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| Pub. date | 2020, 9 |
| Citation | 2020 17WCEE Proceedings |

# 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 ($\delta_{ueq}/\delta_0$) is proposed according to the $\delta_{ueq}/\delta_{\max}$ ratio and the $\delta_{\max}/\delta_0$ ratio (i.e., based on the energy-balance method). A prediction curve is then proposed according to the yield shear coefficient ratio ($\alpha_s/\alpha_0$) of the hysteresis dampers for seismic layer and the $\delta_{ueq}/\delta_0$ 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: $\alpha_1$ is shear coef. of isolation layer, $\alpha_s$ is yield shear coef. of hysteresis damper, $\alpha_f$ is shear coefficient of isolator, $\alpha_0$ is shear coef. of isolation layer (no damping), $\delta_{\max}$ is max. deformation of isolation layer, $\delta_{ueq}$ is equivalent deformation of superstructure, $\delta_0$ 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.

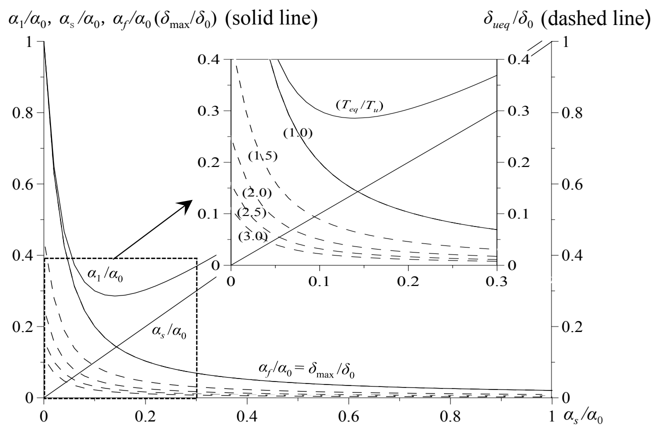



Fig. 1a - Prediction curve of superstructure equivalent deformation

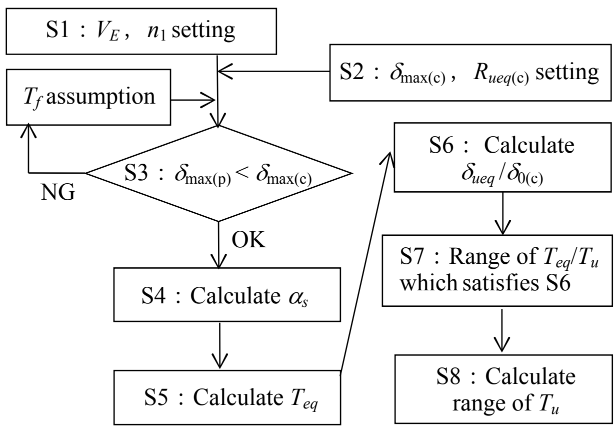



Fig. 2a - Design Steps

# 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

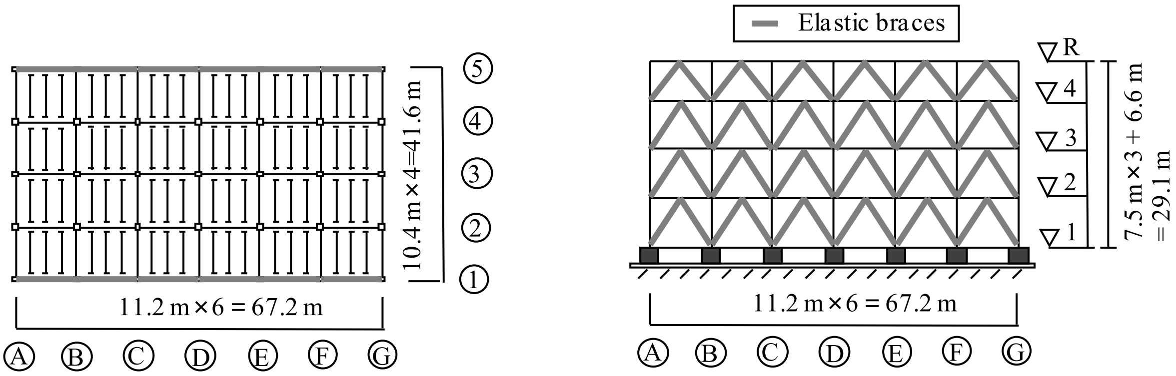
## 2.1 Outline of the analysis model

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 $\phi$800mm and middle column as $\phi$1000mm, 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 $\delta_{sy}$ 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 $\alpha_s$ 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

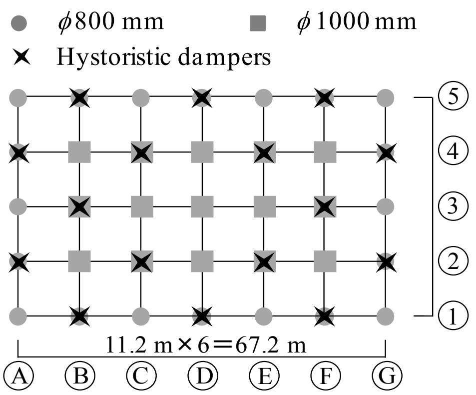
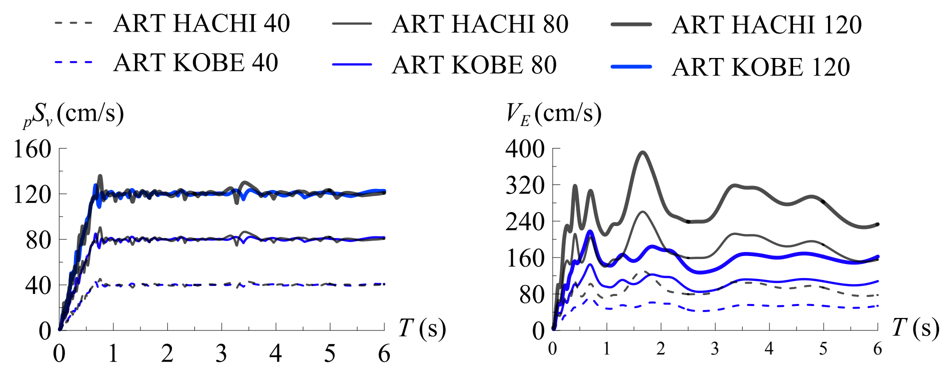



Fig. 2 – Deployment of seismic isolation

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<br>6.0 s |
| Shear coefficient of hysteresis dampers $\alpha_s$ | 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 $\delta_{ueq}/\delta_0$

First, the period of isolators $T_f$, the yield shear coefficient of hysteresis dampers $\alpha_s$, 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 $\delta_{ueq}$ 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.

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

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 $\delta_{ueq}$ and the maximum deformation of isolation layer $\delta_0$ (details given in Section 4.2) without dampers is named as the equivalent deformation ratio $\delta_{ueq}/\delta_0$. The derivation of prediction formula $\delta_{ueq}/\delta_0$ and its validity examination are shown in the next chapter.

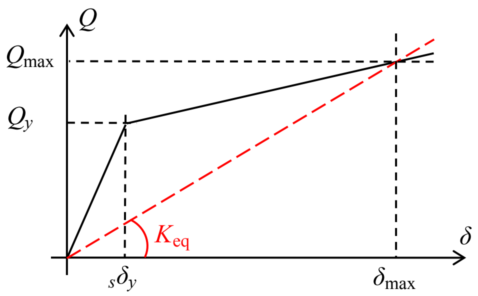



Fig. 4 – Seismic isolation equivalent stiffness

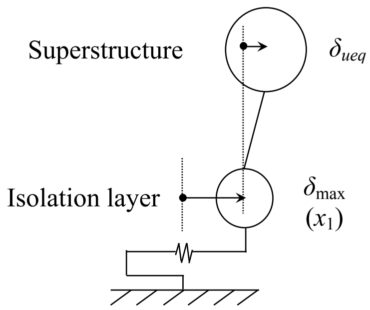



Fig. 5 – Deformation based on mass system

## 4. Proposal of prediction formula of equivalent deformation ratio $\delta_{ueq}/\delta_0$

The equivalent deformation ratio $\delta_{ueq}/\delta_0$ 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 $\delta_{ueq}/\delta_0$ based on the energy balance is proposed. Thereafter, the prediction formula is verified by using the prediction value of equivalent deformation ratio $\delta_{ueq}/\delta_0$, 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 $\delta_{ueq}$ 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 $\delta_{ueq}$ 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.

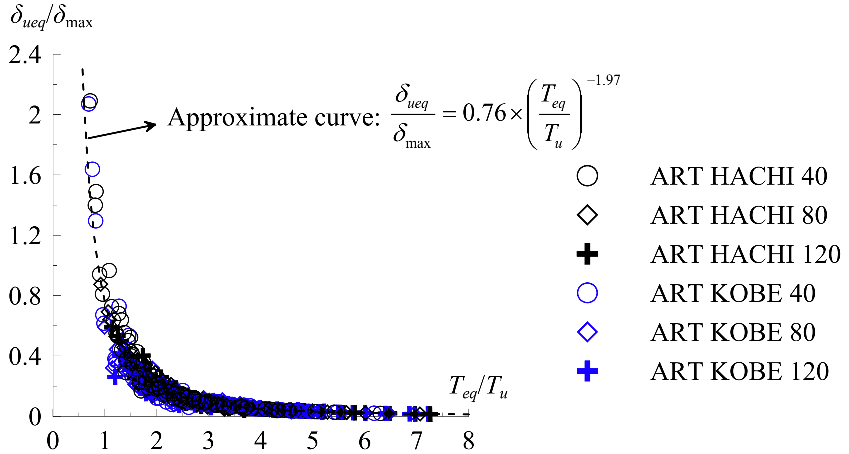



Fig. 6 – Relation between $T_{eq}/T_u$ and $\delta_{ueq}/\delta_{\max}$

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.



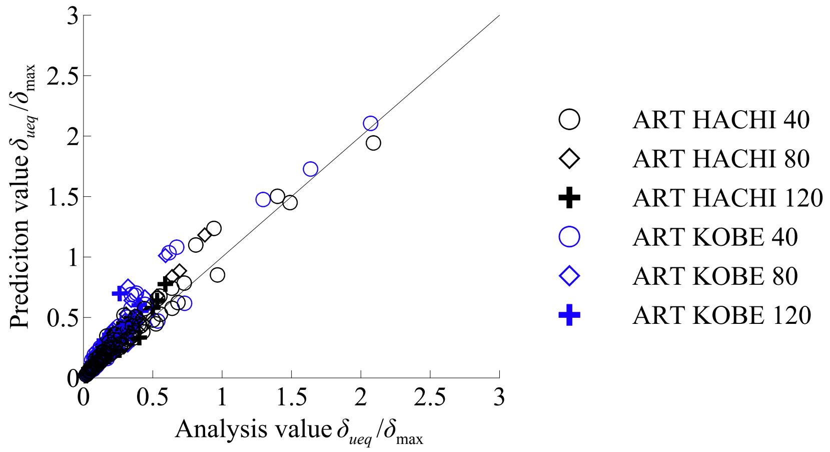



Fig. 7 – Comparison between analysis value and prediction value of $\delta_{ueq}/\delta_{max}$

### 4.2 Prediction method of $\delta_{max}/\delta_0$

Akiyama [8] proposed the following equation, which shows the relationship between the $\delta_{max}/\delta_0$ and the yield shear coefficient ratio of dampers in isolation layer $\alpha_s/\alpha_0$[8], [9].

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

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

Here, $\delta_0$: maximum deformation of isolation layer without dampers and no damping (Eq. (13)), $\alpha_f$: shear coefficient of isolators, $\alpha_0$: 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 $\delta_{max}$ 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 $\delta_{ueq}/\delta_0$ is expressed as Eq. (15).

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

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 $\delta_{ueq}$ is equal to the maximum deformation of isolation layer $\delta_{max}$, 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 $\alpha_s$ are changed because of different input earthquake motions. The comparison between the prediction value of equivalent deformation ratio $\delta_{ueq}/\delta_0$, 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 dampers$\alpha_0$ (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 |



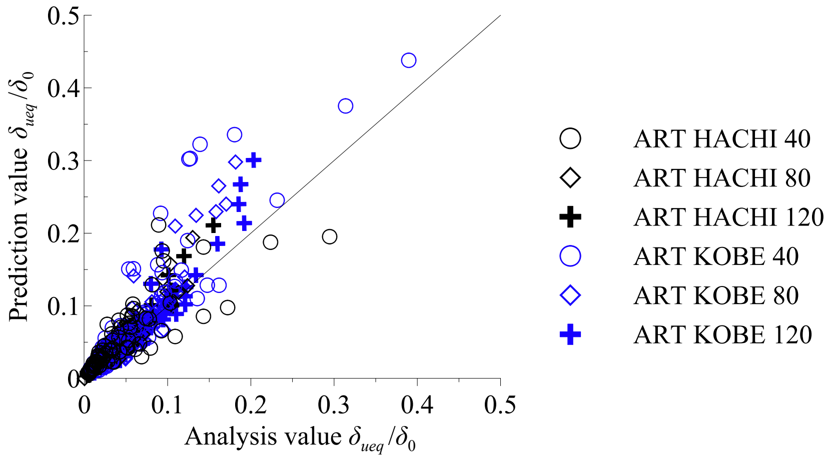



Fig. 8 – Comparison between analysis value and prediction value of $\delta_{ueq}/\delta_0$

According to the figure, the variety of equivalent deformation ratio $\delta_{ueq}/\delta_0$ 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 $\delta_{ueq}/\delta_0$ 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 $\alpha_s/\alpha_0$ as parameters, the prediction curve of equivalent deformation ratio $\delta_{ueq}/\delta_0$ 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 $\alpha_s/\alpha_0$ are set as parameters. The solid line in the figure shows the relationship between the yield shear coefficient ratio of hysteresis dampers $\alpha_s/\alpha_0$ and the shear coefficient ratio of isolators $\alpha_f/\alpha_0$ (left vertical axis). The dashed line represents the relationship between $\alpha_s/\alpha_0$ and the equivalent deformation ratio $\delta_{ueq}/\delta_0$(right vertical axis) based on different parameter, equivalent period ratio $T_{eq}/T_u$. Here, $\alpha_1/\alpha_0$ 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 $\alpha_f/\alpha_0$ is equaled to the maximum deformation ratio of isolation layer $\delta_{max}/\delta_0$ (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 $\delta_{max}/\delta_0$ according to the change of yield shear coefficient ratio of hysteresis dampers $\alpha_s/\alpha_0$, 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 $\delta_{ueq}/\delta_0$ decreases as the yield shear coefficient ratio of hysteresis dampers $\alpha_s/\alpha_0$ increases. Furthermore, it could be confirmed that the equivalent deformation ratio $\delta_{ueq}/\delta_0$ 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 $\delta_{ueq}$ and the maximum of isolation layer $\delta_{max}$ could be obtained, towards the yield shear coefficient ratio of one certain hysteresis dampers $\alpha_s/\alpha_0$ 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.

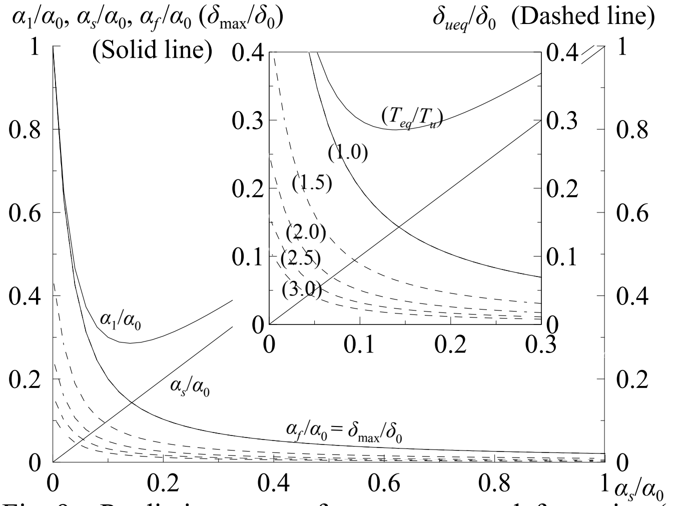


Fig. 9 – Prediction curve of superstructure deformation ($n_1$ = 6)

## 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.

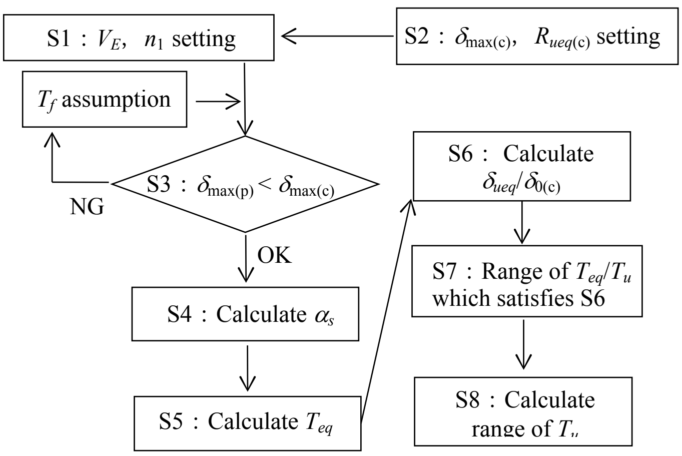


Fig. 10 – Design steps

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 $\alpha_1/\alpha_0$ comes to the minimum value, $\alpha_s/\alpha_0$= 0.14, and $\alpha_f/\alpha_0$= 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 $\delta_0$ 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 $\alpha_f/\alpha_0$ (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 $\delta_{\max(\mathrm{P})}$ exceeds the seismic isolation criteria $\delta_{\max(\mathrm{C})}$, the period of isolators $T_f$ shortened, then the maximum deformation of isolation layer should be recalculated back from STEP 3.

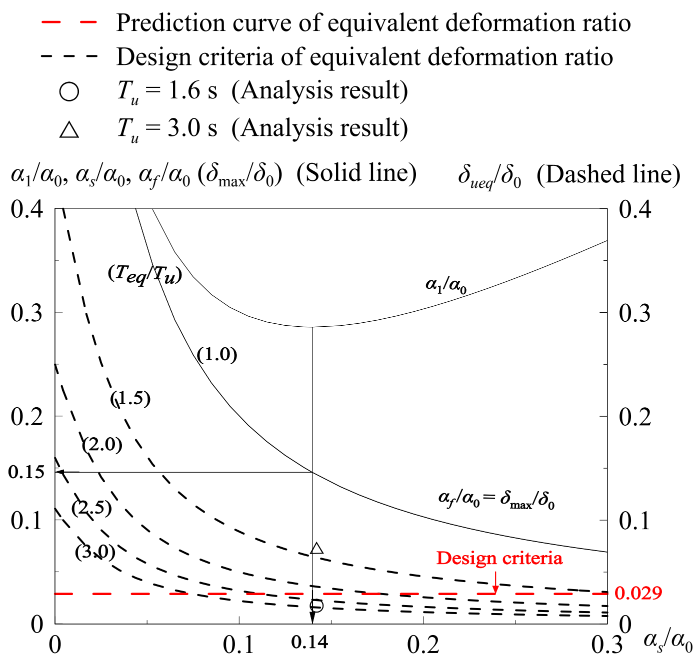


Fig. 11 – Prediction results and curve ($n_1$ = 6)

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

The shear coefficient of isolation layer without dampers $\alpha_0$ 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 $\alpha_1/\alpha_0$ comes to the minimum value, $\alpha_s/\alpha_0$ = 0.14 (Fig. 11), the yield shear coefficient of hysteresis dampers $\alpha_s$ 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 $R_{ueq(C)}$, the equivalent height of superstructure $H_{ueq}$, and the maximum deformation of isolation layer without damping $\delta_0$ is shown as Eq. (17). Hence, the design criteria of equivalent deformation ratio $\delta_{ueq}/\delta_0$ 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 $\alpha_s/\alpha_0$ = 0.14.

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

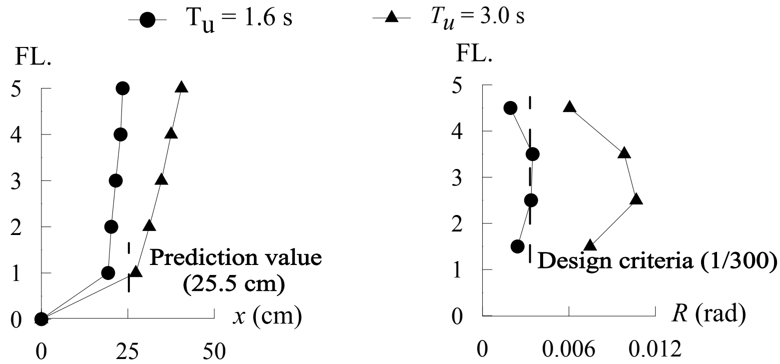
According to the range of seismic equivalent period $T_{eq}$ and equivalent period ratio $T_{eq}/T_u$ of Eq. (25), the range of upper natural period with fixed foundation could be calculated by the following equation.

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

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 $\alpha_s$ = 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 $\delta_{ueq}/\delta_0$, 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 $\delta_{ueq}/\delta_0$ 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 $\alpha_s/\alpha_0$ 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.

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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).

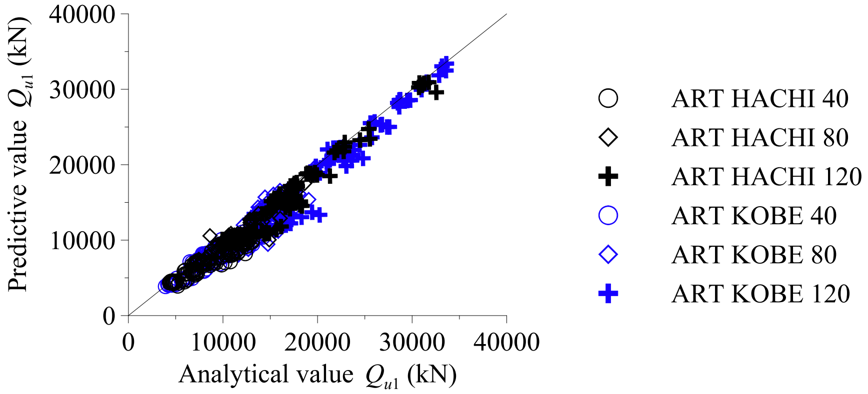


Fig. 1x – Comparison between analytical value and predictive value of $Q_{u1}$

## Appendix 2: Verification of equivalent deformation of superstructure $\delta_{ueq}$

This appendix shows the verification of Eq. (6) about the equivalent deformation of superstructure $\delta_{ueq}$. 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 $\delta_{ueq}$ 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 $\delta_{ueq}$ obtained from Eq. (6).

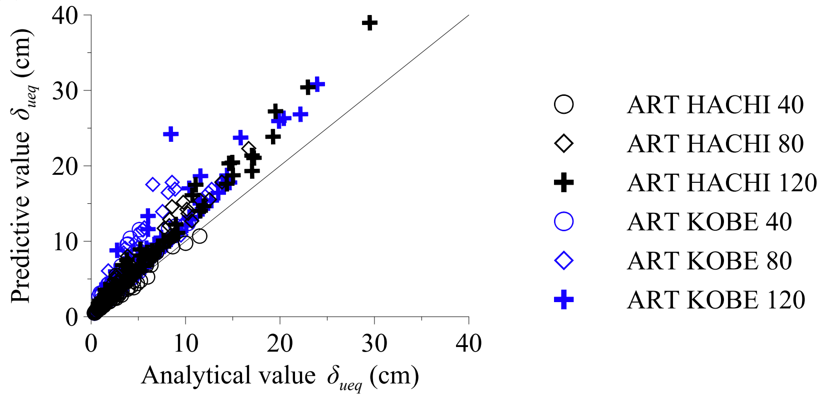


Fig. 2x – Comparison between analytical value and predictive value of $\delta_{ueq}$



 