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Pub. date	2020, 11
Citation	Proceedings of the 15th Annual Meeting of Japan Association for Earthquake Engineering



ENERGY BASED DESIGN METHOD FOR ISOLATED BUILDING CONSIDERING STIFFNESS DISTRIBUTION OF SUPERSTRUCTURE

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ABSTRACT: The number of logistics with seismic isolated system has increased. Fu and Sato et al. proposed a design method (called energy method¹⁾) which considered the isolation equivalent period ratio based on the energy balance. But energy method did not confirm whether the balance between the superstructure and isolation layer can be applied to the buildings with various layer stiffness distributions. In this paper, we consider the stiffness distribution of the superstructure based on the energy method.

Keywords: Isolated Building, Energy Based Design Method, Stiffness Distribution

1. INTRODUCTION

Seismic isolation systems have been applied to buildings with the long 1st mode natural period of superstructures, which can be designed these years. The expansion of the internet market supplies leads to the number of warehouses built. Due to the Tohoku Earthquake in 2011, there were increasing cases of adopting seismic isolation structures to the steel-framed warehouses. These warehouses are designed with long spans and high floor height due to the need of internal spaces. When seismic isolation structures are adopted for such buildings, the difference between the period of the superstructure and the isolation layer decreases, so the effect of the isolation layer may not be fully exhibited.

Fu and Sato et al. proposed a design method for designing seismic isolated buildings that can obtain the appropriate range of the period of superstructure to satisfy the design criteria¹⁾. This is a method of predicting the deformation of superstructure in a seismic isolated building by using the ratio of the equivalent period of seismic isolated layer to the 1st natural period of superstructure based on the energy balance. However, the energy method¹⁾, proposed by Fu and Sato et al., did not confirm whether the balance between the superstructure and isolation layer can be applied to buildings with various layer stiffness distributions, because only the natural period of superstructure and the seismic isolation equivalent period ratio are considered.

Therefore, in this paper, we propose a new design method (refer to Fig. 1) so that the stiffness distribution of the superstructure can be taken into the consideration based on the energy method of Fu and Sato et al.

2. DESIGN METHOD

In this chapter, a new design method considering the stiffness distribution of the superstructure based on the energy method will be introduced.

2.1 Design Flow

The design flow is shown as Fig. 1. The initial condition is set with the total mass M , and the height of the superstructure H_u . The input motion and the design criteria, can be determined from Step 0 to 2. Then the shear force coefficient of hysteresis damper α_{sy} can be calculated in Step 4 and 5. The equivalent period T_{eq} can be obtained by using α_{sy} , and the ratio of equivalent period T_{eq}/T_u in Step 6 and 7. After initially determined the 1st mode period and the stiffness distribution of superstructure T_u and k_i (Step 8), the story shear force coefficient in vertical distribution of superstructure can be calculated by the response amplification factor a in Step 9, comparing between the maximum interlayer deformation angle and the design criteria in Step 10. If the prediction value is greater than the criteria value, it is necessary to correct the stiffness distribution of superstructure by stiffness correction factor β_{ki} in Step 11. The details is described from Section 2.2.

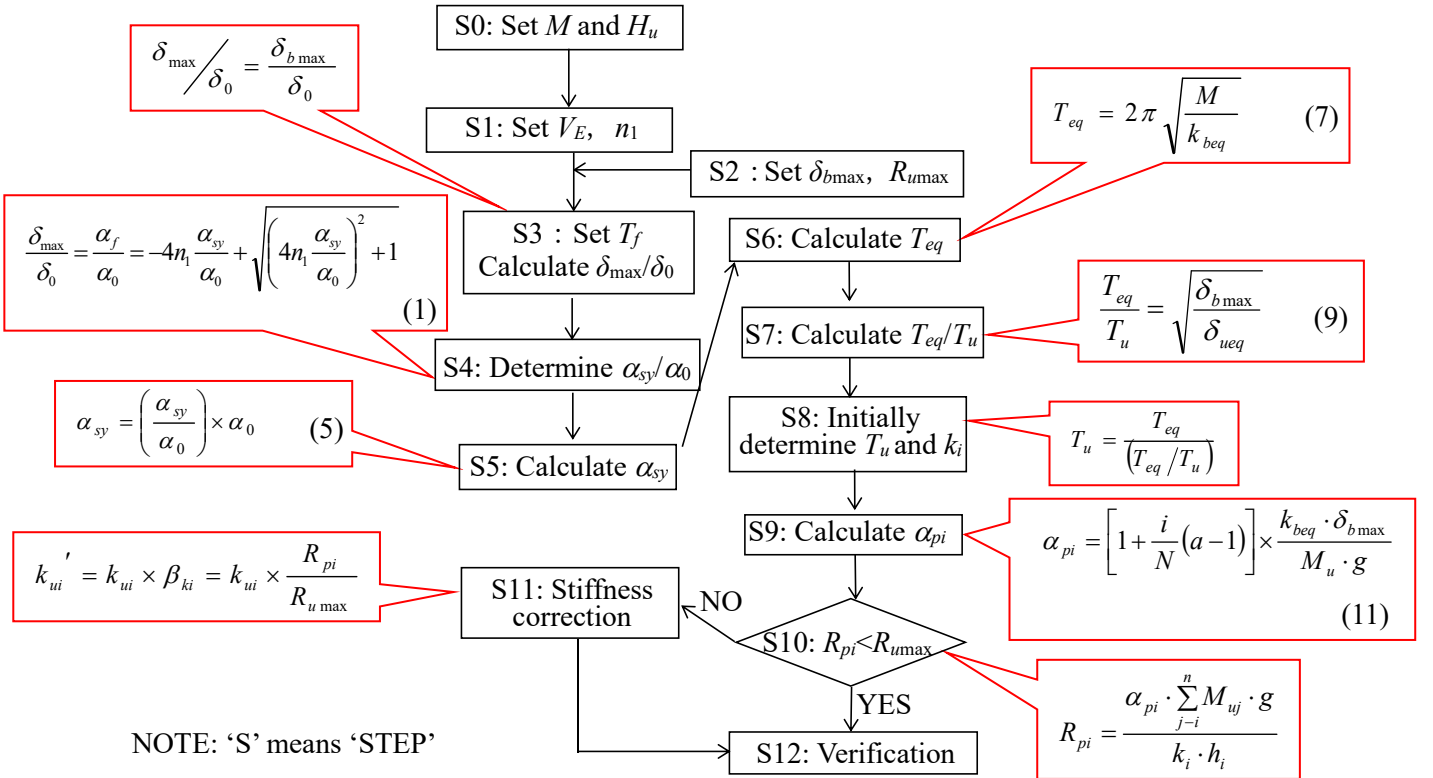


Fig. 1 Design flow

2.2 Energy Balance Method

Akiyama proposed the Eq. (1)²⁾, which shows the relation between the δ_{max}/δ_0 and the yield shear coefficient ratio of dampers in isolation layer α_{sy}/α_0 ^{2), 3)}.

$$\frac{\delta_{bmax}}{\delta_0} = \frac{\alpha_f}{\alpha_0} = -4n_1 \frac{\alpha_{sy}}{\alpha_0} + \sqrt{\left(4n_1 \frac{\alpha_{sy}}{\alpha_0}\right)^2 + 1} \quad (1)$$

$$\delta_0 = \frac{T_f \cdot V_E}{2\pi}, \quad \alpha_0 = \frac{2\pi \cdot V_E}{T_f \cdot g} \quad (2), (3)$$

Here, δ_0 : maximum deformation of isolation layer without dampers and no damping (Eq. (2)), α_0 : shear coefficient of isolation layer without dampers and no damping (Eq. (3)), α_f : shear coefficient of isolators, n_1 : number of equivalent hysteresis loop, V_E : equivalent velocity of total energy input.

Based on Eq. (1), Fig. 2 shows the prediction curve. The black solid line in Fig. 2 shows the relation between the yield shear coefficient ratio of hysteresis dampers α_{sy}/α_0 and the shear coefficient ratio of isolators α_f/α_0 . Here, α_1/α_0 (blue dash line) is the total shear coefficient ratio of isolation layer, which is expressed by a concave curve as Eq. (4). By using Fig. 2, the yield shear coefficient ratio of hysteresis dampers α_{sy}/α_0 can be obtained. Multiplying α_{sy}/α_0 to α_0 , which obtained from Eq. (3), then the yield shear coefficient of hysteresis dampers α_{sy} can be calculated as Eq. (5).

$$\alpha_1/\alpha_0 = \alpha_f/\alpha_0 + \alpha_{sy}/\alpha_0, \quad \alpha_{sy} = (\alpha_{sy}/\alpha_0) \times \alpha_0 \quad (4), (5)$$

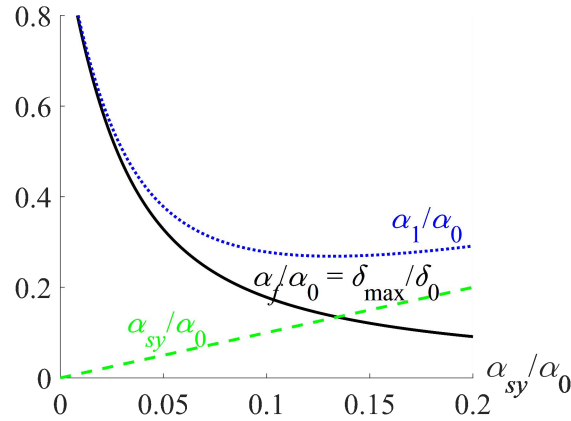


Fig. 2 Prediction curve of superstructure deformation ($n_1 = 6.8$)

Focusing on the dashed line in Fig. 2, it can be confirmed that the equivalent deformation ratio δ_{ueq}/δ_0 decreases as the yield shear coefficient ratio of hysteresis dampers α_{sy}/α_0 increased. By using this prediction curve, the yield shear coefficient ratio of hysteresis dampers α_{sy}/α_0 can be obtained, towards δ_{bmax}/δ_0 instead of the period of isolators T_f and the V_E of input earthquake motion.

2.3 Definition of Equivalent Period Ratio T_{eq}/T_u

In this chapter, the equivalent period T_{eq} and the equivalent deformation of superstructure δ_{ueq} mentioned in step 6 and 7 is introduced. As shown in Fig. 3, k_{eq} is the isolation equivalent stiffness when the deformation of isolation layer reaches the maximum, which is calculated by Eq. (6). The equivalent period T_{eq} is the period based on the equivalent stiffness k_{eq} , which is calculated by Eq. (7). The definition of superstructure and the deformation of isolation layer based on mass system are shown in Fig. 4. 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. (8). The middle floor is defined as the floor that is the closest to the half-height of superstructure.

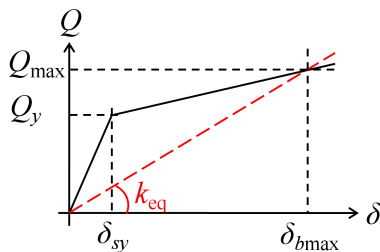


Fig. 3 Seismic isolation equivalent stiffness

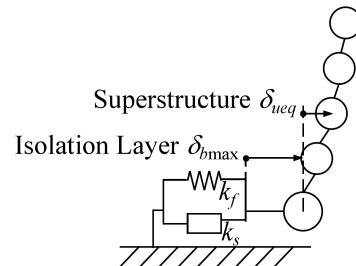


Fig. 4 Deformation based on mass system

According to the reference 1), the relation between the equivalent period T_{eq} and the natural period

of superstructure T_u can be calculated as the root of the ratio of the maximum deformation of isolation layer $\delta_{b\max}$ and the equivalent deformation of superstructure δ_{ueq} , which is shown as Eq. (9).

$$k_{eq} = k_f + \frac{\delta_{sy}}{\delta_{b\max}} \cdot k_s, \quad T_{eq} = 2\pi \sqrt{\frac{M}{k_{eq}}} \quad (6), (7)$$

$$\delta_{ueq} = x_M - x_1, \quad \frac{T_{eq}}{T_u} = \sqrt{\frac{\delta_{b\max}}{\delta_{ueq}}} \quad (8), (9)$$

Here, k_f : stiffness of isolators, k_s : initial stiffness of hysteresis dampers, δ_{sy} : yield deformation of hysteresis dampers, $\delta_{b\max}$: 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 the base-isolated structure, δ_{ueq} : equivalent deformation of superstructure.

2.4 Distribution of Story Shear Coefficient

Liba et al. indicated that the larger the response amplification in the superstructure is, the larger the difference between the story shear force coefficient (calculated by the Energy Method) and the layer shear force coefficient obtained by the response analysis. And there is one evaluation method for layer shear force coefficients which is called the Coefficient Amplification Method⁴.

As shown in Eq. (10), one method for calculating the story shear force coefficient of the top layer α_R is to multiply the story shear force coefficient of the isolation layer C_{r0} calculated by the energy method using the response amplification factor a , according to reference 4).

If we set the response amplification factor of the isolation layer as 1.0 and trapezoidal distribute it in vertical direction. In which way, as shown in Eq. (11), we can obtain the story shear force coefficient of the other stories α_{pi} by the response amplification factor of the certain story. The validity results of story shear coefficient design method can be referred from Appendix B.

$$\alpha_R = C_{r0} \times a, \quad \alpha_{pi} = \left[1 + \frac{i}{N} (a - 1) \right] \times \frac{k_{eq} \cdot \delta_{b\max}}{M_u \cdot g} \quad (10), (11)$$

2.5 Stiffness Correction factor β_{ki}

In this amplification method, when aiming at enhancing the stiffness of superstructure which was calculated by the energy balance, we can use the prediction value of interlayer deformation angle to obtain stiffness correction factor β_{ki} .

As shown in Eq. (12), β_{ki} can be calculated by the prediction value of interlayer deformation angle R_{pi} for each story. Besides, in the case of $R_{pi} \leq R_{u\max}$, the factor β_{ki} would be adopted as 1.0, which represents no correction for stiffness.

$$\beta_{ki} = \begin{cases} \frac{R_{pi}}{R_{u\max}} & (R_{pi} > R_{u\max}) \\ 1 & (R_{pi} \leq R_{u\max}) \end{cases} \quad (12)$$

3. DESIGN EXAMPLE

3.1 Analytical Model

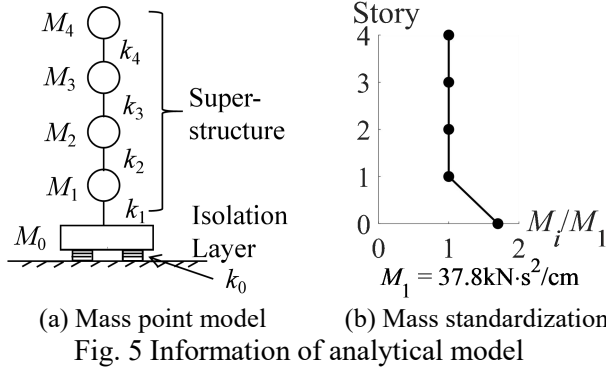
A four-story steel-frame warehouse is used as the mode in this paper. The height of each superstructure story is 7.5m from the 1st to the 4th floor. It is assumed of the building with different stiffness distribution. The analytical model is shown in Fig. 5(a). In this paper, the average density of

the superstructure $\rho = 180 \text{ kg/m}^3$. The mass of isolation layer M_0 is set to be 1.7 times of the first floor M_1 . Fig. 5(b) shows the mass distribution standardized by the mass of the first floor. In vertical axis, Floor 1 to 4 represents the superstructure and Floor 0 represents the isolation layer. In addition, the stiffness of each layer k_i ($i = 1$ to 4) is calculated as Eq. (13)⁵⁾, so that the mode displacement ϕ_i of the 1st natural period of superstructure T_u becomes the straight line. The isolation layer is composed of a group of isolators with linear stiffness k_f and a group of historical dampers with initial stiffness k_s . The initial stiffness of the isolation layer k_0 can be calculated as Eq. (14). The superstructure and isolators are elastic, and the damper is completely elasto-plastic (restoring force characteristics: yield shear force coefficient α_{sy} , yield deformation δ_{sy}). The initial stiffness proportional damping with $h = 2\%$ to T_u is given only to the superstructure.

For the design method of this paper, the initial conditions are shown in Table 1, besides the initial conditions of input motion (n_1 and V_E) can be referred to Section 3.2.

$$\begin{cases} k_N = \frac{\omega_u^2 \times M_N \times \phi_N}{\phi_N - \phi_{N-1}} \\ k_i = \frac{\omega_u^2 \times M_i \times \phi_i + K_{i+1} \times (\phi_{i+1} - \phi_i)}{\phi_i - \phi_{i-1}} \quad (i = 2 \dots N-1) \\ k_1 = \frac{\omega_u^2 \times M_1 \times \phi_1 + K_2 \times (\phi_2 - \phi_1)}{\phi_1} \end{cases} \quad , \quad k_0 = k_s + k_f \quad (13), (14)$$

Here, ω_u : the natural frequency of superstructure, N : the number of story, ϕ_i : the first linear mode ($\phi_i = i$), M_i : the mass of i -th floor.



Parameter	Value
Total mass	215.46 kN·s ² /cm
Height of superstructure H_u	30 m
Natural period of isolators T_f	3.0, 4.0, 5.0, 6.0s
Maximum deformation of isolation layer δ_{bmax}	30, 40, 50, 60cm
Maximum interlayer deformation angle R_{umax}	1/300

3.2 Input Seismic Motion

The input seismic motion is used as the HACHINOHE (1968) EW component as the phase characteristic, and it is a notification wave in which the pseudo-velocity response spectrum pS_v ($h = 5\%$) becomes constant at 80 cm/s after the corner period (which is called ART HACHI). Fig. 6 shows the time-history of acceleration, pseudo-velocity response spectrum pS_v ($h = 5\%$) and the energy spectrum V_E ($h = 10\%$). In the design method of this paper, the average value of the number of equivalent hysteretic loop $n_1 = 6.8$ and the equivalent velocity of total energy input $V_E = 191 \text{ cm/s}$ are used.

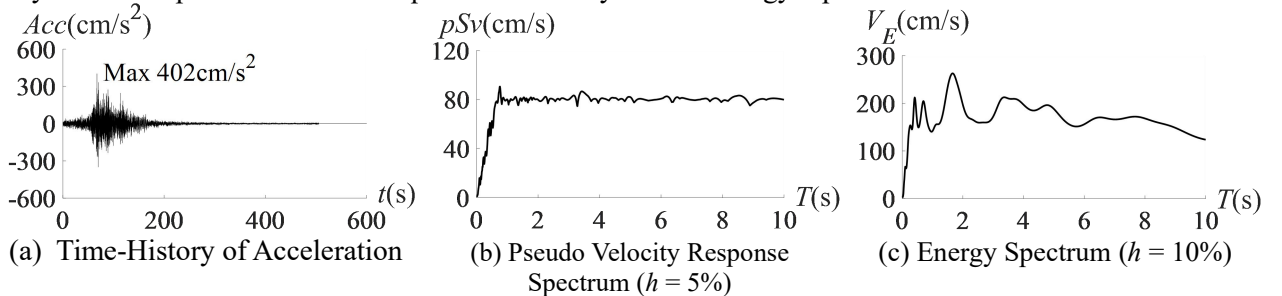
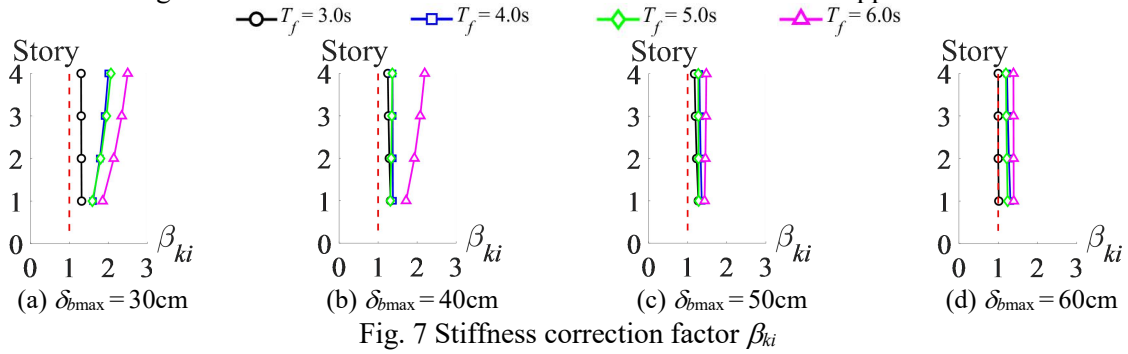


Fig. 6 Analysis input earthquake

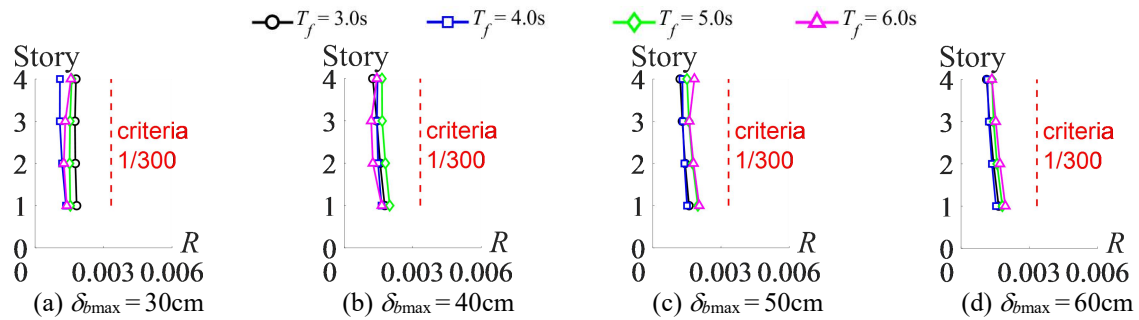
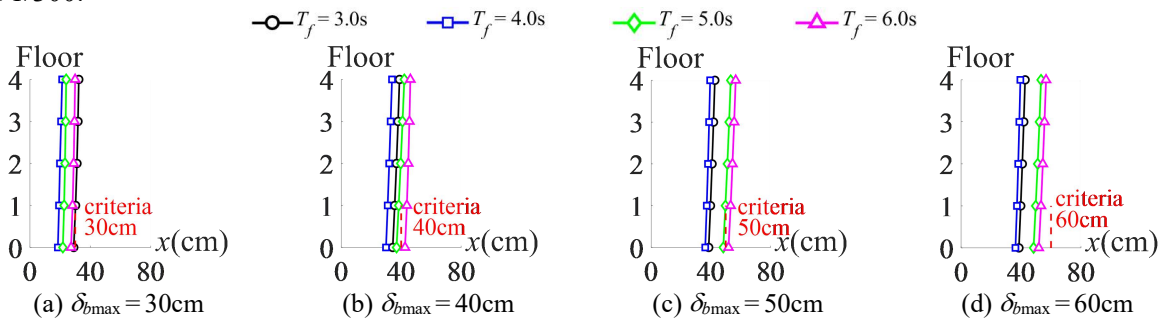
3.3 Results of Stiffness Correction Factor β_{ki}

The results of the stiffness correction factor β_{ki} are shown. The parameter is the period of isolator T_f ranging from 3s to 6s. The formula and the theory can be referred from Section 2.5. According to Fig. 7, it is necessary to correct the stiffness distribution of superstructure for which the prediction value overpasses 1.0. And with the increasing of T_f , the amplitude of the stiffness correction becomes greater. The design results of the stiffness correction factor a are shown in Appendix A.



4. ACCURACY VERIFICATION

The seismic wave ART HACHI ($V_E = 191$ cm/s, $n_1 = 6.8$) is used as the input motion. Using models with the period isolator group $T_f = 3s \sim 6s$, which were set before the design step, as well as the 1st natural period of the superstructure T_u ranging from 0.8s to 1.4s approximately and yield shear force coefficient of hysterics dampers α_{sy} ranges from 0.005 to 0.02 approximately. Fig. 8 and 9 shows the maximum response displacement of each layer and the maximum interlayer deformation angle in vertical distribution of the superstructure, respectively. The target criteria of the deformation of isolation layer range from 30cm to 60cm, and the target criteria of interlayer deformation angle of each story in the superstructure is set as 1/300. From the figure, we can know that almost of the analytical results of the isolation layer deformation is very closed to the design criteria and at the safe side. Besides, the analytical results of the interlayer deformation angle of each story are also at the safe side of 1/300.



5. CONCLUSION

In this paper, we proposed a new design method to the energy method, which proposed by Fu and Sato et al. So that the stiffness distribution of the superstructure can be taken into consideration, and submitted one kind of design step for the appropriate superstructure stiffness.

When designing a seismic isolation structure, the maximum deformation of the isolation layer of the seismic isolation building and the maximum interlayer deformation angle of the superstructure can be obtained by using this prediction method.

According to the comparison between the time-history results and the design criteria values, we can know almost the results are at the safe side, so that the feasibility of the Coefficient Amplification Method can be confirmed.

ACKNOWLEDGMENT

This work was supported by JST Program on Open Innovation Platform with Enterprises, Research Institute and Academia (JPMJOP1723), and by JFE Civil Engineering & Construction Corp. and JFE Steel Corp..

APPENDIX:

[A] STIFFNESS CORRECTION FACTOR a

Story	(a) $\delta_{b\max} = 30\text{cm}$				Story	(b) $\delta_{b\max} = 40\text{cm}$			
	$T_f = 3\text{s}$	$T_f = 4\text{s}$	$T_f = 5\text{s}$	$T_f = 6\text{s}$		$T_f = 3\text{s}$	$T_f = 4\text{s}$	$T_f = 5\text{s}$	$T_f = 6\text{s}$
4	1.301	1.999	2.067	2.497	4	1.249	1.368	1.364	2.193
3	1.304	1.906	1.953	2.344	3	1.266	1.371	1.352	2.079
2	1.308	1.781	1.802	2.139	2	1.288	1.374	1.336	1.928
1	1.314	1.606	1.590	1.853	1	1.318	1.379	1.313	1.717

Story	(c) $\delta_{b\max} = 50\text{cm}$				Story	(d) $\delta_{b\max} = 60\text{cm}$			
	$T_f = 3\text{s}$	$T_f = 4\text{s}$	$T_f = 5\text{s}$	$T_f = 6\text{s}$		$T_f = 3\text{s}$	$T_f = 4\text{s}$	$T_f = 5\text{s}$	$T_f = 6\text{s}$
4	1.177	1.301	1.273	1.478	4	1.000	1.225	1.196	1.388
3	1.199	1.315	1.275	1.467	3	1.000	1.245	1.207	1.390
2	1.230	1.334	1.277	1.453	2	1.000	1.272	1.221	1.392
1	1.273	1.359	1.281	1.433	1	1.015	1.310	1.241	1.395

Table A Stiffness correction factor a

[B] VALIDITY OF STORY SHEAR COEFFICIENT

For examining the validity of the Coefficient Amplification Method, we focus on the prediction value and analytical value of story shear coefficient as standardization results to the isolation layer. The analytical value should be obtained by the model before stiffness correction which has been mentioned in Section 2.5.

As shown in Fig. B, the relation between the prediction value and analytical value of story shear coefficient as standardization results. From the figure, we can know that the standardized prediction values of story shear coefficient are at the safe side of the standardized analytical value. The necessary of the stiffness correction by the Coefficient Amplification Method can be confirmed. Therefore we can obtain the validity of the Coefficient Amplification Method.

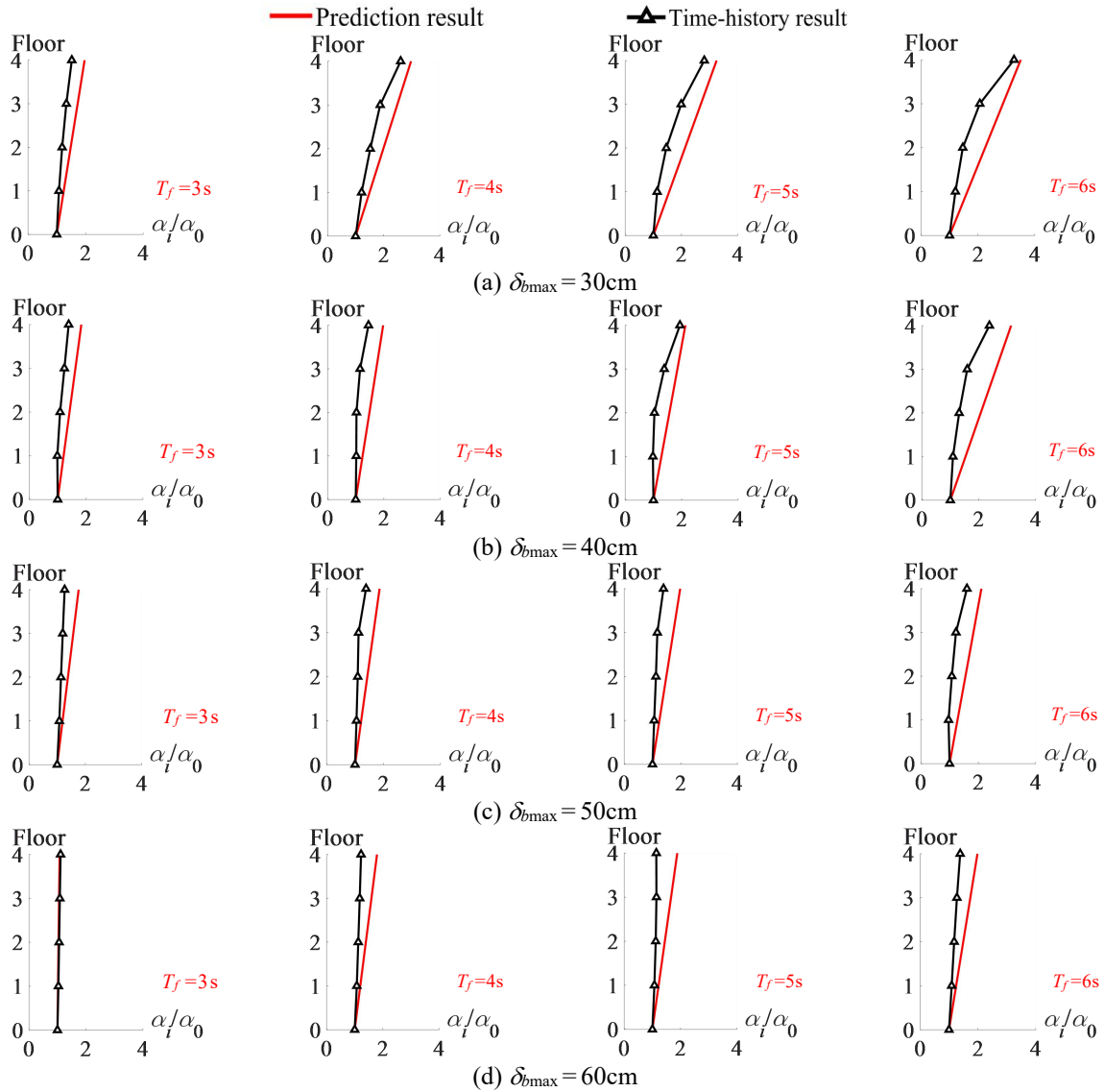


Fig. A Validity of amplification method (ART HACHI)

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