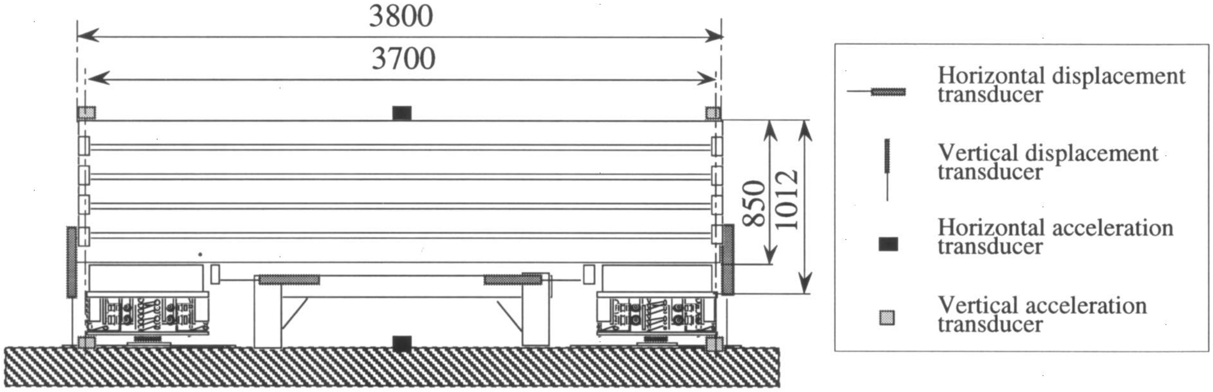

Fig. 11. Schematic view of isolated rigid body model and measurement points

SHAKE TABLE TESTS

Experimental model of the proposed three-dimensional isolation system

Figure 9 shows the experimental model of the isolation system in which four coil springs and viscous dampers are attached onto an upper flange of a lead-rubber bearing that is designed to provide the rated mass of 10,000 kg with a natural period of 2 s. Due to a limitation of the experimental conditions, the isolation device became too small to suppress the rotational motion sufficiently although four sets of rotation-restraint bearings are attached to the columns hanging down from the base slab of the building model. The coil springs were designed to provide the system a vertical natural frequency of below 3.5 Hz which was considered to be impossible to realise by using rubber bearing alone. The viscous dampers were designed to give a damping ratio of 0.05 to the system.

Structure model used for shake table tests and method

Figure 10 shows the rigid mass model supported by four experimental models of the three-dimensional isolation system under the excitation tests. Mass of the model made of five panels of concrete block is 30,000 kg, so that each one of the isolation systems supports 7,500 kg which is lighter than the design load mentioned above. This makes the first horizontal natural frequency of the system higher than expected and the performance of horizontal isolation decreases.

Various earthquake inputs, such as El Centro(Imperial Valley Earthquake, 1940), Hachinohe(Tokachi-Oki Earthquake, 1978), Akita(Nihonkai-Chubu-Oki Earthquake,1982) and Kobe(Hyogo-ken Nanbu Earthquake: JMA, 1995) and a traffic induced vibration recorded at a building foundation over the train-tracks were used for the excitation tests. In the tests, horizontal and vertical response accelerations of the rigid mass model and the shake table, shear deformation of rubber bearings and vertical deflexion of the coil springs were measured as shown in Fig. 11.

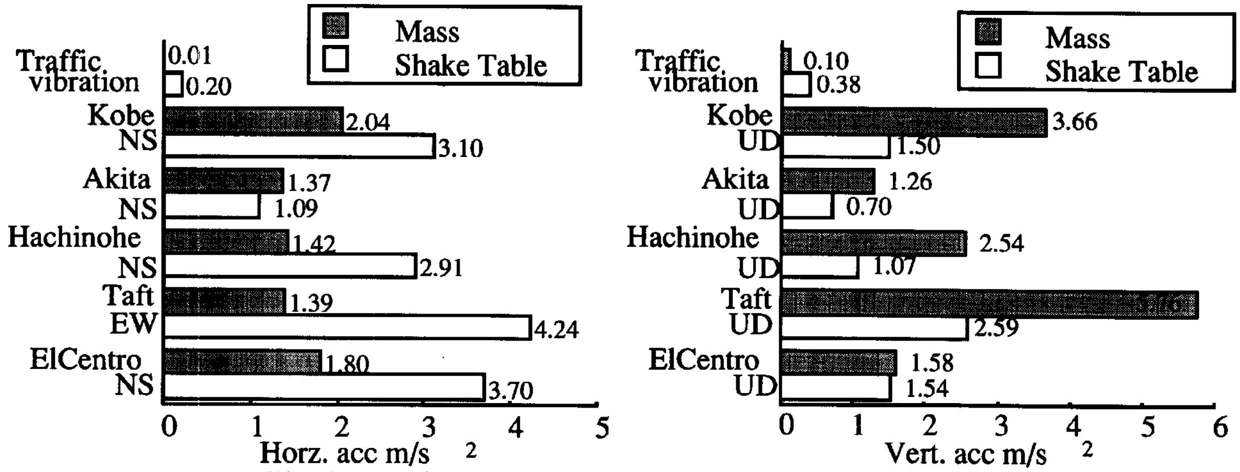

Fig. 12. Performance of isolation to the rigid-mass model

Performance of isolation to the structure

Figure 12 shows the test results for the various inputs, in which the horizontal and vertical response accelerations of the rigid mass when isolated(tinted bars) are compared with the input accelerations measured on the shake table(white bars). In the results for the horizontal directions, the performance of isolation was not adequate against the input having lower dominant frequency such as Akita NS although the good performances were obtained under El Centro NS, Taft EW and Traffic vibration excitations. This was because the first horizontal natural frequency of the system was too high as 0.77 Hz (=1.3 s) to obtain a good performance of isolation as previously mentioned.

For the vertical isolation, a 70 % reduction was obtained in the response acceleration of the rigid body model against the traffic-induced vibration input, although the responses were somewhat amplified under the other seismic inputs. From a point of view that the response acceleration must be reduced than the input acceleration when isolation systems are applied, the results were not satisfactory. In order to obtain sufficient reductions in the maximum response acceleration of superstructures, it is considered that the vertical natural frequency of the system should be tuned to a lower frequency below 1 Hz.

Performance of isolation to the internal equipment

Figure 13 shows the floor response spectra in vertical direction for the isolated rigid mass model indicated by a dotted line and the shake table in a solid line under the El Centro NS(3.70 m/s^2)-UD(1.54 m/s^2) excitation when a damping ratio of the equipment is 0.03. The vertical response when isolated excess the acceleration of the shake table in around the vertical natural frequency of isolation ($\cong$ 0.35 Hz) and this result agrees with the performance of isolation in its maximum value previously shown in Fig. 12. Although a sufficient reduction in the maximum response can not be obtained by the vertical isolation system having its natural frequency of 3~5 Hz, however, it is obvious that the effectiveness of the vertical isolation to the internal equipment having its vertical natural frequency higher than 7~8 Hz is remarkable. The most direct benefit from the vertical seismic isolation is in this point, not in the purpose to reduce the maximum response of the buildings. However, it is considered that R & D of three-dimensional seismic isolation systems should be done with more attentions because the performance of vertical isolation will remarkably increase with a lower natural frequency such as 1 Hz and with a higher damping capacity to suppress an excessive deflexion accompanying the vertical isolation.

Figure 14 is the result which shows the remarkable effectiveness of the vertical isolation against the traffic induced vibration excitation (Horz.: 0.20 m/s^2, Ver.: 0.38 m/s^2).

Effectiveness of the rotational motion restraint device

Figure 15 shows the effectiveness of the rotational motion restraint device. It was observed that about a 20 % of reduction in the vertical response acceleration and displacement regarding rocking motions accompanying the vertical isolation when the restraint-device was applied into the system. Both responses were calculated by eliminating the component regarding the vertical translation responses from the measured responses at both sides of the rigid-mass model. Further investigations will be carried out this year by loading tests using a full-size isolation system to clarify the effects of the anti-rocking mechanism.

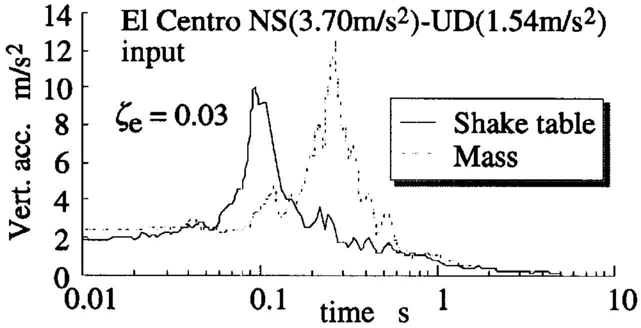

Fig. 13. Performance of the vertical isolation to equipment

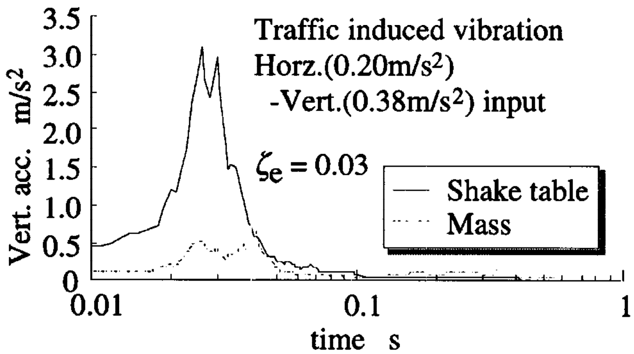

Fig. 14. Performance of the vertical isolation to equipment

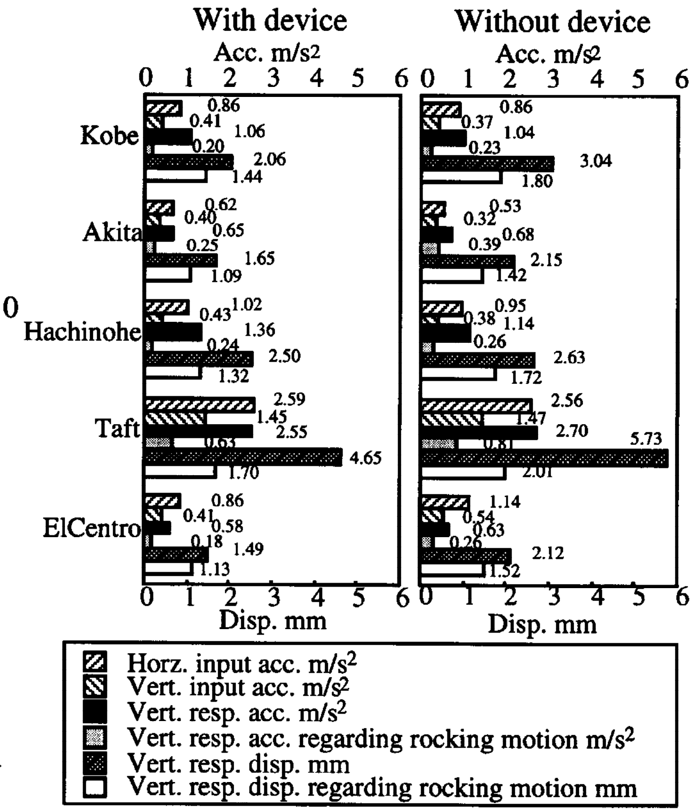

Fig. 15. Effectiveness of the rotational motion restraint device

CONCLUSIONS

In this study, the shake table tests were conducted to investigate the performance of the proposed three-dimensional isolation system against both seismic and traffic-induced vibration inputs. It was confirmed that the three-dimensional isolation system having its vertical natural frequency of around 3.5 Hz was very much effective for reducing response acceleration of the building and the internal equipment against traffic-vibration excitation and effective for the internal equipment against seismic inputs. Although the rocking motion of the building model was reasonably suppressed by the rotational motion restraint device, however, further investigations have to be carried out by making a full-size system to clarify the effectiveness of the device more precisely because any sorts of anti-rocking systems are essential to the three-dimensional vibration isolation system especially when isolate entire buildings against strong seismic motions.

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