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DESIGN PROPOSAL FOR CONTROLLING SEISMIC BEHAVIORS OF INTER-STORY ISOLATION BUILDING STRUCTURES

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SUMMARY

In this paper, seismic behaviors of inter-story isolation building structures are investigated through numerical approaches. Emphasis is put on assuring mechanical relations between inter-story isolating effect and the maximum ductility responses of the isolated story. Namely, participation of plastic behaviors of the inter-story isolation device are focused as the indicate to be evaluated for seismic isolating efficiency by installing inter-story isolation system. Parametric simulations for inter-story isolation system are executed for different models of isolated stories and different models of stiffness of structural frame. Seismic responses of inter-story isolation buildings under strong ground motion are compared with various cases of the maximum ductility responses of the isolation device. As a result, it is assured that, since aseismic property of the whole structural system is significantly subjected by plastic behaviors of isolation device, aseismic response by using isolation system can be predicted by evaluating of maximum ductility response.

INTRODUCTION

Recently, some practical cases to construct inter-story isolation buildings are appeared in Japan. Some reasons for the installations of such kind of structural system can be considered as that; 1) Reduction of accelerations of upper structure on the isolating story may contribute to decrease shear force responses lower structure below the isolating story, 2) Overturning moments of building may be reduced by the

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virtual effects which the upper structures are enforced as if to keep immovable condition, 3) Since inter-story isolation device can separate the building system into two independent structural parts which are upper and lower structures, flexibility of structural design may be expanded. On the other hand, structural design of inter-story isolation system has unassured problems how to determine mechanical properties of isolation devices to actualize required seismic isolating effects and also how to predict response interactions between upper and lower structures. In the following section, standard types of inter-story isolating systems are investigated and typical aseismic characteristics of those kinds of structural systems are evaluated. Specification point of this study is to make the plastic behaviors of isolation devices relate to seismic isolating effect. For this aim, the maximum ductility response are used as the indicate to mention those plastic characteristics of isolation device.

ANALYTICAL MODEL AND PROCEDURE

Structural Model of Inter-Story Isolated System

Structural models to be used in the following analyses are shown in Figure 1. The model of inter-story isolation system is illustrated in left side. The right one is corresponding to the structural model which can emulate seismic response of ordinary buildings subjected to strong ground motions and this model is used comparatively evaluating seismic effect of inter-story isolation system.

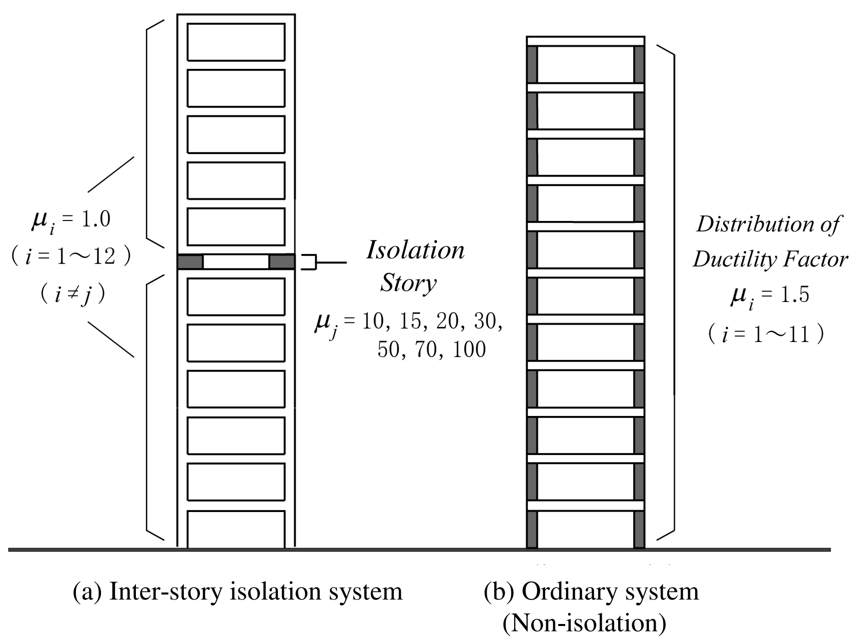


Figure 1 Structural model

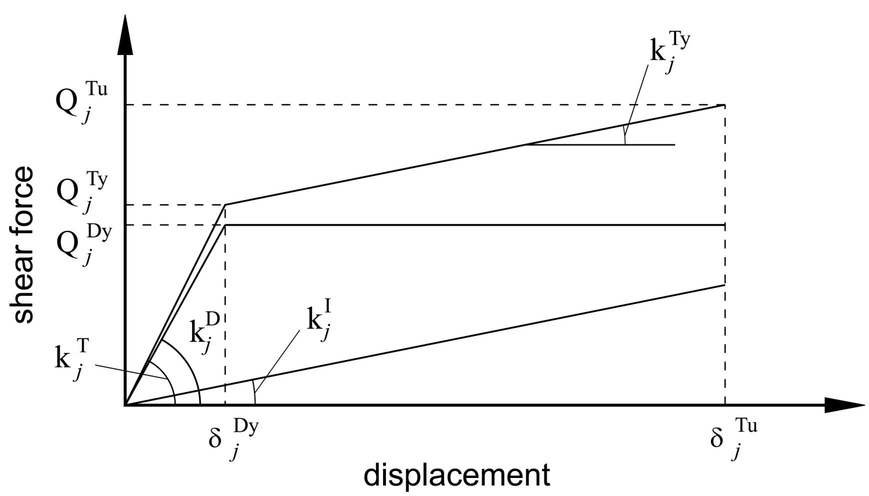
Specification of the Model of Inter-Story Isolation System

(1) As seen in figure 1 (a), structural system with twelve distributed mass which are supported by twelve horizontal stiffness are used (in which, one set of mass and spring is corresponding to the isolating story).
(2) Stiffness distribution of structural model except isolating story is designed as that the dominant structural model deformation proportionally is fit to inversed-triangular shape.
(3) Each mass is uniformly distributed and has 1.0 (ton・s^2/cm) of weight.

(4) Three kinds of different cases of the level of structural stiffness are prepared. Those parameters are determined by considering 1st natural period T_1=0.4, 0.8 and 1.2 (s) of the "structural systems" which are reproduced by fixing deformations of isolating story (in the following, this reproduced model are called as "locked model").
(5) Damping of the structural model is supposed by considering first modal vibration of the locked model and determined as to be proportional with stiffness matrix. Damping ratio is supposed as 2% of weight.
(6) Hysteresis characteristics of each story excepting isolating story is regarded as elastic model.

Specification of isolation device

(1) In the following, three cases are considered 4, 7 and 10 story are selected as isolating stories. Those cases are corresponded to 0.25, 0.50 and 0.75 of non dimensional height, respectively.
(2) Hysteresis characteristics of isolating story is defined a model of bi-linear type which is corresponding to hybrid system equipping an elastic spring and an elasto-plastic damper (as seen in Figure 2).
(3) As seen in Figure 2, elastic stiffness defined by K_j^T and plastic stiffness defined by K_j^{Ty} are 1st and 2nd gradient of hysterisis of isolating story. Those quantities are determined by $K_j^{Ty} = \zeta K_j^T$. In the following, the ratio of plastic stiffness by elastic one is supposed as 10% (ζ=0.10).
(4) Plastic stiffness K_j^{Ty} is calculated by considering the condition as that the 1st natural period of 1DOF system which is composed by single mass with total weight of the upper structures above isolating story is fit to 3 (s). This 1DOF system is called "rigidified upper-body model".
(5) Viscous damping of isolating story is neglected.
(6) In the following case studies, by tuning with yield shear force of isolating story, some typical cases which are assigned by the different value of the maximum ductility response μ_j=10.0, 15.0, 20.0, 30.0, 50.0, 70.0 and 100.0 are focused.



Q_j^{Dy} : yield shear force of damper	k_j^D : initial stiffness of damper
Q_j^{Ty} : yield shear force of isolating story	k_j^I : stiffness of spring element
Q_j^{Tu} : max. shear force of isolating story	k_j^T : initial stiffness of isolating story ($= k_j^I + k_j^D$)
δ_j^{Dy} : yield displacement of damper	k_j^{Ty}: yield stiffness of isolating story ($= k_j^I$)
δ_j^{Tu} : max. displacement of isolating story	(j : location of isolating story)

Figure 2 Hysteresis characteristics of isolating story

Specification of the Model of Ordinary (Non-Isolation) Structural System

(1) 11 mass are uniformly distributed and each mass has 1.0 (ton・s^2/cm). Stiffness distributions when every stories are within elastic region is determined by removing isolating story from the corresponding “locked model” of inter-story isolation system.

(2) Hysteresis characteristics of every stories is supposed as bi-linear type model. The ratio of plastic stiffness by elastic one is supposed as 20% (ζ_i =0.20) on every stories.

(3) Ordinary model are assigned as having the result when plastic deformations are uniformly occurred on every stories, by turning with values yield shear force of each story. Namely, in this case study, the typical cases as that the maximum ductility responses of all stories have the same value of 1.5 (μ_i =1.5) is mentioned out as the ordinary model.

Equation of Motion

Equation of motion of inter-story isolating structural system is represented as the following formula within elastic region of the isolating story.

$$\boldsymbol{M}\,\ddot{\boldsymbol{x}}(t)+\boldsymbol{C}\,\dot{\boldsymbol{x}}(t)+\boldsymbol{K}\,\boldsymbol{x}(t)=-\boldsymbol{M}\,\boldsymbol{e}\,\ddot{u}_G(t) \qquad (1)$$

in which, $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are matrices of mass, damping and stiffness. $\boldsymbol{e}$ is vector of all components with 1 and $\ddot{u}_G(t)$ is accelerations of seismic excitations.

$$\boldsymbol{M}=\begin{bmatrix} m_1 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ 0 & m_2 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & m_i & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & m_j & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \cdots & m_{N-1} & 0 \\ 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & m_N \end{bmatrix} \qquad (2)$$

m_i : Mass of each story ($i \neq j$), m_j : Mass of isolated story

$$\boldsymbol{C}=\frac{2h_1}{\omega_1}\begin{bmatrix} k_1+k_2 & -k_2 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ -k_2 & k_2+k_3 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & k_{i-2}+\left(\dfrac{h_j}{\omega_j}\Big/\dfrac{h_1}{\omega_1}\right)k_j^{Ty} & -\left(\dfrac{h_j}{\omega_j}\Big/\dfrac{h_1}{\omega_1}\right)k_j^{Ty} & \cdots & 0 & 0 \\ 0 & 0 & \cdots & -\left(\dfrac{h_j}{\omega_j}\Big/\dfrac{h_1}{\omega_1}\right)k_j^{Ty} & \left(\dfrac{h_j}{\omega_j}\Big/\dfrac{h_1}{\omega_1}\right)k_j^{Ty}+k_i & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \cdots & k_{N-1}+k_N & -k_N \\ 0 & 0 & \cdots & 0 & 0 & \cdots & -k_N & k_N \end{bmatrix} \qquad (3)$$

k_i : Stiffness of each story ($i \neq j$), k_j^{Ty}: stiffness of isolating story (in plastic region)
h_1 : Damping ratio for 1st mode vibration of "locked model"
ω_1 : 1st natural circular frequency of "locked model"
h_j : Damping ratio of isolating story
ω_j : Natural circular frequency which is calculated on the 1DOF system, "rigidified upper-body model"

$$\boldsymbol{K} = \begin{bmatrix} k_1 + k_2 & -k_2 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ -k_2 & k_2 + k_3 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & k_{i-2} + k_j^T & -k_j^T & \cdots & 0 & 0 \\ 0 & 0 & \cdots & -k_j^T & k_j^T + k_i & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \cdots & k_{N-1} + k_N & -k_N \\ 0 & 0 & \cdots & 0 & 0 & \cdots & -k_N & k_N \end{bmatrix} \quad (4)$$

k_j^T : stiffness of isolating story (in elastic region)

Numerical integrations for response analysis are operated by using *Newmark's* β method (β=1/4) through this study. Integrated time interval $\Delta t = 0.002$ (s). To find out targeted cases whish are focused by the assigned values the maximum ductility responses, inversed numerical analysis are operates by tuning with the value of yield shear strength of isolating story. Those convergent calculating procedures are programmed by using the secant method and flow of those procedures is shown in Figure 3.

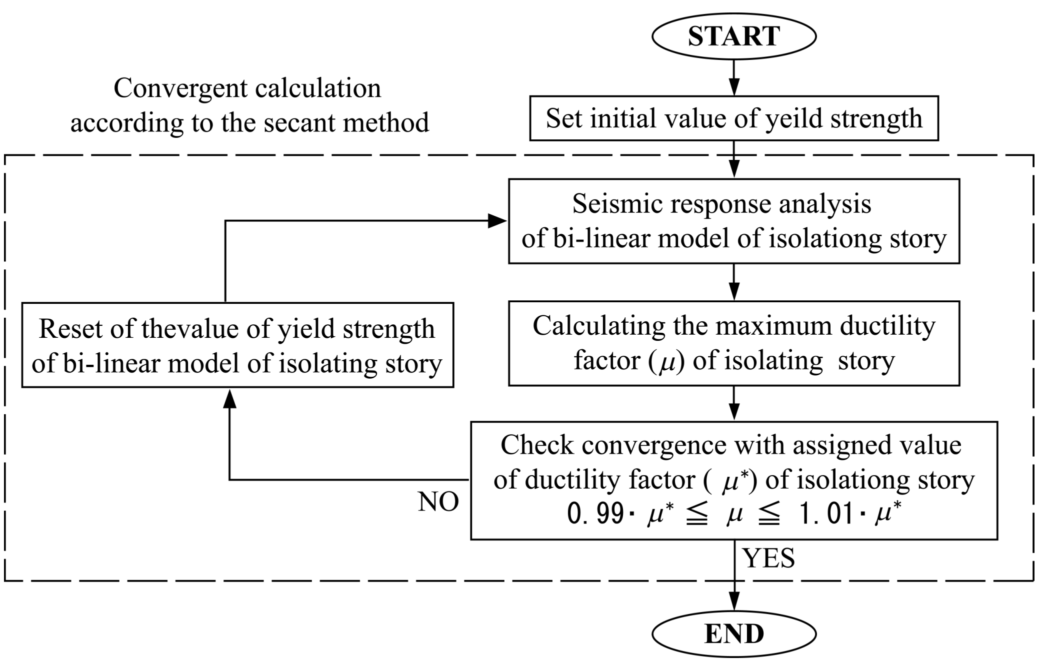


Figure 3 Flow of convergent calculating procedure

BCJ-L2 (Artificial Seismic Wave for Structural design recommended by Building Center in Japan) is adopted as input ground motion. Response spectrum corresponding to this ground motion are shown in Figure 4.

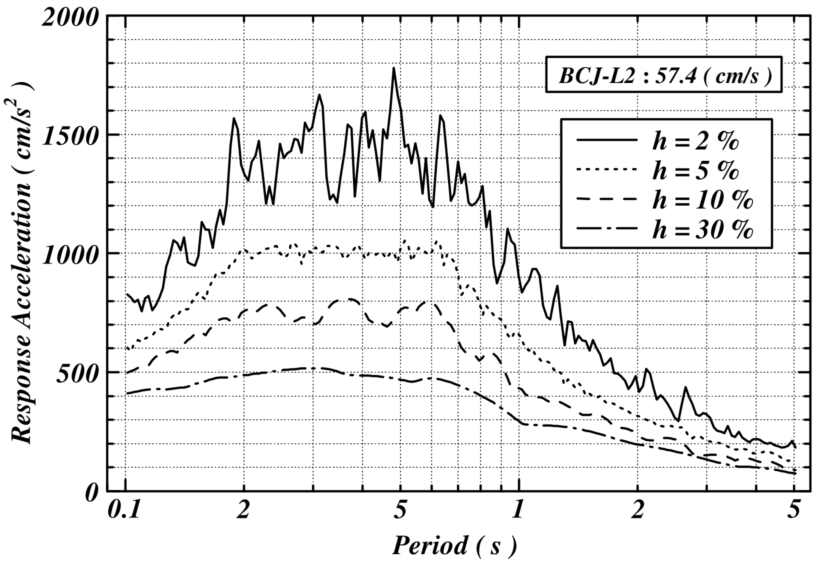


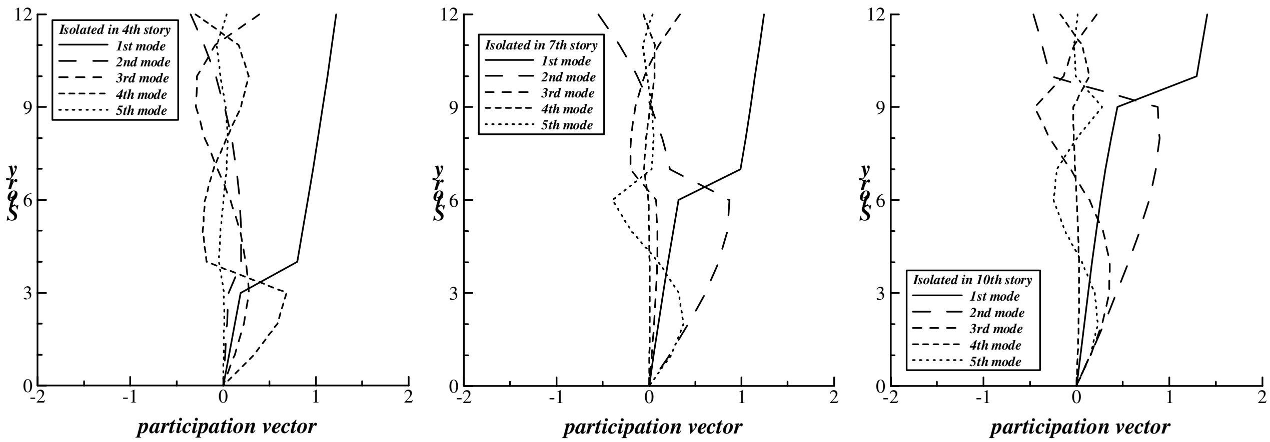
Figure 4 Response acceleration of input motion (BCJ-L2)

MODAL PARTICIPATION OF INTER-STORY ISOLATION SYSTEM

To consider vibrations of inter-story isolating structural model when the stiffness of isolating story is acting on elastic or plastic region, modal participation vectors from 1st to 5th order are illustrated in Figure 5.1 and 5.2, in which 1st natural period of "locked model" is 0.8 (s). Figure 5.1 is the case to have the value of elastic stiffness K_j^T isolating story and Figure 5.2 is the case to have plastic stiffness K_j^I. Table 1.1 and 1.2 show natural periods and those tables are corresponded to the case of Figure 5.1 and 5.2, respectively.

As seen in Figure 5.2, modal response of the upper structure above isolating story are effectively isolated from the input motions when stiffness of the isolated story has the value of plastic region. In this case, in the lower structures, modal responses of neighbor stories below isolation stories may be excited under input near natural frequencies of the high-orders.

By comparing Figure 5.1 and 5.2, it can be considered as that:
1) isolating effects (in the sense of response reductions) of upper structure are assured in the case that isolating story has the stiffness of plastic region.
2) response of the lower story may be moderates in the case that the isolation story has elastic region.

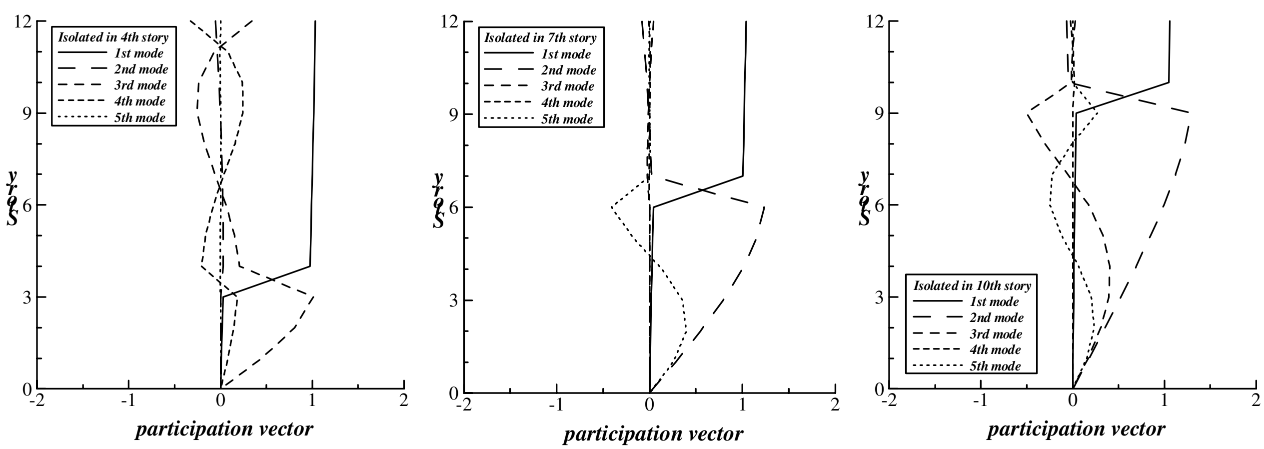


(a) 4th-story isolation (b) 7th-story isolation (c) 10th-story isolation

Figure 5.1 Modal participation vector (when spring of isolation story has the stiffness in elastic region)

Table 1.1 Natural period of inter-story isolating system
(when spring of isolation story has the stiffness in elastic region)

Isolating story	1st (s)	2nd (s)	3rd (s)	4th (s)	5th (s)
4	1.224	0.372	0.218	0.192	0.147
7	1.226	0.372	0.291	0.168	0.143
10	1.193	0.537	0.228	0.208	0.142

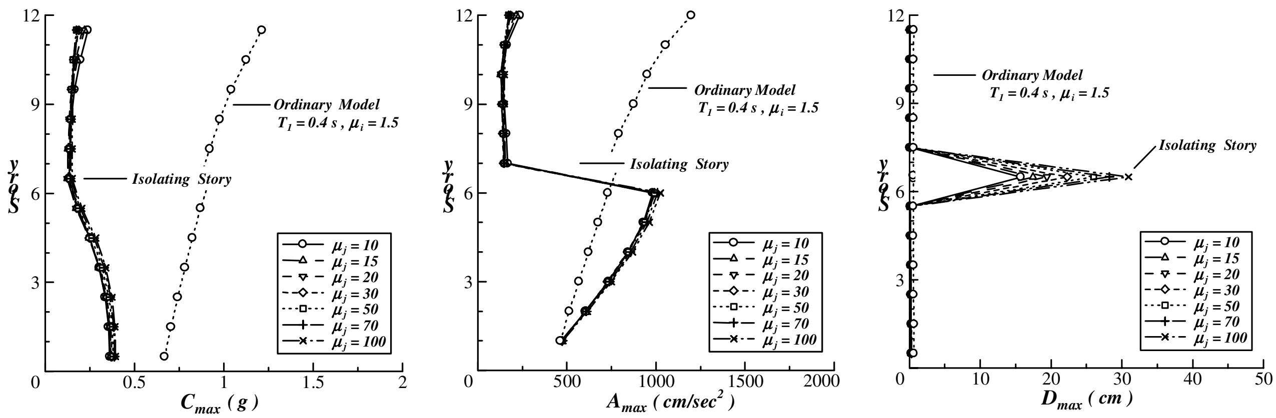


(a) 4th-story isolation (b) 7th-story isolation (c) 10th-story isolation

Figure 5.2 Modal participation vector (when spring of isolation story has the stiffness in plastic region)

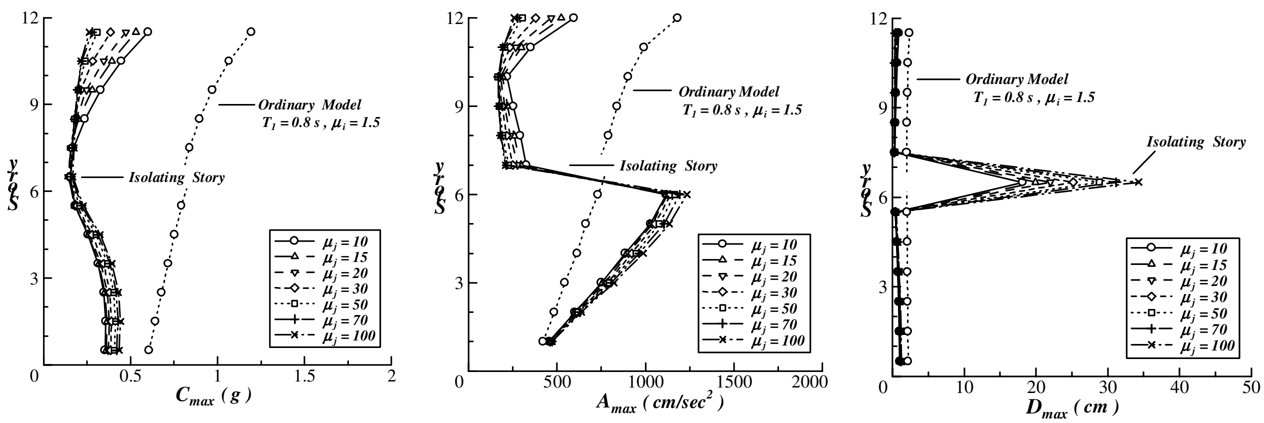
Table 1.2 Natural period of inter-story isolating system
(when spring of isolation story has the stiffness in plastic region)

Isolating story	1st (s)	2nd (s)	3rd (s)	4th (s)	5th (s)
4	3.093	0.394	0.220	0.216	0.149
7	3.091	0.410	0.313	0.171	0.146
10	3.069	0.620	0.231	0.214	0.143



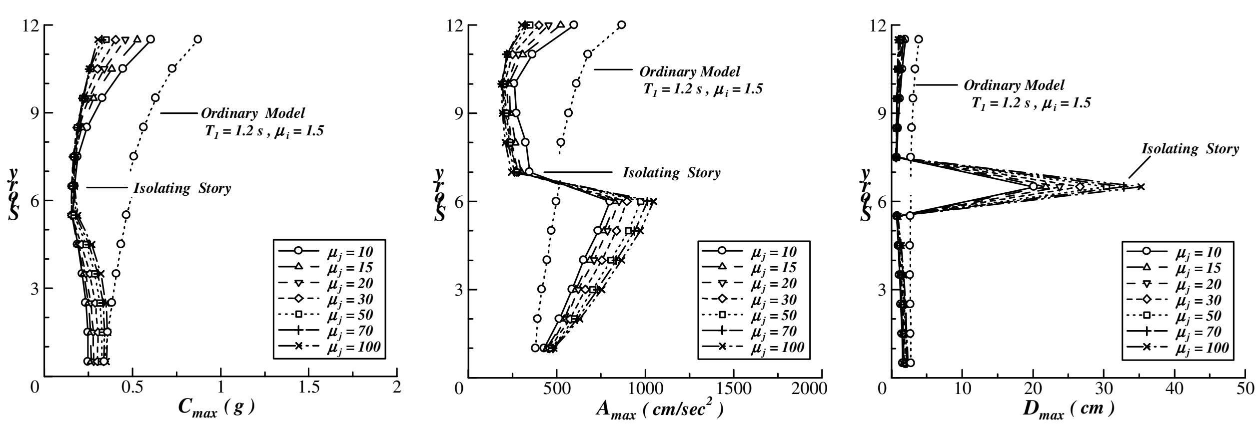
(a) Shear force (b) Acceleration (c) Displacement

Figure 6.1 7th-story isolation model (Natural period of “locked model” : T_1 = 0.4 s)



(a) Shear force (b) Acceleration (c) Displacement

Figure 6.2 7th-story isolation model (Natural period of “locked model” : T_1 = 0.8 s)



(a) Shear force (b) Acceleration (c) Displacement

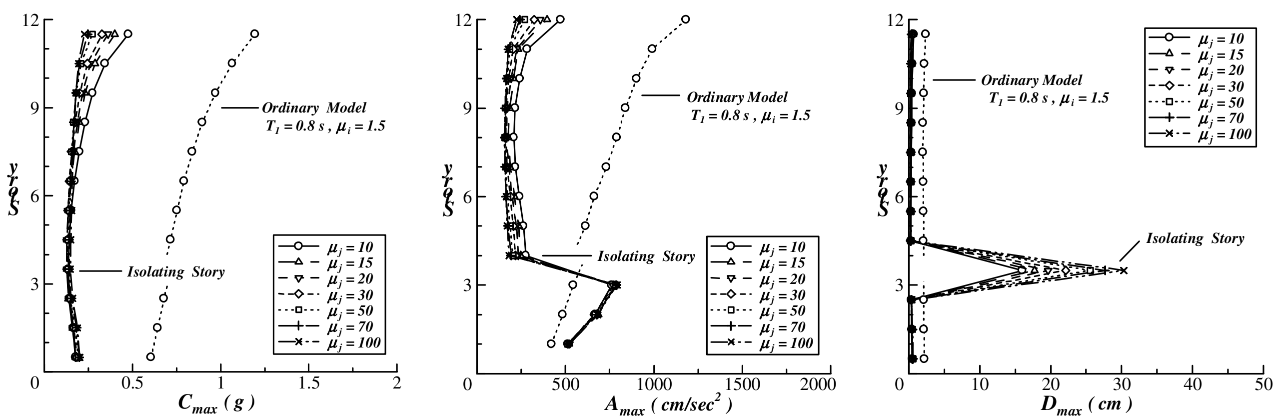
Figure 6.3 7th-story isolation model (Natural period of “locked model” : T_1 = 1.2 s)

Table 2.1 Natural period of 7th-story isolated model
(when spring of isolation story has the stiffness in elastic region)

Natural period of "locked model"	1st (s)	2nd (s)	3rd (s)	4th (s)	5th (s)
0.4 *s*	1.021	0.200	0.155	0.085	0.073
0.8 *s*	1.226	0.372	0.291	0.168	0.143
1.2 *s*	1.524	0.535	0.397	0.249	0.208

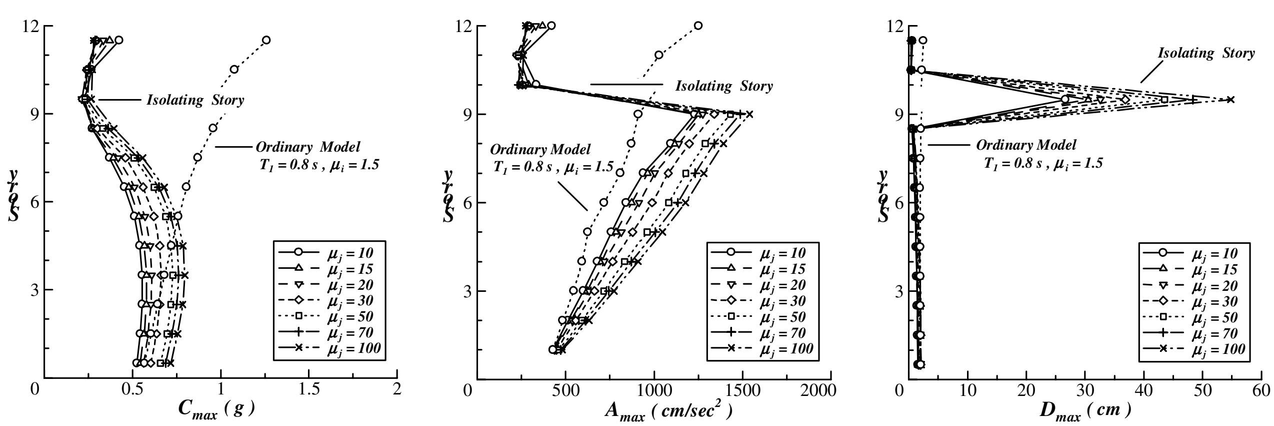
Table 2.2 Natural period of 7th-story isolated model
(when spring of isolation story has the stiffness in plastic region)

Natural period of "locked model"	1st (s)	2nd (s)	3rd (s)	4th (s)	5th (s)
0.4 *s*	3.023	0.207	0.157	0.085	0.073
0.8 *s*	3.091	0.410	0.313	0.171	0.146
1.2 *s*	3.206	0.603	0.466	0.256	0.219



(a) Shear force (b) Acceleration (c) Displacement

Figure 6.4 4th-story isolation model (Natural period of "locked model" : T_1 = 0.8 s)



(a) Shear force (b) Acceleration (c) Displacement

Figure 6.5 10th-story isolation model (Natural period of "locked model" : T_1 = 0.8 s)

Figure 6.1, 6.2 and 6.3 show the seismic responses of the 7th-story isolation systems corresponding to the cases that 1st natural periods of their "locked model" T_1 = 0.4, 0.8 and 1.2, respectively. In those figures, (a), (b) and (c) are corresponded to the distributions of the maximum shear forces $S_{max,\ i}$, the maximum acceleration responses $A_{max,\ i}$ and the maximum displacement responses $D_{max,\ i,}$ respectively. By comparing those figures, the following remarks are pointed:

1) Difference of the structural responses according to the maximum ductility response of isolating story μ_j can be recognized to be increased in the case that the 1st natural periods of their "locked model" T_1 has large value. Namely, when structural flames are considerably rigidified, it is found that influences of the plastic behavior of isolating story can be decreased for seismic responses of the lower structure below the isolating story.

2) Seismic response of the upper structure above the isolating story can be effectively reduced according to increasing the maximum ductility response of isolating story μ_j. Namely, seismic isolation effects of the upper structure can be significantly related to plastic behaviors of the isolating story and those relations can be indicated to the value of the maximum ductility response of isolating story μ_j. On the other side, response of the lower structures are deteriorated by increment of μ_j, because that transformations of the seismic energy may be shut out at the isolating story.

3) Seismic isolation effects of the upper structure above the isolating story are deteriorated according to decreasing the maximum ductility response of isolating story μ_j. At this time, response of the lower structures are reduced by decrement of μ_j, because that seismic energy may be leaked to the upper structure through the isolating story.

As the references, the natural periods from the 1st to 5the order of the 7th-story isolation models are shown in Table 2.1 and 2.2. The models on Table 2.1 is corresponding to the cases that the stiffness of the isolated story has the value of elastic region. The models on Table 2.2 is corresponding to the cases that the stiffness of the isolated story has the value of plastic region.

Figure 6-4 and 6-5 show the seismic responses of the 4th-story isolation system and 10th-story isolation systems corresponding to the case that 1st natural periods of their "locked model" T_1 = 0.8, respectively. By comparing those figures with Figure 3-2 (which is corresponding to the 7th-story isolation system with the same value of 1st natural periods of its "locked model" T_1 = 0.8), the following remarks are also pointed:

1) Responses of the lower structure below isolating story are increased according to the higher location of the isolating story. At this time, similar level of response of the isolating story can be appeared. Namely, since those differences of the response on the lower structures may be depended to difference of seismic input energy, it is appeared that the energy absorptions of the lower structure are pointed as significant item to require the further considerations.

2) Seismic isolation effects of the upper structure above isolating story can be e significantly related to plastic behaviors of the isolating story and those relations can be indicated to the value of the maximum ductility response of isolating story μ_j. These tendencies are commonly confirmed to the every cases of different locations of the isolating story.

CONCLUDING REMARKS

In this paper, investigations to be assure typical seismic behaviors of inter-story-isolation systems are operated through numerical studies. As a concluding remarks, it is appeared that seismic isolation effects of the inter-story isolation systems can be significantly related to the plastic behaviors, because that energy barrier for seismic motion are effectively functioned under participations on plastic regions of inter-story isolating story. In such meanings, it seems that the maximum ductility response of isolating story can be used as the indicate to evaluate the seismic isolation effects of the inter-story isolation systems.

REFFERENCES

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