SAFETY EVALUATION OF SEISMICALLY ISOLATED HOUSES WITH DISPLACEMENT RESTRAINT DEVICES UNDER SEVERE EARTHQUAKE MOTIONS

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ABSTRACT :

Recently earthquake ground motions with large amplitude and/or long period component act on seismically isolated buildings. In case of family houses, responses of isolated layers will probably exceed design limitation of isolators during severe earthquakes. To keep a function of isolation during a main- and after-shocks, the isolator should be protected from failure through adding to kinds of shock absorbing devices. To investigate effects of the devices for the reduction of displacement responses of isolators, and influences on the responses of superstructures, a numerical calculation is conducted. A relationship between responses of superstructure and isolator is summarized through several parametric studies on kinds of earthquake motions and operating positions of shock absorbing devices. It is made clear that the response of superstructures is evaluated based on the relative velocity of isolators at the operating position and the controlled displacement of isolated layer.

KEYWORDS: Seismic Isolation, Family House, Displacement Restraint Device, Safety of Superstructure, Severe and Long Period Earthquake

1. INTRODUCTION

A seismic isolation gives acceleration responses of buildings being reduced, through an elongation of predominant period in buildings by low stiffness and large deformation characteristics of isolators. Recently earthquake ground motions have been observed whose maximum velocities exceed 100 m/s or whose predominant periods are very long, such as earthquake motions observed in earthquakes of Turkey(1999)[1)], Taiwan(1999) [2)], Mexico(1985) [3)] and Japan(2003)[4)], etc. When these motions act on seismically isolated buildings, displacement responses of isolated layers are estimated to be large. In case of family houses, clearances at surroundings or isolated layers are not enough to the large displacement. As a result, a collision of isolated part or a failure of isolator will probably occur during earthquakes. It is necessary that effects of collision will be less or isolators will be protected from failure, to keep the safety during a main- and after-shocks and the sustainability of family houses after earthquakes.

To keep a function of isolation during and after earthquakes, the isolator should be protected from failure through adding to kinds of shock absorbing devices (hereafter referred to as displacement restraint device). The displacement restraint devices such as a rubber[5)] or a wire-rope[6)] will reduce a maximum displacement response of isolators. The stiffness of the displacement restraint device need be larger than that of the isolator, to reduce the displacement response. At that time, the shear force of the isolated layer with the displacement restraint device is much larger than that without ones. As the shear force of the superstructure is also larger, the responses of superstructure should be evaluated. In order to estimate the effect of displacement restraint device on response of seismically isolated houses, a numerical calculation is conducted. A relationship between responses of superstructure and isolator is summarized through several parametric studies. Earthquake motions and mechanical characteristics of the isolated systems and the displacement restraint devices, and operating positions of displacement restraint device, etc. are considered as parameters.

2. SAFETY OF SUPERSTRUCTURE UNDER SEVERE EARTHQUAKE

To continue the function of houses after earthquakes means to protect isolators from damages. To protect isolators from damage, the displacement response of isolators should be kept not to exceed the limit displacement of isolators. The displacement restraint device is added to the isolation system, as shown in Fig. 1.

It is a desirable situation that both superstructures and isolators will not be damaged, while in case when the earthquakes whose amplitudes are larger than assumed motions in the design, it is difficult to keep non-damage in both superstructure and isolators. Conditioned that the isolators will continue to be operating to maintain the function of houses, the situation of superstructure is summarized in Table 1. The relationship between the operational condition of displacement restraint device and response of superstructure needs to be evaluated.

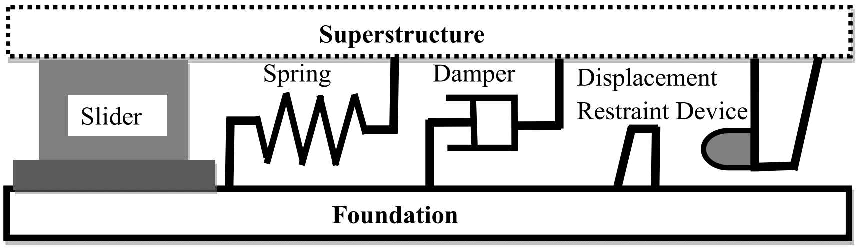


Fig. 1 An example of components in seismically isolated layer

Table 1 Situation of superstructure subjected to earthquake motion

Situation of superstructure	Non-damage	A certain damage, Repairable	Until safety limit
Upper limit of story drift angle	1/200	1/50	1/20
Explanation	To have enough capacity of displacement of isolator To escape collision of displacement restraint device	To have enough capacity of displacement of isolator to a limited extent To reduce influence of collision on response of superstructure	Not to have enough displacement of isolator To keep safety limit for human life

3. CALCULATED MODEL OF SEISMICALLY ISOLATED SYSTEM

3.1. Overall Model

The seismically isolated house model has three degrees of freedom. The house is two-story superstructure with 2,700 mm in each story height. And the lowest mass is corresponding to that in a 1st floor level. The lowest story is an isolated layer. The mass ratios of the overall system along the height are 1.0, 1.0 and 0.6.

3.2 Superstructure

Relationships between story shear force (Q) and story drift (δ) in the family house of two stories and characteristic values are summarized in Table 2. The shear force is expressed to non-dimensional shear force (C), dividing by total weight of higher part than the story. Two kinds of the superstructure model are set. One is a slip type which is a representative of steel structures with braces, and the second one is a tri-linear type is that of steel frames. The stiffness of non structural members is not included in the characteristic values. The damping factors are assumed to be 5 %, and the damping force is set to be proportional to stiffness of springs. It is verified that the response of story drifts at 1st story in two models are almost equal under the BCJ motion.

3.3 Isolated Layer

Two types of models, rolling and sliding types are selected. These are used in the isolation systems of practical family houses in Japan. Characteristics of combination of isolators are summarized in Table 3. The rolling type is composed of a roller with coefficient of friction of 0.005, a restoring device whose natural period is 3 s and a viscous damper of 25% in damping factor. The sliding type is composed of a slider with coefficient of friction of 0.05 and restoring device whose natural period is 4 s. To check the effect of viscous damper on the response of superstructure, the damping factors of 25% and 50% are added to the fundamental case.

Table 2 Characteristics of superstructure

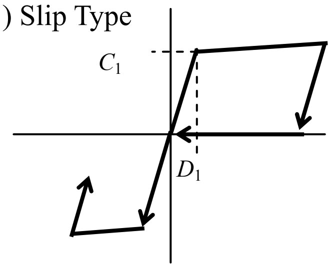
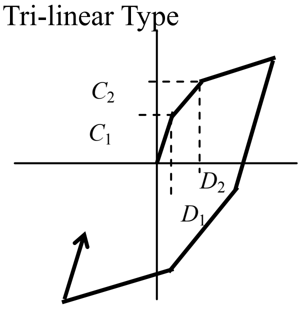
Kind of Model	Characteristics of C and δ Curve
1) Slip Type 	Stiffness :Initial Stiffness: k_1 Second Stiffness : $k_2 = 0.05k_1$ Yield Point: 1st Story : $\delta_1 = H/120$, $C_1 = 0.56$ 2nd Story: $\delta_1 = H/120$, $C_1 = 0.8$ Damping Factor: $h = 0.05$ (Proportional to Initial Stiffness)
2) Tri-linear Type 	Stiffness :Initial Stiffness: k_1, Second Stiffness : $k_2 = 0.4k_1$, Third Stiffness : $k_3 = 0.05k_1$ 1st Yielding Point:1st Story : $\delta_1 = H/200$, $C_1 = 0.2$ 2nd Story: $\delta_1 = H/200$, $C_1 = 0.3$ 2nd Yielding Point:1st Story : $\delta_2 = H/75$, $C_2 = 0.333$ 2nd Story: $\delta_2 = H/75$, $C_2 = 0.5$ Damping Factor: $h = 0.05$ (Proportional to Initial Stiffness)
Note; δ: Story drift, H: Height of story, C: Ratio of shear force to weight	

Table 3 Characteristics of isolated layer

System	Friction Coefficient	Period with Second Stiffness of Isolator	Viscous Damping Factor	Model Name
Rolling	0.005	T_t=3s	h_v=25% (Proportional to Stiffness at of T_t)	R-hv25
			h_v=50%	R-hv50
			h_v=75%	R-hv75
Sliding	0.05	T_t=4s	h_v=0%	S-hv00
			h_v=25%	S-hv25
			h_v=50%	S-hv50

3.4 Displacement Restraint Device

To reducing the displacement response at isolated layer, two kinds of the displacement restraint devices are used as shown in Table 4. One has linear characteristics of force and displacement, and the other has quadratic ones. The displacement restraint device is able to be operated at a certain displacement of isolated layer (δs). When the displacement of isolated layer is less than δs, the system will have the ordinal isolated system. On the other hand, when the displacement is equal to or more than δs, the displacement restraint device will be effective. To investigate the effect of device, the relationship between the non-dimensional shear force and displacement is assumed to be three sets of δs and the displacement at C=1.0 point (δ_e), as shown in Table 5. Considering the clearance of the isolation system for the house, the maximum δ_e is adjusted to be 400mm.

Table 4 Mechanical models for displacement restraint device

Type	Property	Function
STP_A	Linear	$C = a(\delta - \delta_s)$
STP_B	quadratic	$C = a(\delta - \delta_s)^2$

Table 5 Operated displacement and displacement at *C*=1.0

Type	Displacement at operating point (δ_s)	Displacement at *C*=1.0 point (δ_e)
STP_1	200mm	230mm
STP_2	300mm	350mm
STP_3	300mm	400mm

4. EARTHQUAKE MOTIONS

Predominant periods of isolated houses are assumed to be 3 to 4 seconds. Earthquake motions observed in domestic and oversea earthquakes which have a large amount of velocity response in these periods are selected, as shown in Table 6 and Fig. 2. The motions of TCU and TOM have a larger response velocity spectrum with period and those of TAK and KAW have a less response velocity with period. Through the period, the level of motion of TOM is the lowest and the motions of TAK, TCU and KAW are a very high peak and response velocities. The motion of BCJ, which has a constant response velocity spectrum, is a minimum requirement of the earthquake motion at severe stage in the response and limit capacity method of Japanese Building Standard.

Table 6 Selected earthquake motions and their peak amplitudes

EQ Name	Information of Earthquake	Peak Acceleration (cm/s^2)	Peak Velocity (cm/s)	Peak Displacement (cm)
TAK	Takatori NS (1995 Hyogoken-Nanbe EQ) [7]	617	136.7	38.9
TCU	TCU068 (1999 Chi-Chi EQ) [8]	502	150.3	111.2
TOM	Tomakomai NS (K-NET HKD129) (2003 Tokachi-oki EQ) [9]	72.9	30.3	28.3
KAW	Kawaguchi EW(2004 Mid-Niigata EQ, Japan) [10]	1675	135.6	40.5
BCJ	BCJ L2 (Design Response Spectrum) [11]	355	55.2	39.8

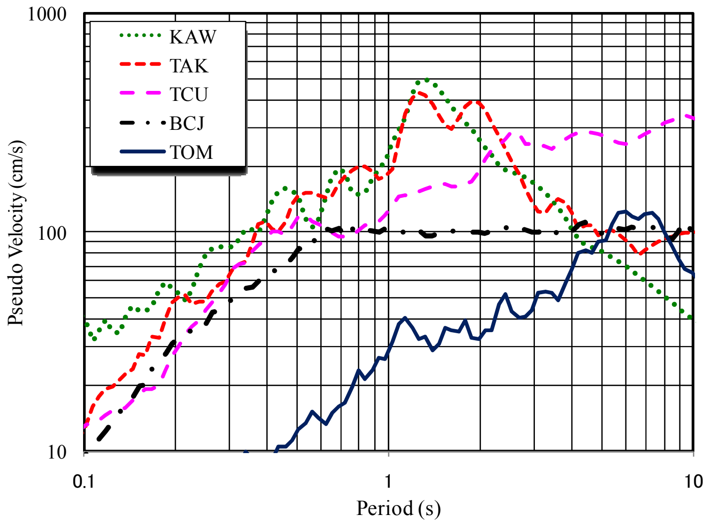
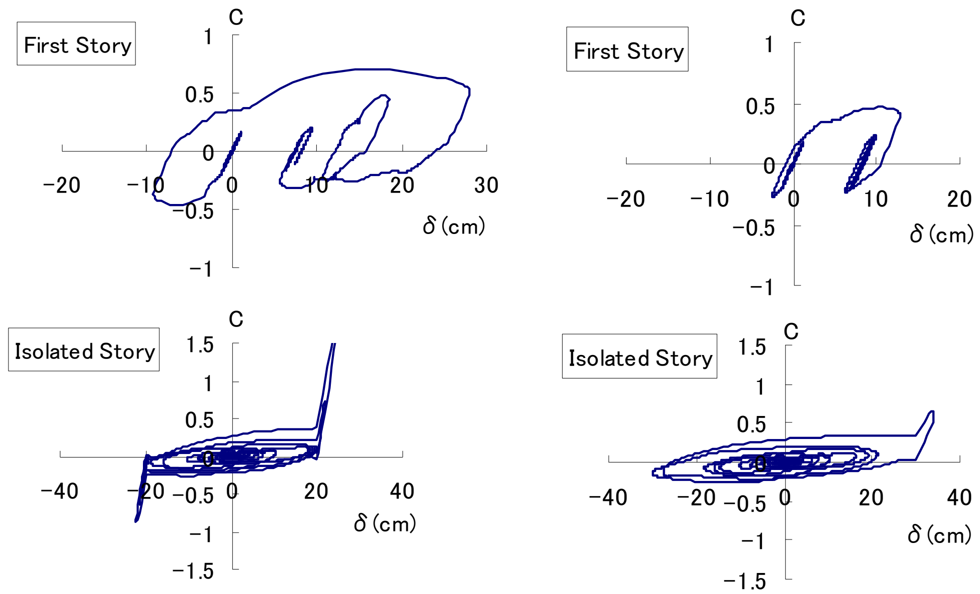


Fig. 2 Pseudo velocity responses of selected earthquake motions (Damping Factor = 5%)

5. RESPONSE OF SUPERSTRUCTURE UNDER DISPLACEMENT RESTRAINT DEVICE

Figure 3 presents the response of 1st story and isolated layer in case of R-hv50 and tri-linear model against the motion of TAK. The response under two kinds of operated displacements, STP_1 and STP_3, of STP_A is drawn. In case when the displacement restraint device is operated at a near point (STP_1, δ_s =200mm), a large amount of shear force occurs. As a result, a large story drift (drift angle: about 1/10) occurs at the 1st story. While in case when the displacement restraint device is operated at a far point (STP_3, δ_s =300mm), the ratio of shear force is decreased and the story drift is less (drift angle: about 1/20).



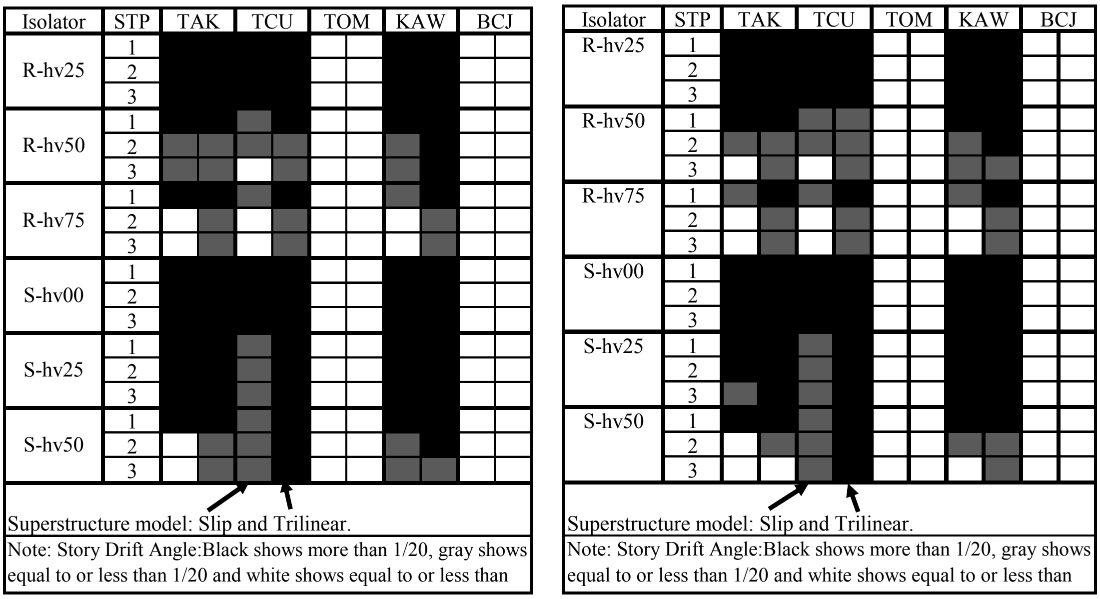
（a）STP_1 （b）STP_3

Fig. 3 Example of response of R-hv50（superstructure: tri-linear, motion: TAK）

Figure 4 summarizes the story drift angle at 1st story of superstructure with two characteristics of displacement restraint devices. The limits of story drift angle are defined to three categories based on Table 1. One is the angle equal to or less than 1/50 (white color in Fig. 4), the second one is equal to or less than 1/20 (grey) and one another is more than 1/20 (black).

In cases of TOM and BCJ motions, the angles are less than 1/50, because the displacement responses at isolated layer are low. Usually the displacement is less than the distance at operating point. Another three earthquakes give large story drifts more than 1/20 in cases of low viscous damping models (R-hv25, S-hv00 and S-hv25) and models with short operating points (STP_1). Under the motions of TAK, TCU and KAW, whose response velocity are high, the displacement responses at isolated layer without the displacement restraint device are large. The relative velocity at isolated layer is very high and the controlled displacement is very large. As a result, when the large shear force occurs in the displacement restraint device, the story drift at stories of superstructure is also large.

With increasing the viscous damping, the angles are reduced to less than 1/20. The angle in case of the tri-linear model in superstructure is a little larger than that in the slip model. The displacement restraint device with quadratic relation (STP_B) gives a less angle than that with linear relation (STP_A). The difference between two kinds of displacement restraint devices is not so remarkable.



a)STP_A b)STP_B

Fig. 4 Map of story drift angle at 1st story of superstructure

6. RESPONSE OF ISOLATED SYSTEM AND SAFETY OF SUPERSTRUCTURE

To evaluate the effect of displacement restraint device on the response of superstructure, two indices are considered, as shown in Fig. 5. One is the relative velocity at isolated layer which occurs passing through the operating point, conditioned that the displacement restraint device is not installed. When there are several times of passing through, the maximum velocity (*Vop*) will be selected. It is pointed out that the velocity is corresponding to the kinetic energy. The other is the amount of displacement which is defined to be the difference between the displacement at isolated layer without displacement restraint device and the distance at operating point from origin. The displacement is called the controlled displacement (*Dcon*). The controlled displacement is corresponding to the restoring energy of isolated layer.

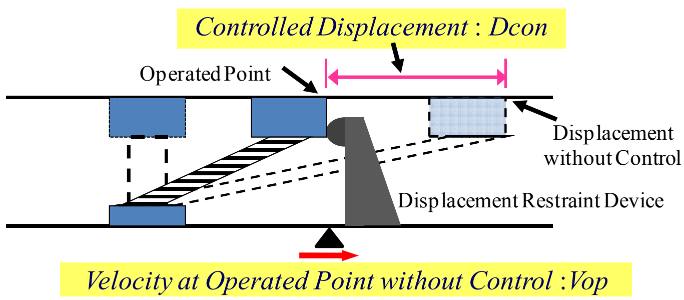
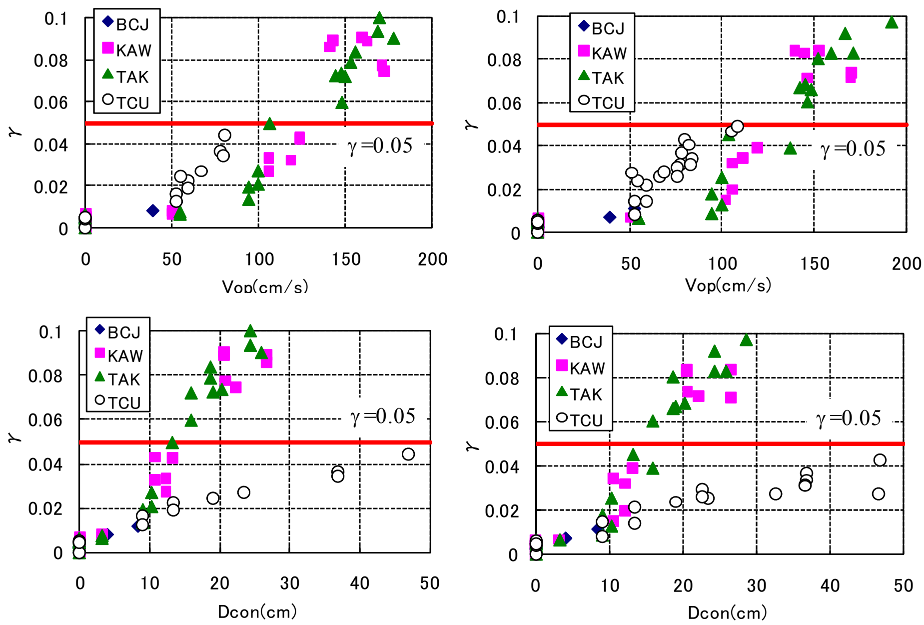


Fig.5 Schematic view of velocity at operating point and controlled displacement

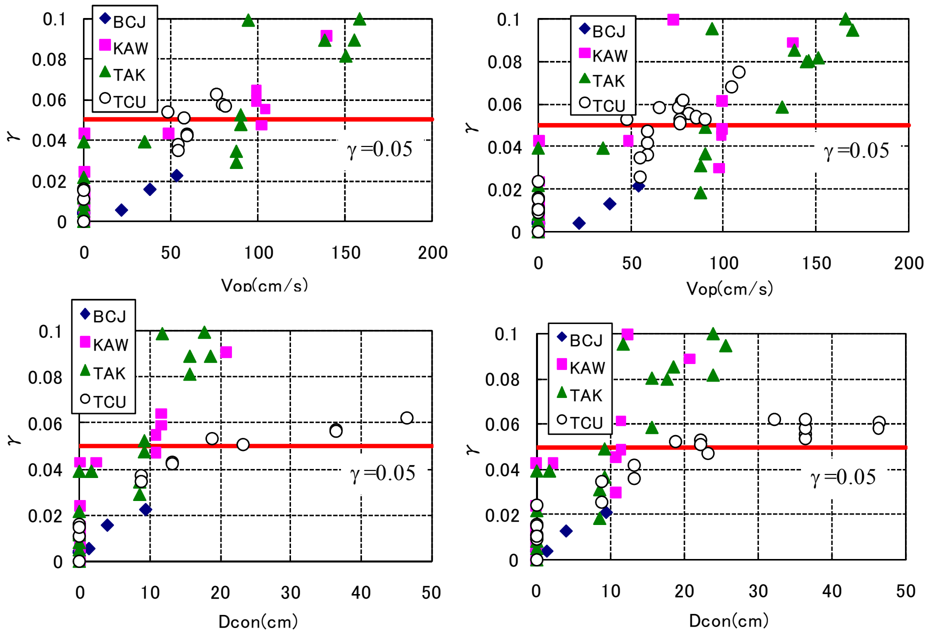
Figures 6 and 7 present the relationship between indices and story drift angle of 1st story (γ) with characteristics of superstructure of slip and tri-linear types, respectively. The larger each index of *Vop* or *Dcon* is, the larger story drift angle is. The safety limit of superstructure is set to be 0.05 in γ, as drawn in Figs. 6 and 7. In the motion of BCJ, the γ is less than the safety limit. The γ is comparatively larger, under the motions of TAK and KAW. In the motion of TCU, the angle is not so large even if the *Dcon* is large. From the comparison between characteristics of displacement restraint devices, the *Vop* and *Dcon* in case of the quadratic one (STP_B) are larger than in case of linear one (STP_A). The difference of response from characteristics of devices is not so remarkable.

The border values where the superstructures are safe or unsafe are obtained as follows; In case of slip type of superstructure, the *Vop* is about 120 m/s and the *Dcon* is about 13 cm. In case of tri-linear type of superstructure, the *Vop* is about 50m/s and the *Dcon* is about 10 cm. In cases of the large velocity at operating point and large controlled displacement, it is difficult to keep the safety limit of structure.



<STP_A> <STP_B>

Fig. 6 Relationship between controlled indices and story drift angle of 1st story (Slip type)



<STP_A> <STP_B>

Fig. 7 Relationship between controlled indices and story drift angle of 1st story (Tri-linear type)

6. CONCLUDING REMARKS

Under earthquake motions with large velocity, the displacement response of isolators is large. To keep the function of isolation during and after earthquakes, the isolator should be protected from damage by adding to the shock absorbing device called the displacement restraint device. The relationship between responses of superstructure and isolator is investigated through numerical simulation. The results are summarized as follows;

1) Two indices of the relative velocity of isolated layer at operating point and the controlled displacement are very useful to predict the structure safety of superstructure.
2) In case when the relative velocity and/or the large controlled displacement in isolated layers are large, the responses of superstructure exceed the safety limit.
3) With increasing damping effect, the responses of superstructure are less and the structural safety is kept.
4) The difference of response from characteristics of displacement restraint devices is not so remarkable.

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