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ENERGY BALANCE-BASED METHOD FOR RESPONSE CONTROL STRUCTURES WITH HYSTERETIC DAMPERS AND VISCOUS DAMPERS

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Abstract. *Structural control devices are widely implemented in order to reduce the seismic response of buildings. These devices are typically categorized as hysteretic dampers and viscous dampers. If the structures employ only one of these dampers, the prediction of seismic response under strong motions is not difficult. However, it is desirable to predict the seismic response of buildings using both dampers simultaneously, because the use of these dampers to improve the seismic performance of buildings has increased in recent years. A prediction method called the energy balance-based method has been proposed in past studies to evaluate seismic performance. This sentence is confusing. I suggest the following: The existing method is able to predict the response of control structures with one type of damper. However, the existing method has not been able to predict the seismic response of buildings with multiple dampers.This paper describes a method that can handle these cases by rearranging the mathematical expression presented in past studies.*

1 INTRODUCTION

After The Southern Hyogo prefecture earthquake in 1995, structural control devices have been widely used in order to decrease the seismic response of various buildings in Japan [1]. These devices are typically categorized as hysteretic and viscous dampers, according to their different characteristics as shown in Fig. 1.

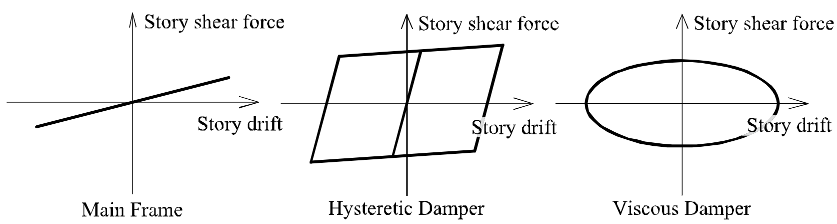


Fig. 1 Hysteretic characteristics of main frame and the two types of dampers

The hysteretic damper, which absorbs energy through the plasticity of steel, depends on story drift; whereas the viscous damper depends upon the differential of the story drift. If structures employ only one of these dampers, predicting their seismic response under strong ground motions is not difficult. However, it is desirable to predict the seismic response of the buildings using both dampers simultaneously. This is because, in recent years, the use of these dampers to improve seismic performance of buildings has increased.

Akiyama [2, 3] proposed a prediction method based on energy balance, called the energy balance-based method, to quantitatively evaluate the seismic performance. The existing method adapts the response control structures with the respective types of dampers; however, the adaptability to predict the seismic response of the buildings, which are composed of both dampers, has not been clarified. This paper describes a method that can deal with these cases by rearranging the mathematical expression presented in past studies. The main concept of the proposed method is that the theory of vertical distribution governs energy distribution for each story. The proposed method is validated by comparing its results with time-history analyses. In addition, the effectiveness and applicability of using both dampers are verified using this method.

2 METHODOLOGY BASED ON ENERGY BALANCE

2.1 Energy Balance Equation for Passive Control Structures

The energy balance equation, which is focused on the passive control structure composed of both hysteretic and viscous dampers, is expressed as

$$ {}_fW_e(t) + {}_sW_p(t) + {}_hW_d(t) = E(t) \tag{1} $$

where ${}_fW_e$ denotes the elastic vibration energy of the main frame; ${}_sW_p$ denotes the dissipation energy by hysteretic dampers; ${}_hW_d$ denotes the damping energy by viscous dampers, and E represents the input energy that can be evaluated by the energy spectra V_E. All terms shown in Eq. (1) are time-dependent; therefore, focusing on the seismic response of structures under strong motions, the elastic vibration energy ${}_fW_e$ is approximately equal to zero when ground motion is converged.

An N-story structure is set up to discuss the evaluation of the respective energies in Eq. (1). The maximum story shear coefficient of the main frame is ${}_f\alpha_i$, that of hysteretic dampers is ${}_s\alpha_i$, that of viscous dampers is ${}_h\alpha_i$, and that of the sum of whole elements is α_i at the i-th story, as follows :

$$ {}_f\alpha_i = \frac{{}_fQ_{\max i}}{\sum_{j=i}^{N} m_j g},\ {}_s\alpha_{yi} = \frac{{}_sQ_{yi}}{\sum_{j=i}^{N} m_j g},\ {}_h\alpha_i = \frac{{}_hQ_{\max i}}{\sum_{j=i}^{N} m_j g},\ \alpha_i = \frac{Q_{\max i}}{\sum_{j=i}^{N} m_j g} \qquad \text{(2-1~4)} $$

where m denotes mass, g denotes gravitational acceleration, and Q, shown in the numerator of the above formulas, is the maximum shear force of each element at the i-th story. The story shear coefficient α_0 and story drift δ_0 of the equivalent linear system are defined as

$$ \alpha_0 = \frac{2\pi \cdot V_E}{T \cdot g},\ \ \delta_0 = \frac{T \cdot V_E}{2\pi}, \qquad \text{(3-1, 2)} $$

which are the benchmarks for seismic response. In Eq. (3), T represents a natural period, and V_E can be expressed using equivalent mass M as

$$V_E = \sqrt{\frac{2E}{M}} \tag{4}$$

where M is the summation of all structures. In order to clarify the following discussion, the stiffness ratio κ_i between the equivalent linear system and the main frame of N-story structure is defined as

$$\kappa_i = \frac{{}_f k_i}{k_{eq}}. \tag{5}$$

Using above definition, the quantities of energy in Eq. (1), ${}_f W_e$, ${}_s W_p$, and ${}_h W_d$, can be described. When the structure exhibits a maximum response, ${}_f W_e$ is expressed as [4]

$${}_f W_e = \sum_{i=1}^{N} \frac{{}_f Q_{\max i} \cdot \delta_{\max i}}{2} \approx \frac{1}{2} M V_E^2 \cdot \left(\frac{{}_f \alpha_i / \bar{\alpha}_i}{\alpha_0} \right)^2. \tag{6}$$

In Eq. (6), $\bar{\alpha}_i$ represents the optimum story shear coefficient, which represents the behavior of a multi-story structure investigated through several numerical simulations [3]. Correspondingly, ${}_s W_p$ is derived as follows [5].

$${}_s W_p = {}_s \gamma_i \cdot {}_s W_{pi} \approx 4\, {}_s \gamma_i \cdot {}_s Q_{yi} \cdot \delta_{\max i} = \frac{1}{2} M V_E{}^2 \cdot 8\, {}_s \gamma_i \cdot c_i \cdot \bar{\alpha}_i^2 \left(\frac{{}_s \alpha_{yi} / \bar{\alpha}_i}{\alpha_0} \right) \cdot \left(\frac{{}_f \alpha_i / \bar{\alpha}_i}{\alpha_0} \right). \tag{7}$$

In the above equation, ${}_s\gamma_i$ is the coefficient of energy distributed by hysteretic dampers that is defined as

$$\frac{1}{{}_s \gamma_i} = \frac{{}_s W_{pi}}{\sum_{j=1}^{N} {}_s W_{pj}} = \frac{s_i \cdot {}_s p_i{}^{-ni}}{\sum_{j=1}^{N} s_j \cdot {}_s p_j{}^{-ni}} \quad [\, 1 \le n_i \le 12] \tag{8}$$

$$\text{where } s_i = \left(\sum_{j=i}^{N} \frac{m_j}{M} \right)^2 \cdot \bar{\alpha}_i^2 \cdot \left(\frac{{}_f k_1}{{}_f k_i} \right), \quad {}_s p_i = \frac{{}_s \alpha_{yi} / {}_s \alpha_{y1}}{\bar{\alpha}_i} \tag{9-1, 2}$$

and c_i in Eq. (7) is expressed as

$$c_i = \frac{1}{\kappa_i} \left(\sum_{j=i}^{N} \frac{m_j}{M} \right)^2. \tag{10}$$

The damping energy by viscous dampers ${}_h W_d$ is also derived as

$${}_h W_d = {}_h \gamma_i \cdot {}_h W_{di} \Rightarrow \pi \cdot {}_h \gamma_i \cdot {}_h Q_{\max i} \cdot \delta_{\max i} = \frac{1}{2} M V_E^2 \cdot 2\pi\, {}_h \gamma_i \cdot c_i \cdot \bar{\alpha}_i^2 \left(\frac{{}_h \alpha_i / \bar{\alpha}_i}{\alpha_0} \right) \cdot \left(\frac{{}_f \alpha_i / \bar{\alpha}_i}{\alpha_0} \right) \tag{11}$$

assuming that the maximum damping force of viscous damper ${}_h Q_{\max i}$ occurs at the same circle when the story drift achieves the maximum response $\delta_{\max i}$ [6]. In Eq. (11), the coefficients of energy distribution by viscous dampers ${}_h\gamma_i$ are defined as

$$\frac{1}{{}_h \gamma_i} = \frac{{}_h W_{di}}{\sum_{j=1}^{N} {}_h W_{dj}} = \frac{s_i' \cdot h_i}{\sum_{j=1}^{N} s_j' \cdot h_j} \tag{12}$$

where s_i' corresponds to the deformation distribution as

$$s_i' = \left(\sum_{j=i}^{N} \frac{m_j}{M} \right)^2 \cdot \bar{\alpha}_i^2 \cdot \left(\frac{{}_f k_1}{{}_f k_i} \right)^2 = \frac{\delta_{\max i}^2}{\delta_{\max 1}^2} \tag{13-1}$$

and h_i can be expressed using the damping coefficient of viscous dampers C_i installed at each story as

$$h_i = \frac{C_i \cdot T}{4\pi M} . \tag{13-2}$$

2.2 Prediction Method for Structures with both Hysteretic and Viscous Dampers

According to the abovementioned mathematical expressions, the energy balance equation shown in Eq. (1) can be written as

$$\left(\frac{{}_f \alpha_i / \bar{\alpha}_i}{\alpha_0} \right)^2 + 8 {}_s\gamma_i \cdot c_i \cdot \bar{\alpha}_i^2 \left(\frac{{}_s \alpha_{yi} / \bar{\alpha}_i}{\alpha_0} \right) \cdot \left(\frac{{}_f \alpha_i / \bar{\alpha}_i}{\alpha_0} \right) + 2\pi {}_h\gamma_i \cdot c_i \cdot \bar{\alpha}_i^2 \left(\frac{{}_h \alpha_i / \bar{\alpha}_i}{\alpha_0} \right) \cdot \left(\frac{{}_f \alpha_i / \bar{\alpha}_i}{\alpha_0} \right) = 1 \tag{14}$$

The solution of the above quadratic equation is expressed as

$$\frac{{}_f \alpha_i / \bar{\alpha}_i}{\alpha_0} = -\left\{ {}_s A_i \left(\frac{{}_s \alpha_{yi} / \bar{\alpha}_i}{\alpha_0} \right) + {}_h A_i \left(\frac{{}_h \alpha_i / \bar{\alpha}_i}{\alpha_0} \right) \right\} + \sqrt{ \left\{ {}_s A_i \left(\frac{{}_s \alpha_{yi} / \bar{\alpha}_i}{\alpha_0} \right) + {}_h A_i \left(\frac{{}_h \alpha_i / \bar{\alpha}_i}{\alpha_0} \right) \right\}^2 + 1 } \tag{15}$$

where ${}_sA_i = 4c_i \bar{\alpha}_i^{\,2} {}_s\gamma_i$ and ${}_sA_i = \pi\, c_i \bar{\alpha}_i^{\,2} {}_h\gamma_i$. Eq. (15) represents the distribution of energy for each component of the entire structure. In order to predict the seismic response, such as the story drift, the distribution of story shear force needs to be assumed. In this paper, the maximum story shear force of the entire structure, Q_{maxi}, corresponds to the following formula that considers the phase difference between the maximum shear force caused by viscous dampers and that caused by the main frame.

$$Q_{\max i} = \sqrt{ {}_f Q_{\max i}^2 + {}_h Q_{\max i}^2 } + {}_s Q_{yi} \ . \tag{16}$$

Based on the above equation, the maximum story drift at the i-th story is expressed as

$$\frac{\kappa_i \cdot \delta_{\max i}}{\delta_0} = \frac{\kappa_i}{\delta_0} \cdot \left(\frac{{}_f Q_{\max i}}{{}_f k_i} \right) = \left(\sum_{j=i}^{N} \frac{m_i}{M} \right) \cdot \bar{\alpha}_i \cdot \left(\frac{{}_f \alpha_i / \bar{\alpha}_i}{\alpha_0} \right) . \tag{17}$$

Considering the above discussion, the relationship between the maximum story drift δ_{maxi} and the maximum story shear coefficient α_i is represented as

$$\frac{\alpha_i / \bar{\alpha}_i}{\alpha_0} = \sqrt{ B_i^2 + \left(\frac{{}_h \alpha_i / \bar{\alpha}_i}{\alpha_0} \right)^2 } + \frac{1}{2 {}_s A_i} \left(\frac{1}{B_i} - B_i \right) - \frac{{}_h A_i}{{}_s A_i} \left(\frac{{}_h \alpha_i / \bar{\alpha}_i}{\alpha_0} \right) , \tag{18}$$

and the other expression is

$$\frac{\alpha_i / \bar{\alpha}_i}{\alpha_0} = \sqrt{ B_i^2 + \left\{ \frac{1}{2 {}_h A_i} \left(\frac{1}{B_i} - B_i \right) - \frac{{}_s A_i}{{}_h A_i} \left(\frac{{}_s \alpha_{yi} / \bar{\alpha}_i}{\alpha_0} \right) \right\}^2 } + \left(\frac{{}_s \alpha_{yi} / \bar{\alpha}_i}{\alpha_0} \right) \tag{19}$$

$$\text{where} \qquad B_i = \frac{1}{\left(\sum_{j=i}^{N}\frac{m_j}{M}\right)\cdot\bar{\alpha}_i}\cdot\left(\frac{\kappa_i\cdot\delta_{\max i}}{{}_f\delta_0}\right). \tag{20}$$

The procedure for predicting the seismic response is as follows:

(i) In the first approximation, when the viscous dampers are not installed, the distribution of story drifts $\delta_{\max i}$ is calculated based on Eqs. (17) and (18).

(ii) The coefficients of energy distribution by viscous dampers ${}_h\gamma_i$ are evaluated using the results of the first approximation.

(iii) Based on the evaluated results of ${}_h\gamma_i$, the distribution of story drifts $\delta_{\max i}$ can be recalculated.

Compare an estimate of the results of step (i) and step (iii). If the distribution of the story drift is almost equal, the other response can be evaluated by Eqs. (15), (16), and (17); otherwise, return to step (i) and use $\delta_{\max i}$ evaluated in step (iii).

3 RESPONSE EVALUATION OF PASSIVE CONTROL STRUCTURES AND VERIFICATION OF PREDICTIVE METHOD BY NUMERICAL SIMULATION

3.1 Seismic Response of Passive Control Structures Based on the Predictive Method

In order to investigate the seismic response determined by structural components such as the stiffness of the main frame and the quantity of dampers, this paper focuses on the response of the first story, which is described as the story drift and the story shear coefficient. The relationship of the first story is derived by substituting i = 1 in Eq. (15) as follows:

$$\frac{{}_f\alpha_1}{\alpha_0} = -\left\{{}_sA_1\left(\frac{{}_s\alpha_{y1}}{\alpha_0}\right)+{}_hA_1\left(\frac{{}_h\alpha_1}{\alpha_0}\right)\right\}+\sqrt{\left\{{}_sA_1\left(\frac{{}_s\alpha_{y1}}{\alpha_0}\right)+{}_hA_1\left(\frac{{}_h\alpha_1}{\alpha_0}\right)\right\}^2+1}\;. \tag{21}$$

Correspondingly, the story shear coefficient of the entire structure is expressed as

$$\frac{\alpha_1}{{}_f\alpha_0} = \sqrt{\left[-\left\{{}_sA_1\left(\frac{{}_s\alpha_{y1}}{\alpha_0}\right)+{}_hA_1\left(\frac{{}_h\alpha_1}{\alpha_0}\right)\right\}+\sqrt{\left\{{}_sA_1\left(\frac{{}_s\alpha_{y1}}{\alpha_0}\right)+{}_hA_1\left(\frac{{}_h\alpha_1}{\alpha_0}\right)\right\}^2+1}\right]^2+\left(\frac{{}_h\alpha_1}{\alpha_0}\right)^2}+\left(\frac{{}_s\alpha_{y1}}{\alpha_0}\right)\;, \tag{22}$$

and the mathematical expressions corresponding to Eqs. (18) and (19) are shown in the following formulas:

$$\frac{\alpha_1}{\alpha_0} = \sqrt{\left(\frac{\kappa_1\cdot\delta_{\max 1}}{\delta_0}\right)^2+\left(\frac{{}_h\alpha_1}{\alpha_0}\right)^2}+\frac{1}{2\,{}_sA_1}\left\{\left(\frac{\delta_0}{\kappa_1\cdot\delta_{\max 1}}\right)-\left(\frac{\kappa_1\cdot\delta_{\max 1}}{\delta_0}\right)\right\}-\frac{{}_hA_1}{{}_sA_1}\left(\frac{{}_h\alpha_1}{\alpha_0}\right) \tag{23}$$

$$\frac{\alpha_1}{\alpha_0} = \sqrt{\left(\frac{\kappa_1\cdot\delta_{\max 1}}{\delta_0}\right)^2+\left[\frac{1}{2\,{}_hA_1}\left\{\left(\frac{\delta_0}{\kappa_1\cdot\delta_{\max 1}}\right)-\left(\frac{\kappa_1\cdot\delta_{\max 1}}{\delta_0}\right)\right\}-\frac{{}_sA_1}{{}_hA_1}\left(\frac{{}_s\alpha_{y1}}{\alpha_0}\right)\right]^2}+\left(\frac{{}_s\alpha_{y1}}{\alpha_0}\right) \tag{24}$$

3.2 Analysis Condition for Numerical Tests

In order to verify the validity of the prediction method and to assess the seismic behavior of the passive control structure that varies due to the number of dampers, numerical tests are set up. The numerical tests are shown in Fig. 2.

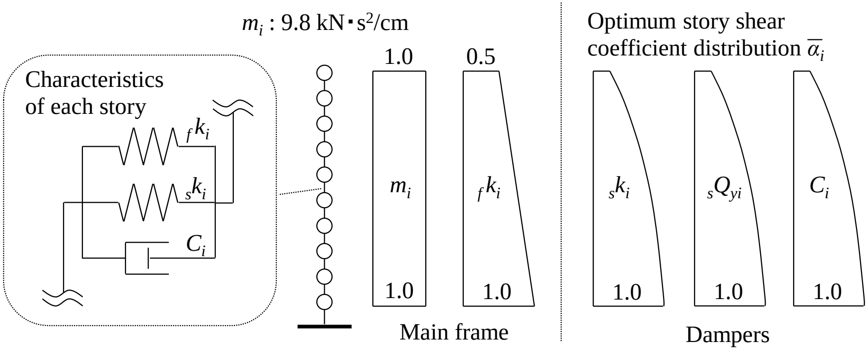


Fig. 2 Outline of the analysis condition for numerical tests

As shown in Fig. 2, the numerical tests are conducted by the ramped mass model. The story characteristics are determined by the stiffness of the main frame $_fk_i$, the hysteretic dampers $_sk_i$, and the damping coefficient C_i, which represents the influence of viscous dampers. The stiffness of the main frame is linear spring, which is determined by adjusting that the natural period only frame is equaled 1.0 and 2.0 s, and that the distribution is obeyed as Fig. 2. The yield displacement of hysteretic dampers $_s\delta_{yi}$ equals 0.64 cm because the damper is installed as an inverted v shape in the main frame, which is 4.2 m × 6.4 m in elevation. The distribution of all parameters related to the dampers is confirmed to be the optimum story shear coefficient $\overline{\alpha}_i$, as shown in Fig. 2.

3.3 Evaluation of Seismic Response for the Passive Control Structure

According to the above analysis, the parameters required to use the prediction method based on energy balance can be calculated as $_s\gamma_1$ = 6.40, $_h\gamma_1$ = 6.05, and κ_1 = 5.38. The characteristics expressed by Eq. (22) are shown in Fig. 3. This figure also shows the analytical results, where the input motion is the 1968 Tokachi-oki earthquake (observed at Hachinohe) normalized at 50 cm/s.

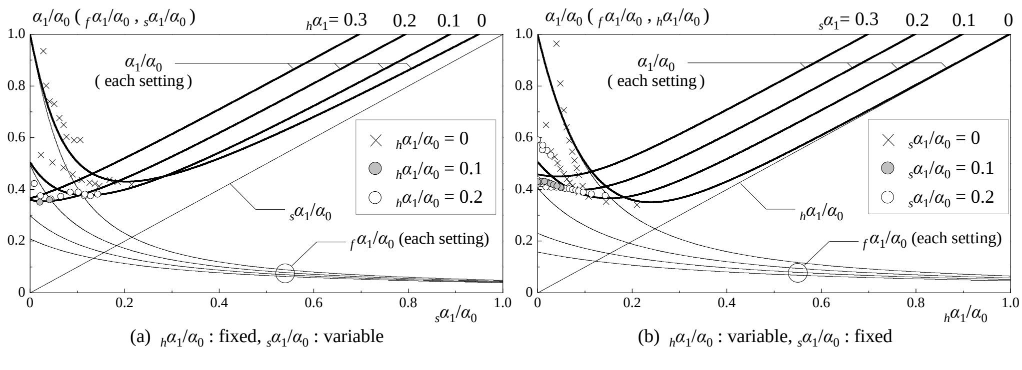
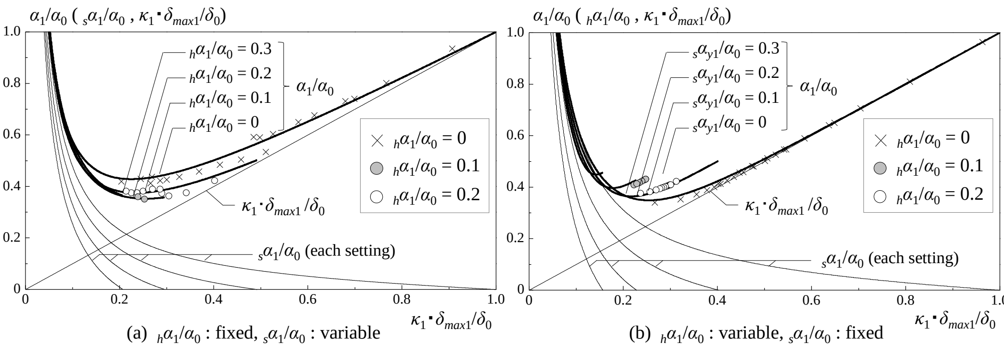


Fig. 3 Distribution of the story shear force based on energy balance

Fig. 3 shows the analytical results. The maximum story drift angle is below 1/200 rad; in this range, the effectiveness of dampers cannot be observed. The validity of the method can be confirmed by comparing the analytical results with respective lines evaluated by Eq. (22). Fig. 3 (a) and (b) show the evaluation results that display the influence of hysteretic dampers and viscous dampers.

As shown in Fig. 3 (a), the reduction of story shear force, which depends on the increasing viscous damper, can be seen at ${}_h\alpha_1 / {}_f\alpha_0 < 0.2$. Other than at ${}_h\alpha_1 / {}_f\alpha_0 > 0.3$, the effectiveness of installing both dampers cannot be seen because the story shear force increases monotonically. Fig. 3 (b) shows that the reduction of the story drift cannot be anticipated by increasing the quantities of hysteretic dampers. The relationship between story drift and story shear force, which is expressed by Eqs. (23) and (24), is shown in Fig. 4 with analytical results.



(a) ${}_h\alpha_1/\alpha_0$: fixed, ${}_s\alpha_1/\alpha_0$: variable (b) ${}_h\alpha_1/\alpha_0$: variable, ${}_s\alpha_1/\alpha_0$: fixed

Fig. 4 Relationship between story shear force and story drift based on energy balance

Fig. 4 (a) shows that the reduction of story drift corresponds to the increase in the quantities of viscous dampers when the story shear force is minimal. In contrast, the more the number of hysteretic dampers, the more is the decrease in the story drift (Fig. 4). The evaluation results indicate that the synergistic effects of using both dampers are expected at the specific range, and the range is predictable based on energy balance.

4 CONCLUSION

This paper focused on the evaluation of passive control structures using both hysteretic dampers and viscous dampers on basis of energy balance. The findings are as follows:

- The mathematical expression corresponds to the distribution of energy. The distribution of story shear force on each story and the relationship between story shear force and story drift at a specific story is derived by using an optimum story shear coefficient $\bar{\alpha}_i$ on basis of the energy balance equations.
- The validity of the proposed prediction method is verified through the comparison between the seismic response evaluated by the proposed prediction method and the analytical results calculated by ramped mass model under strong observed motion.
- The seismic response of the passive control structures using both dampers can be evaluated by the prediction method, and the results of this method indicate that the synergistic effects of using both dampers are expected at the specific range; the range is predictable based on energy balance.

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