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RESPONSE PREDICTION CURVE OF EQUIVALENT DEFORMATION BETWEEN SUPERSTRUCTURE AND SEISMIC ISOLATION LAYER BY ENERGY BALANCE

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Abstract

After the 1995 Great Hanshin Earthquake, seismic isolation technology has been extensively applied to buildings characterized to have long-period superstructures. In recent years, after the 2011 Great Tohoku Earthquake, this technology has been widely adopted to logistics warehouses which are typically designed to be long spans with high storey height to create large internal spaces. For base-isolated logistics warehouses, the natural period of the superstructure becomes longer, and the difference between natural period of the superstructure and the seismic isolation comes to be small. In such a case, the seismic isolation performance decreases, and previously proposed analytical methods using story shear coefficient distributions may not predict the deformation of the superstructure. This study proposes a response prediction technique based on the energy-balance method, and on the natural periods of the superstructure and isolation layer. This response prediction for equivalent deformation magnification ratio (δ_{ueq}/δ_0) is proposed according to the $\delta_{ueq}/\delta_{max}$ ratio and the δ_{max}/δ_0 ratio (i.e., based on the energy-balance method). A prediction curve is then proposed according to the yield shear coefficient ratio (α_s/α_0) of the hysteresis dampers for seismic layer and the δ_{ueq}/δ_0 ratio (Fig. 1a). By this proposed technique, maximum deformation of the superstructure can be predicted without carrying out response history analysis. Furthermore, from the prediction curve, we are able to estimate the range of yield shear coefficient of hysteresis dampers or appropriate period of superstructure to accommodate the deformation of the base isolation layer (Fig. 2a).

Keywords: base-isolated building; superstructure period; equivalent deformation; prediction curve

Note: α_1 is shear coef. of isolation layer, α_s is yield shear coef. of hysteresis damper, α_f is shear coefficient of isolator, α_0 is shear coef. of isolation layer (no damping), δ_{max} is max. deformation of isolation layer, δ_{ueq} is equivalent deformation of superstructure, δ_0 is max. deformation of isolation layer (no damping), V_E is speed conversion value of input energy, n_1 is equivalent repeating number, T_f is fundamental period of isolator (superstructure is rigid), T_{eq} is equivalent period of the structure, T_u is fundamental period of superstructure (fixed foundation), c is criteria value.

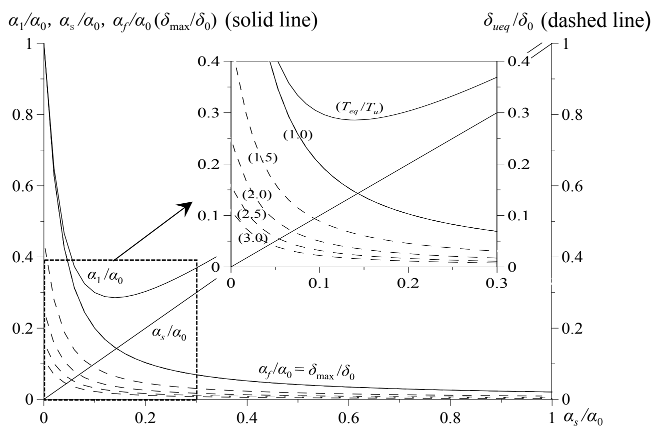


Fig. 1a - Prediction curve of superstructure equivalent deformation

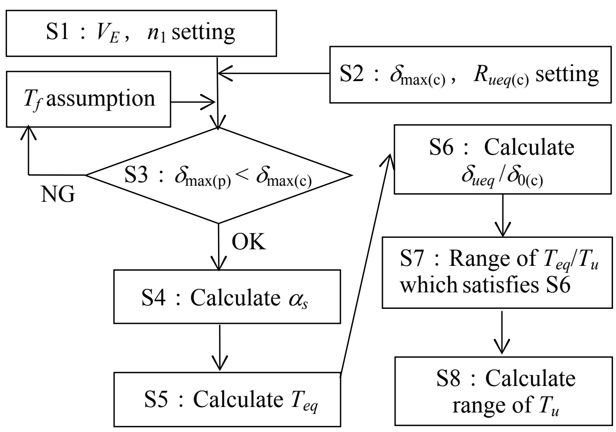


Fig. 2a - Design Steps

1. Introduction

Since 1995, the concept of base-isolation has been used in designing a large number of buildings. Recently, base-isolated structures have been adopted to steel-frame buildings and super high-rise buildings. Building designs have incorporated base-isolation systems with long natural period[1]. Moreover, the development of the internet delivery market and the impact of the 2011 Tohoku-Pacific Ocean Earthquake has increased the usage of seismic isolation structures in steel-framed logistic warehouses. These warehouses are designed with long spans and high floor heights to meet the demand for large internal spaces. When seismic isolation structure is adopted in such buildings, the difference between the superstructure period and the seismic isolation period lessens, thereby reducing the beneficial effects of seismic isolation. A new prediction method using response spectrum with verified accuracy improvement was proposed for the maximum response of seismic isolation layer[2], [3]. It has been confirmed in previous studies that the shear coefficient of superstructure becomes larger in a seismic isolation building with longer natural period of the superstructure with fixed foundation; moreover, the energy could be absorbed by superstructure[4]. Thus, the deformation of superstructure would increase. Kasai used a method to simplify the model to consider the flexibility of superstructure. Due to the change of seismic isolation effects which results from the balance between the superstructure and the isolation layer, the stiffness, and the damping ofisolation layer. The mechanism of seismic isolation response was shown and a seismic isolation performance curve was proposed[5].

This paper proposes a method that couldobtainan appropriate range to satisfy the design criteria for the superstructure period of base-isolated buildings. Specifically, based on the energy balance theory, the deformation prediction formula for the superstructure of base-isolation buildingsare proposed, using the equivalent period ratio of isolation layer and the natural period of superstructure, when the foundation is fixed. In thispaper, the naturalperiod of superstructure with fixed foundation, the period of the isolators, the yield shear coefficient of hysteretic dampers installed in isolation layer, and the input ground motion are used as parameters. Furthermore, by using this prediction formula, a design example is provided for the appropriate period ofsuperstructure to converge the seismic isolation layer deformation and the interlayer deformation angle of superstructure within the design criteria.

2. Analysis conditions and outline of input earthquake motion

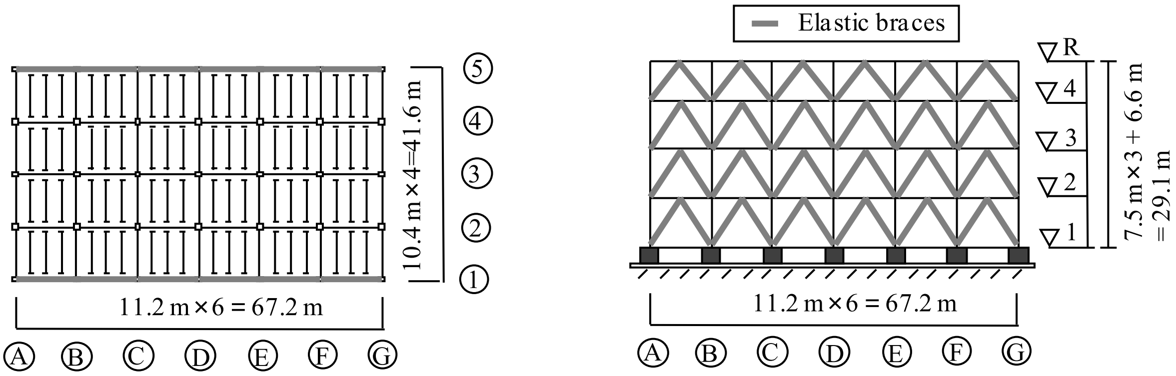
2.1 Outline of the analysis model

This paper's analysis is based on a four-story steel-frame logistic warehouse with spans that are 11.2m in long direction and 10.4m in short direction, and a flat surface of 67.2m × 41.6m. The height of each floor is 7.5m from the 1st to the 3rd and 6.6m for the 4th floor. Fig. 1 shows the standard floor (a) and a set of dampers layout in long axis direction (b). The sum of total floor permanent load and earthquake load is 10.8kN/m^2. The size of each column is adopted as □-400 × 400 × 22 ~ 28, and each beam is adopted as H-700 × 300 × 14 × 22 in long direction, and H-700 × 250 × 14 × 28 in short direction. The seismic isolation layer consists of natural rubber-based laminated rubbers and hysteresis dampers. Figure 2 shows the deployment of isolation layer. The laminated rubbers are set below outer column as ϕ800mm and middle column as ϕ1000mm, for 20 and 15 respectively, and 16 dampers besides. The natural period of rigid frame (foundation fixed) is 3.0s. For this analysis, elastic braces are placed at route 1 and route 5 to adjust the natural period of superstructure when foundation is fixed T_u. The superstructure and the isolators are elastic and the dampers are placed as restoring force with full elasto-plasticity. The yield deformation of hysteresis dampers δ_{sy} is 3cm. The initial stiffness proportional damping h is set as 2% of the natural period of superstructure T_u, when the foundation is fixed.

By changing the section of the elastic braces that are set as analysis parameters, the natural period of superstructure T_u varies from 0.8 to 2.6s. In addition, the period of the isolators T_f, when the superstructure is rigid, is set as 4 and 6s, and the yield shear coefficient of hysteresis dampers α_s installing in seismic isolation layer varies from 0.01 to 0.05 (Table 1).

2.2 Input earthquake motion

HACHINOHE (1968) EW and JMA KOBE (1995) NS are used as the input earthquake motion. The pseudo velocity response spectrum $_pS_v$ (h= 5%) becomes constant at 80 cm/s after the corner period. In the analysis, notification wave of input earthquake would be changed into 0.5, 1.0, and 1.5 times, namely ART HACHI 40, ART HACHI 80, ART HACHI 120, ART KOBE 40, ART KOBE 80, and ART KOBE 120. The pseudo velocity response spectrum $_pS_v$ (h = 5%) and the energy spectrum V_E (h = 10%) are showed in Fig. 3.



(a) Standard floor (b) Dampers lateral layout

Fig. 1 – Profiling and axis diagram

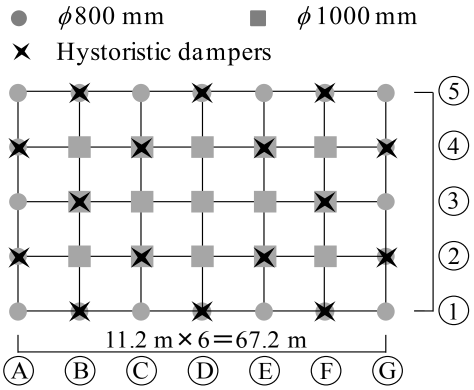
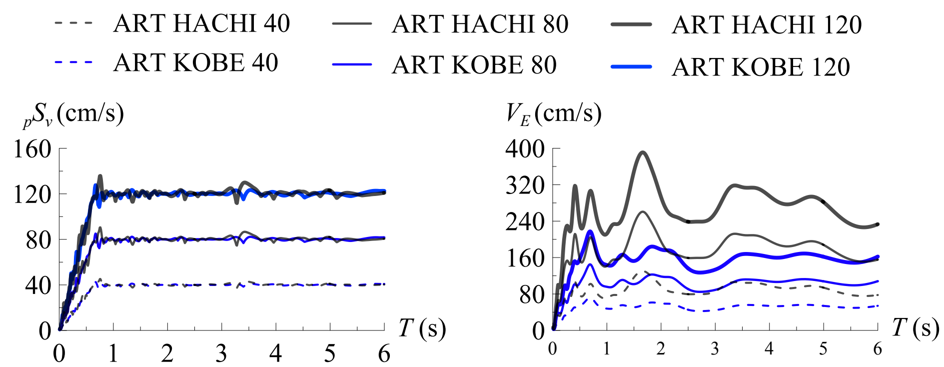


Fig. 2 – Deployment of seismic isolation

Table 1 – Analysis parameter

Superstructure	
Fundamental Period T_u	0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.6 s
Isolated layer	
Period of isolators T_f	4.0 s 6.0 s
Shear coefficient of hysteresis dampers α_s	0.010,0.015,0.020, 0.030,0.040,0.050



(a) Pseudo Velocity Response Spectrum (h = 5%) (b)Energy Spectrum (h = 10%)

Fig. 3 – Analysis input earthquake

3. Definition of equivalent period T_{eq}/T_u and equivalent deformation ratio δ_{ueq}/δ_0

First, the period of isolators T_f, the yield shear coefficient of hysteresis dampers α_s, and the isolation equivalent period T_{eq} are defined. Second, the ratio of isolation equivalent period T_{eq} to natural period of superstructure T_u with fixed foundation (namely, equivalent period ratio) will be defined. Finally a prediction formula about the equivalent period ratio T_{eq}/T_u that causes the effects of superstructure deformation will be proposed. As shown in Fig. 4, K_{eq} is the isolation equivalent stiffness when the deformation of isolation layer reaches the maximum, which is calculated by Eq. (1). The equivalent period T_{eq} is the period based on the equivalent stiffness K_{eq}, which is calculated by Eq. (2).

The definition of superstructure and the deformation of isolation layer based on mass system are shown in Fig. 5. The equivalent deformation of superstructure δ_{ueq} is defined as the difference between the maximum displacement of the first floor and the middle floor of superstructure, which is calculated by Eq. (3). The middle floor is defined as the floor that is the closest to the half-height of superstructure.

$$K_{eq} = k_f + \frac{{}_s\delta_y}{\delta_{\max}} \cdot k_s \qquad T_{eq} = 2\pi\sqrt{\frac{M}{K_{eq}}} \qquad \delta_{ueq} = x_{\mathrm{M}} - x_1 \qquad (1), (2), (3)$$

Here, k_f: stiffness of isolators, k_s: initial stiffness of hysteresis dampers, ${}_s\delta_y$: yield deformation of hysteresis dampers, $\delta_{\max}$: maximum deformation of isolation layer, M: total mass of superstructure, x_M: maximum displacement of middle floor of superstructure, x_1: maximum displacement of the first floor of superstructure in base-isolated structure

In this paper, the ratio between the equivalent deformation of superstructure δ_{ueq} and the maximum deformation of isolation layer δ_0 (details given in Section 4.2) without dampers is named as the equivalent deformation ratio δ_{ueq}/δ_0. The derivation of prediction formula δ_{ueq}/δ_0 and its validity examination are shown in the next chapter.

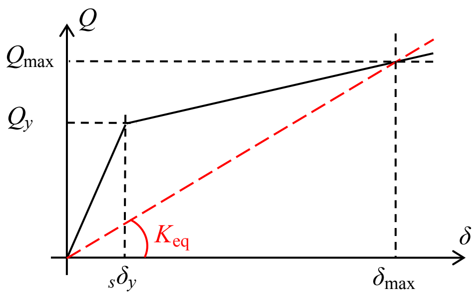


Fig. 4 – Seismic isolation equivalent stiffness

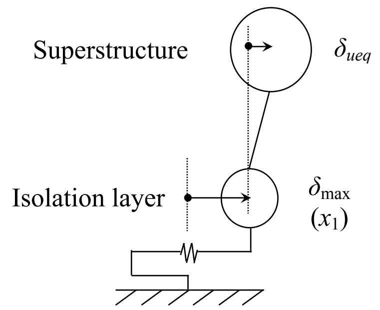


Fig. 5 – Deformation based on mass system

4. Proposal of prediction formula of equivalent deformation ratio δ_{ueq}/δ_0

The equivalent deformation ratio δ_{ueq}/δ_0 could be expressed as Eq. (4). In this chapter, the prediction method, and the prediction accuracy of $\delta_{ueq}/\delta_{\max}$ are considered, and the prediction formula of equivalent deformation ratio δ_{ueq}/δ_0 based on the energy balance is proposed. Thereafter, the prediction formula is verified by using the prediction value of equivalent deformation ratio δ_{ueq}/δ_0, obtained from the prediction formula and the results of time history response analysis.

4.1 Prediction method and verification of $\delta_{ueq}/\delta_{\max}$

$\delta_{ueq}/\delta_{\max}$, which is the ratio between the equivalent deformation of superstructure and the maximum deformation of isolation layer obtained from the time history response analysis, represents the response amplification of superstructure.

It assumes that the maximum shear coefficient of the first layer of superstructure equals to the maximum shear coefficient of isolation layer. By using the maximum shear force of isolation layer, the maximum shear force Q_{u1}, which transmits to the first layer of superstructure, could be expressed as Eq. (5). Besides, the verification of Eq. (5) is shown in Appendix 1.

$$\frac{\delta_{ueq}}{\delta_0} = \frac{\delta_{ueq}}{\delta_{\max}} \cdot \frac{\delta_{\max}}{\delta_0} \qquad Q_{u1} = \frac{M_u}{M} \cdot Q_{\max} \qquad (4), (5)$$

Here, M_u: total mass of the upper layer above the first layer, $Q_{\max}$: maximum shear force of isolation layer

The equivalent deformation of superstructure δ_{ueq} is calculated by Eq. (6). As shown in Fig. 4, the maximum deformation of isolation layer $\delta_{\max}$ could be expressed by using the isolation equivalent stiffness K_{eq} (Eq. (7)). Besides, the verification of Eq. (6) is shown in Appendix 2.

$$\delta_{ueq} = \frac{Q_{u1}}{K_{ueq}} \qquad \delta_{\max} = \frac{Q_{\max}}{K_{eq}} \tag{6), (7}$$

K_{ueq} is the equivalent stiffness of superstructure when the foundation is fixed, which is expressed as Eq. (8). Similarly, the isolation equivalent stiffness K_{eq} is calculated by Eq. (9).

$$K_{ueq} = \frac{4\pi^2 M_u}{T_u^{\,2}} \qquad K_{eq} = \frac{4\pi^2 M}{T_{eq}^{\,2}} \tag{8), (9}$$

According to Eq. (5) to (7), $\delta_{ueq}/\delta_{\max}$ could be derived as Eq. (10). Then substituting the Eq. (8) and (9) into the Eq. (10), $\delta_{ueq}/\delta_{\max}$ could be expressed as -2 power of the equivalent period ratio T_{eq}/T_u as Eq. (11).

$$\frac{\delta_{ueq}}{\delta_{\max}} = \frac{M_u}{M} \cdot \frac{K_{eq}}{K_{ueq}} \qquad \frac{\delta_{ueq}}{\delta_{\max}} = \left(\frac{T_{eq}}{T_u}\right)^{-2} \tag{10), (11}$$

According to the seismic isolation design guidelines[6], it indicates that the response amplification of superstructure depends on the rigidity ratio of superstructure and isolation layer, which is synonymous with Eq. (11).

The relationship between the equivalent period ratio T_{eq}/T_u and $\delta_{ueq}/\delta_{\max}$ by six kinds of input earthquake motions is shown as Fig 6. According to the figure, it could be seen that $\delta_{ueq}/\delta_{\max}$ increases as the equivalent period ratio T_{eq}/T_u decreases. The dashed line is the approximate curve obtained by the least-squares method[7]. It could be confirmed that $\delta_{ueq}/\delta_{\max}$, which shows a proper correspondence with the Eq. (11), is approximately in the ratio to -2 power of equivalent period ratio T_{eq}/T_u. Also, when the equivalent period ratio T_{eq}/T_u is 1.0, it could be confirmed that the equivalent deformation of superstructure δ_{ueq} is approximately equaled to the maximum deformation of isolation layer $\delta_{\max}$ ($\delta_{ueq}/\delta_{\max} = 1$). According to the figure, the reason for the difference between the approximate curve and the Eq. (11) is that the maximum shear coefficient of the first layer and the isolation layer are assumed to be equaled.

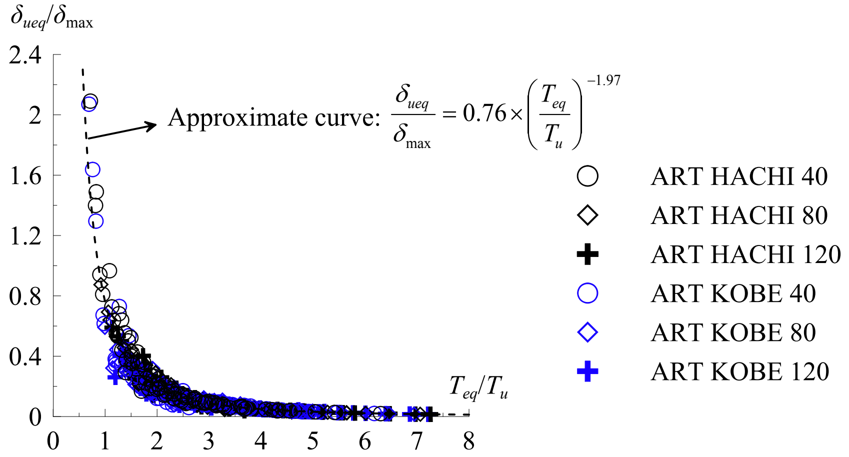


Fig. 6 – Relation between T_{eq}/T_u and $\delta_{ueq}/\delta_{\max}$

The relationship between the time history response analysis results (analytical values) and the prediction values obtained from Eq. (11) about $\delta_{ueq}/\delta_{\max}$ is shown in Fig. 7. Here, since the purpose is to verify the validity of Eq. (11), the maximum deformation of isolation layer $\delta_{\max}$ when T_{eq} is calculated by Eq. (11) is obtained from the results of time history response analysis. As shown in the figure, there is a small variation among predicted values of $\delta_{ueq}/\delta_{\max}$, which correspond to the analytical values.

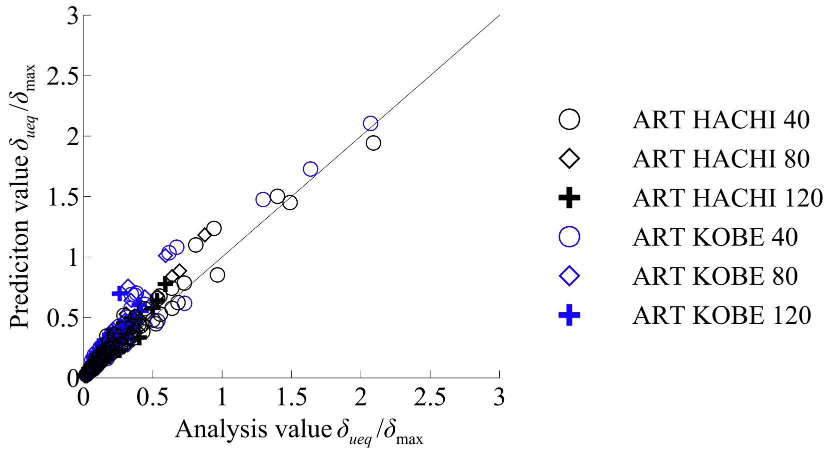


Fig. 7 – Comparison between analysis value and prediction value of $\delta_{ueq}/\delta_{max}$

4.2 Prediction method of δ_{max}/δ_0

Akiyama [8] proposed the following equation, which shows the relationship between the δ_{max}/δ_0 and the yield shear coefficient ratio of dampers in isolation layer α_s/α_0[8], [9].

$$\frac{\delta_{max}}{\delta_0} = \frac{\alpha_f}{\alpha_0} = -4n_1\frac{\alpha_s}{\alpha_0} + \sqrt{\left(4n_1\frac{\alpha_s}{\alpha_0}\right)^2 + 1} \tag{12}$$

$$\delta_0 = \frac{T_f \cdot V_E}{2\pi} \qquad \alpha_0 = \frac{2\pi \cdot V_E}{T_f \cdot g} \qquad (13), (14)$$

Here, δ_0: maximum deformation of isolation layer without dampers and no damping (Eq. (13)), α_f: shear coefficient of isolators, α_0: shear coefficient of isolation layer without dampers and no damping (Eq. (14)), n_1: equivalent number of repetitions, V_E: equivalent velocity of total energy

It is assumed that the superstructure is rigid in Eq. (12) and all the input energy is absorbed by the isolation layer. In cases where the energy is also absorbed by the superstructure of base-isolated building, the maximum deformation of isolation layer δ_{max} is above the evaluation safety.

4.3 Verification of prediction formula

Substituting Eq. (11) and (12) into Eq. (4), the prediction formula of equivalent deformation ratio δ_{ueq}/δ_0 is expressed as Eq. (15).

$$\frac{\delta_{ueq}}{\delta_0} = \left(\frac{T_{eq}}{T_u}\right)^{-2} \cdot \left(-4n_1\frac{\alpha_s}{\alpha_0} + \sqrt{\left(4n_1\frac{\alpha_s}{\alpha_0}\right)^2 + 1}\right) \tag{15}$$

When the equivalent period ratio T_{eq}/T_u is 1.0, Eq. (15) coincides with Eq. (12), which means, as in the Section 4.1, when T_{eq}/T_u is 1.0, the equivalent deformation of superstructure δ_{ueq} is equal to the maximum deformation of isolation layer δ_{max}, which means $\delta_{ueq}/\delta_0 = \delta_{max}/\delta_0$.

Table 2 shows the average values of n_1 when the natural period of superstructure T_u (foundation is fixed), the period of isolators T_f, and the yield shear coefficient of hysteresis dampers α_s are changed because of different input earthquake motions. The comparison between the prediction value of equivalent deformation ratio δ_{ueq}/δ_0, which is obtained from Eq. (15) by using the values from Table 2, and the analysis value, which is obtained from the time history response analysis, is shown in Fig 8. In addition, when calculating the shear coefficient of isolation layer without dampersα_0 (Eq. (14)), the average value of V_E obtained from analysis is used into calculating.

Table 2 –n_1 of each input earthquake

	ART HACHI 40	ART HACHI 80	ART HACHI 120	ARTKOBE 40	ARTKOBE 80	ARTKOBE 120
Average value	3.3	6.4	8.0	0.9	1.7	2.2

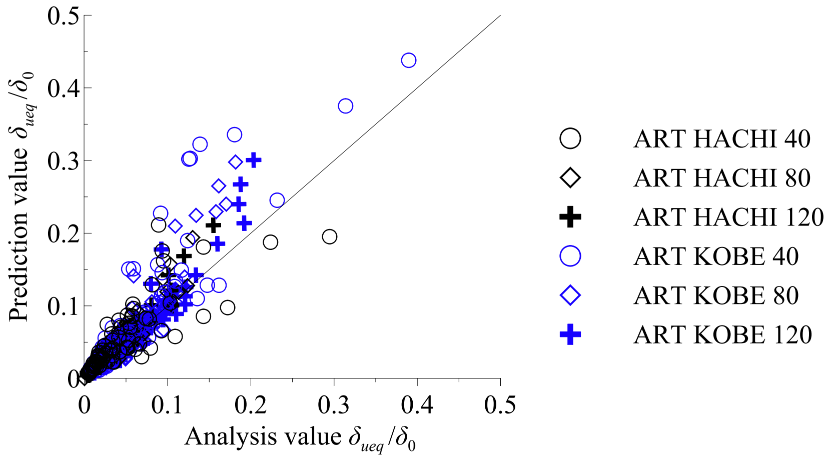


Fig. 8 – Comparison between analysis value and prediction value of δ_{ueq}/δ_0

According to the figure, the variety of equivalent deformation ratio δ_{ueq}/δ_0 between the prediction value and the analytical value could be confirmed. Since the prediction value of $\delta_{ueq}/\delta_{max}$ was proposed as Eq. (11), a proper correspondence could be found from Fig. 7, the variation could be considered by the equivalent repetition number $n_1$according to energy balance formula (Eq. (12)). According to the formula Eq. 12, the prediction value, and the analytical value of equivalent deformation ratio δ_{ueq}/δ_0 substantially correspond. It is recommended to use the prediction formula (Eq. (15)) in the range where the energy absorption proportion of superstructure is less than 20%.

5. Prediction curve and design example

In this chapter, regarding the yield shear coefficient ratio of hysteresis dampers α_s/α_0 as parameters, the prediction curve of equivalent deformation ratio δ_{ueq}/δ_0 is created by the equivalent period ratio T_{eq}/T_u. Then, by using the prediction curve, a design example will be shown regarding the natural period of superstructure T_u when the foundation is fixed. In addition, input earthquake motion ART HACHI 80 is used, who is obtained as an integer from Table 2 ($n_1 = 6$).

5.1 Predictive curve of superstructure deformation based on equivalent period ratio

Based on Eq. (15), Fig. 9 shows the prediction curve in which the equivalent period ratio T_{eq}/T_u and the yield shear coefficient ratio of hysteresis dampers α_s/α_0 are set as parameters. The solid line in the figure shows the relationship between the yield shear coefficient ratio of hysteresis dampers α_s/α_0 and the shear coefficient ratio of isolators α_f/α_0 (left vertical axis). The dashed line represents the relationship between α_s/α_0 and the equivalent deformation ratio δ_{ueq}/δ_0(right vertical axis) based on different parameter, equivalent period ratio T_{eq}/T_u. Here, α_1/α_0 is the total shear coefficient ratio of isolation layer, which is expressed by a concave curve as equation shown below and in Fig. 9.

$$\alpha_1/\alpha_0 = \alpha_f/\alpha_0 + \alpha_s/\alpha_0 \tag{16}$$

Focusing on the solid line in Fig. 9, as described in Section 4.1, the shear coefficient ratio of isolators α_f/α_0 is equaled to the maximum deformation ratio of isolation layer δ_{max}/δ_0 (Eq. (12), when there is no damping, due to the rigid superstructure. By using this relationship, we could obtain the change of maximum deformation of base isolation δ_{max}/δ_0 according to the change of yield shear coefficient ratio of hysteresis dampers α_s/α_0, then judge whether the base-isolated deformation could satisfy the design criteria.

Focusing on the dashed line in Fig. 9, it could be confirmed that the equivalent deformation ratio δ_{ueq}/δ_0 decreases as the yield shear coefficient ratio of hysteresis dampers α_s/α_0 increases. Furthermore, it could be confirmed that the equivalent deformation ratio δ_{ueq}/δ_0 becomes small as the equivalent period ratio T_{eq}/T_u increases.

By using this prediction curve, the relationship between the equivalent deformation of superstructure δ_{ueq} and the maximum of isolation layer δ_{max} could be obtained, towards the yield shear coefficient ratio of one certain hysteresis dampers α_s/α_0 instead of the period of isolators T_f and the V_E of input earthquake motion.

Then, the range of equivalent period ratio T_{eq}/T_u could be read, wherein the equivalent deformation ratio satisfies the design criteria.

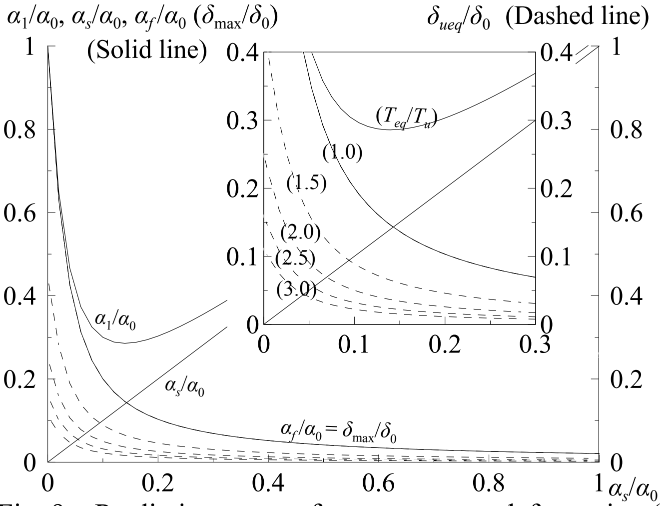


Fig. 9 – Prediction curve of superstructure deformation (n_1 = 6)

5.2 Design example using prediction curve

In this design example, the input earthquake motion, the deformation of isolation layer, and the interlayer deformation angle criteria of superstructure are set. Then, by using the prediction curve of equivalent deformation ratio, we could propose the method of determining the range of the natural period T_u, wherein the conditions were satisfied when the foundation is fixed. The design steps are shown in Fig. 10.

In this section, the same model, as shown in Section 2.1, is used. The mass of superstructure except the floor directly above isolation layer M_u= 14,314 ton, the total mass of building M = 20,252 ton, and the height from the first floor to the middle floor is H_{ueq}= 1,500 cm.

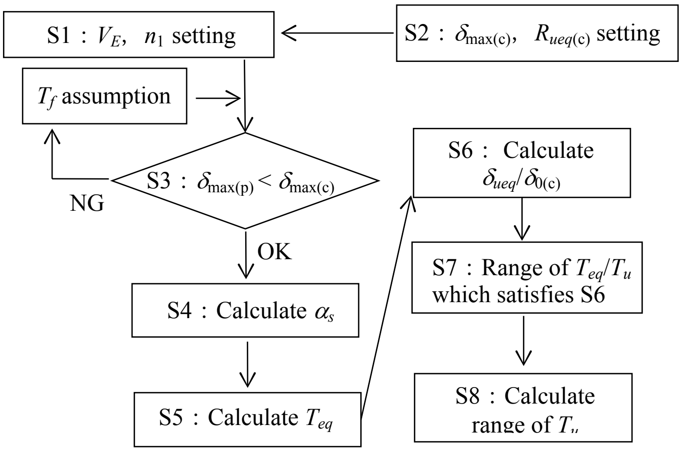


Fig. 10 – Design steps

STEP 1: Set the input earthquake motion

By assuming the input earthquake motion as ART HACHI 80, set V_E = 180 cm/s, n_1 = 6.

STEP 2: Set design criteria

For the earthquake motion ART HACHI 80 of level 2, the deformation of isolation layer $\delta_{\max(C)}$ = 40 cm, interlayer deformation angle of superstructure $R_{ueq\,(C)} = (\delta_{ueq}/H_{ueq})$ = 1/300 are set for the design criteria of the base-isolated building.

STEP 3: Confirm maximum deformation of isolation layer

When n_1 = 6, the relationship between the total shear coefficient ratio of isolation layer $\alpha_1/\alpha_0$and the yield shear coefficient ratio of dampers $\alpha_s/\alpha_0$is shown by the solid line in Fig 11. According to Fig. 11, when α_1/α_0 comes to the minimum value, α_s/α_0= 0.14, and α_f/α_0= 0.15. If the period of isolation layer with isolators only T_f is 6s, the maximum deformation of isolation layer with no dampers and non-damping isolators δ_0 is 172cm, calculate by using Eq. (13) (result is calculated by Eq. (17).

$$\delta_0 = \frac{V_E \cdot T_f}{2\pi} = \frac{180 \times 6}{2\pi} = 172 \quad \text{cm} \tag{17}$$

Using Eq. (12) and α_f/α_0 (Eq. (18)) obtained from Fig 11, the predictive maximum deformation of isolation layer becomes 25.5cm. Thus, it could be confirmed that the prediction value fits within the seismic isolation criteria (40 cm).

$$\frac{\alpha_f}{\alpha_0} = \frac{\delta_{\max}}{\delta_0} = 0.15 \tag{18}$$

$$\delta_{\max(\mathrm{P})} = \frac{\delta_{\max}}{\delta_0} \cdot \delta_0 = 0.15 \times 172 = 25.5 \quad \text{cm} < 40 \quad \text{cm} \tag{19}$$

In addition, if the predictive maximum deformation of isolation layer $\delta_{\max(P)}$ exceeds the seismic isolation criteria $\delta_{\max(C)}$, the period of isolators T_f shortened, then the maximum deformation of isolation layer should be recalculated back from STEP 3.

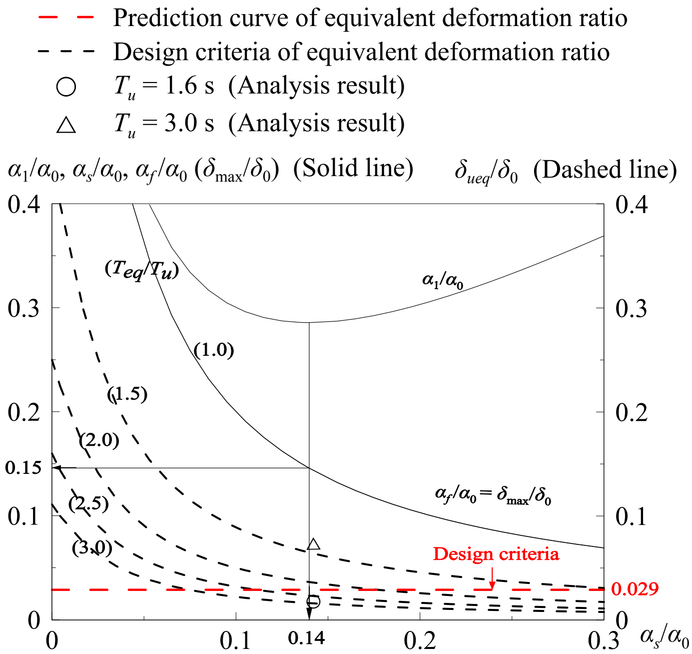


Fig. 11 – Prediction results and curve (n_1 = 6)

STEP 4: Calculate the yield shear coefficient of hysteresis dampers in isolation layer

The shear coefficient of isolation layer without dampers α_0 is determined as shown in Eq. (20) by using Eq. (14).

$$\alpha_0 = \frac{2\pi V_E}{T_f \cdot g} = \frac{2\pi \times 180}{6 \times 980} = 0.19 \tag{20}$$

When α_1/α_0 comes to the minimum value, α_s/α_0 = 0.14 (Fig. 11), the yield shear coefficient of hysteresis dampers α_s of isolation layer is 0.027 (Eq. (21)).

$$\alpha_s = \frac{\alpha_s}{\alpha_0} \cdot \alpha_0 = 0.14 \times 0.19 = 0.027 \tag{21}$$

STEP 5: Calculate seismic equivalent period

Natural rubber-based laminated rubber isolators and hysteresis dampers are placed in the isolation layer. This laminated rubber is modeled into elasticity. The stiffness of isolators k_f is obtained from Eq. (22).

$$k_f = \frac{4\pi^2 M}{{T_f}^2} = \frac{4\pi^2 \times 20252}{6^2} = 22209 \quad \text{kN/m} \tag{22}$$

The hysteresis dampers use the element that is characterized by full elastic-plastic restoring force. In addition, the yield deformation ${}_s\delta_y$ is adopted as 3cm. The initial stiffness of hysteresis dampers k_s is obtained from Eq. (23).

$$k_s = \frac{\alpha_s \cdot Mg}{{}_s\delta_y} = \frac{0.027 \times 20252 \times 9.8}{0.03} = 177891 \quad \text{kN/m} \tag{23}$$

By substituting the stiffness of isolators k_f, the initial stiffness of hysteresis dampers k_s, the yield deformation of hysteresis dampers ${}_s\delta_y$, and the maximum deformation of isolation layer $\delta_{\max}$ = 25.5 cm into Eq. (1), the seismic equivalent stiffness K_{eq} could be calculated as Eq. (24).

$$K_{eq} = k_f + \frac{{}_s\delta_y}{\delta_{\max}} k_s = 22209 + \frac{3}{25.5} \times 177891 = 43496 \quad \text{kN/m} \tag{24}$$

Therefore, the seismic equivalent period could be obtained as Eq. (25) by Eq. (2), when the deformation of isolation layer $\delta_{\max}$ is 25.5cm.

$$T_{eq} = 2\pi\sqrt{\frac{M}{K_{eq}}} = 2\pi \times \sqrt{\frac{20252}{43496}} = 4.3 \quad \text{s} \tag{25}$$

STEP 6: Calculate the design criteria of equivalent deformation ratio

According to the design criterion of interlayer deformation angle of superstructure $R_{ueq(\mathrm{C})}$, the equivalent height of superstructure H_{ueq}, and the maximum deformation of isolation layer without damping δ_0 is shown as Eq. (17). Hence, the design criteria of equivalent deformation ratio δ_{ueq}/δ_0 could be calculated as Eq. (26).

$$\frac{\delta_{ueq}}{\delta_0} = \frac{R_{ueq} \cdot H_{ueq}}{\delta_0} = \frac{1/300 \times 1500}{172} = 0.029 \tag{26}$$

STEP 7: Read the range of equivalent period ratio

The design criteria of equivalent deformation ratio are represented by dot-and-dash line In Fig. 11. From this figure, it could be confirmed that the range of equivalent period ratio T_{eq}/T_u should be approximately 2.5 or above, to make the equivalent deformation ratio equal to or smaller than the design criteria, based on α_s/α_0 = 0.14.

STEP 8: Calculate the natural period of superstructure when foundation is fixed

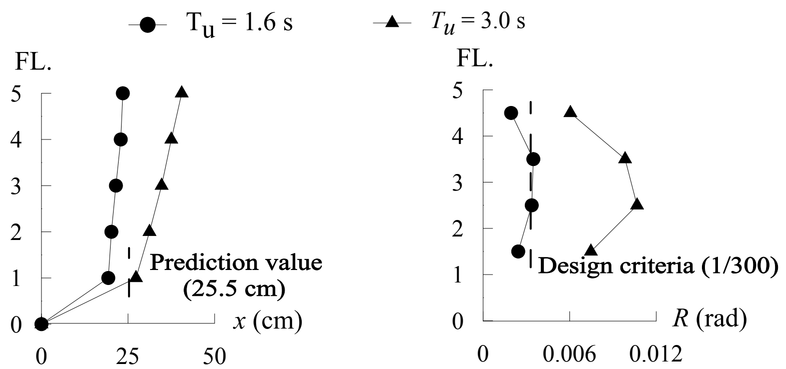
According to the range of seismic equivalent period T_{eq} and equivalent period ratio T_{eq}/T_u of Eq. (25), the range of upper natural period with fixed foundation could be calculated by the following equation.

$$T_u \le \frac{T_{eq}}{2.5} = \frac{4.3}{2.5} = 1.7 \quad \text{s} \tag{27}$$

5.3 Verification and comparison by time history response analysis

Using the model, with the period of isolators only T_f = 6.0 s, the natural period of superstructure with fixed foundation T_u = 1.6 s, and the yield shear coefficient of hysteresis dampers α_s = 0.027, the input earthquake motion with V_E = 180 cm/s is used. Figure 11 shows the result of time history response analysis (○ in the figure). The resultof case T_u = 3.0 s is also shown for comparison (△ in the figure). From the figure, we could know that the equivalent deformation ratio δ_{ueq}/δ_0, in the case ofthe natural period of superstructure (fixed foundation) T_u= 1.6s, satisfies the design criteria. Contrarily, it could also be confirmed that the equivalent deformation ratio δ_{ueq}/δ_0 in T_u = 3.0 s does not satisfy the design criteria.

The maximum response displacement distribution in vertical direction of each layer and the maximum interlayer deformation angle of superstructure is shown in Fig 12. From this figure, it could be confirmed that the maximum deformation of isolation layer is close to the predicted value of models with natural period of superstructure (fixed foundation) T_u = 3.0 or 1.6 s. Contrarily, with the natural period of superstructure (fixed foundation) T_u decreasing from 3.0s to 1.6s,the maximum interlayer deformation angle of superstructure reduces from 1/287 to 1/515. From the results above, by using the natural period of superstructure (fixed foundation) T_u, obtained from thepreviously shown method, the maximum deformation of isolation layer and the maximum interlayer deformation angle of superstructure satisfying the design criteria could be confirmed. Besides, the energy absorption ofsuperstructure (with T_u=3.0s and 1.6s) is 16.31% and 6.84% respectively.



(a) Maximum response displacement x(b)Maximum interlayer deformation angle$R$

Fig. 12 – Vertical distribution

6. Conclusion

In this paper, for the base-isolated building with based isolation layer consisting of natural rubber-based laminated rubber isolators and hysteresis dampers, the ratio betweenthe seismic equivalent period T_{eq} and the natural period of superstructure (fixed foundation) T_u is focused, the prediction formula showing the relationship between equivalent period ratio T_{eq}/T_u and deformation of base-isolated building, was proposed. Moreover, by using the prediction curve based on prediction formula, a design method was demonstrated for determining the natural period of superstructure (fixed foundation),which could satisfy the design criteria of deformation of isolation layer and interlayer deformation angle of superstructure.

When designing the seismic isolation structure based on the energy balance, it is possible to predict the deformation of superstructure without time history response analysis, by using this design method. Furthermore, for any α_s/α_0 from the prediction curve, the relationship between superstructure deformation and maximum deformation of isolation layer could be read, and the range of equivalent period ratio, which makes the equivalent deformation ratio satisfy the design criteria, could be obtained.

7. References

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Appendix 1: Verification of the 1st floor maximum shear force of superstructure Q_{u1}

This appendix shows the verification of Eq. (5) about the 1st floor maximum shear force of superstructure Q_{u1}. If we input 6 types of earthquake motions which were mentioned in section 2.2, the relationship between time history response analytical value and predictive value of the 1st floor maximum shear force of superstructure Q_{u1} is shown in appendix Fig. 1x. According to this figure, the predictive values obtained from Eq. (5) correspond to the analytical values. We could confirm that the variation is small. As mentioned above, we could confirm that it is possible to calculate the 1st floor maximum shear force of superstructure Q_{u1} obtained from Eq. (5).

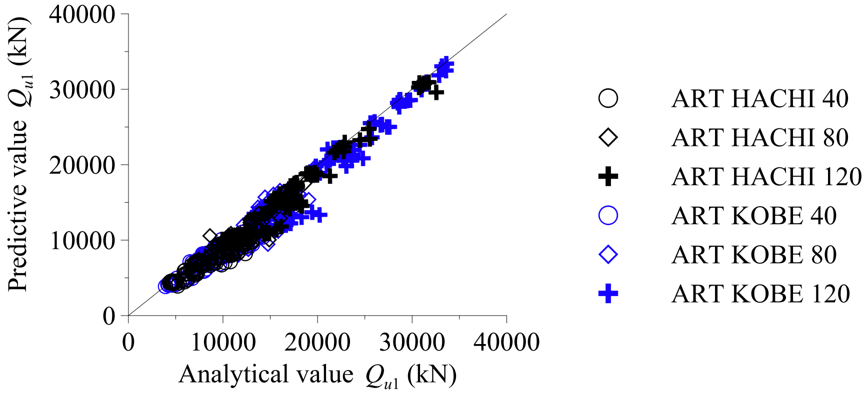

Fig. 1x – Comparison between analytical value and predictive value of Q_{u1}

Appendix 2: Verification of equivalent deformation of superstructure δ_{ueq}

This appendix shows the verification of Eq. (6) about the equivalent deformation of superstructure δ_{ueq}. If we input 6 types of earthquake motions which were mentioned in section 2.2, the relationship between time history response analytical value and predictive value of equivalent deformation of superstructure δ_{ueq} is shown in appendix Fig. 2x. According to this figure, the predictive values that are obtained from the theoretical formula, are almost the same; however, they are relatively bigger than analytical values. Therefore, we could confirm that it is possible to calculate the equivalent deformation of superstructure δ_{ueq} obtained from Eq. (6).

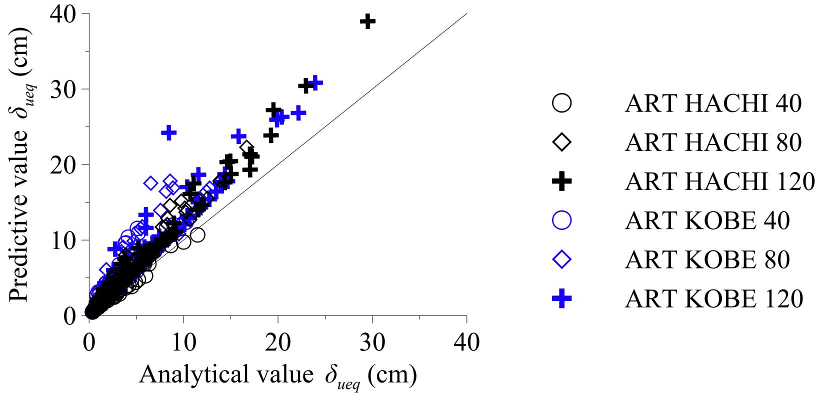

Fig. 2x – Comparison between analytical value and predictive value of δ_{ueq}

