A Study on Vertical Distribution of Shear Force Coefficient for Seismic Design of Seismically Isolated Buildings

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SUMMARY:
This paper proposes an evaluation method of shear force coefficient for seismic design of seismically isolated buildings. This evaluation method is based on earthquake response analyses on seismically isolated -buildings and is obtained from the relationship between vertical distribution of shear force coefficient and response amplification caused by higher-mode responses. In addition, the proposed evaluation method of response amplification is valid for evaluation of overturning moment. Furthermore, this evaluation method is applied to various restoring force model of isolation layer such as Tri-linear or Ramberg-Osgood characteristics by using approximation method. In conclusion, this proposed method evaluates vertical distribution of shear-force coefficient for various kinds of seismically isolated buildings and shows suitable correspondence compared with the results of non-linearity time history analysis.

Keywords: Seismic isolation, Shear force coefficient, Higher modal response, Isolation ratio, Non-linearity factor

1. INTRODUCTION

Since the Hyogoken-Nanbu Earthquake (1995), in Japan, seismic isolation system has been esteemed for structural safety and maintaining of functional capacities. Furthermore, the effects of response reducing of Seismically Isolated (SI-) buildings have been demonstrated in Tohoku-Chiho Taiheiyo-Oki Earthquake (2011), thereby it will possible to spread more and more in the future. Generally, it is ideal for SI-buildings that the superstructure behaves as rigid-body. Therefore, in several countries, there are seismic design codes (UBC, FEMA etc...) using Equivalent Linearizing Analysis Method without Non-linear Time History Analysis (NTHA) for SI-buildings which are modeled as an equivalent single degree of freedom system. Seismic force at i-th mass F_i are calculated as inverted triangle distribution which evaluated by the weight and height distribution of the buildings as follows:

$$F_i = Q_{iso} \cdot w_i \cdot h_i / \sum (w_i \cdot h_i) \tag{1.1}$$

where Q_{iso} is the base shear of isolation layer, w_i is the weight at level i , h_i is the distribution of at that level i. On the other hand, in Japan, the shear force coefficient on the superstructure in the recommendation for design of SI-buildings (AIJ 2001) is as follows:

$$\alpha_i = \alpha_f + a_i \cdot \overline{\alpha}_i \cdot \alpha_s \tag{1.2}$$

where α_i, α_f and α_s are the shear force coefficient of i-th story of SI-buildings, elastomeric isolator and elasto-plastic dampers, respectively. $\overline{\alpha}_i$ is the optimum yield shear force coefficient distribution considered the natural periods and weight distribution. α_i is given by Eq.1.3. Where N is the number of structure story, $\overline{a}$ is given by Eq.1.4.

$$a_i = \{(\bar{a}-1)/(N-1)\}i + (N-\bar{a})/(N-1) \tag{1.3}$$

$$\begin{aligned} \bar{a} &= 3.1238 - 0.1238 b_s & 1 \le b_s < 10 \\ \bar{a} &= 2.0127 - 0.0127 b_s & 10 \le b_s < 80 \\ \bar{a} &= 1.0 & 80 \le b_s \end{aligned} \tag{1.4}$$

where b_s is the ratio of horizontal stiffness of the first story of superstructure in base fixed condition to that of dampers in isolated condition ($=k/k_s$,). However, Japanese design code for SI-buildings (MVIT 2001) is as follows:

$$\alpha_i = \gamma \cdot \frac{Q_{iso}}{M \cdot g} \cdot \frac{A_i(Q_h + Q_v) + Q_e}{Q_h + Q_v + Q_e} \tag{1.5}$$

where M is the total mass of the structure, g is the gravitational acceleration, γ is the multiplier including the effects of aging, temperature and property dispersion by manufacturing, Q_e, Q_h and Q_v is shear force of elastomeric isolators, elasto-plastic dampers and fluid dampers, respectively. A_i is the optimum yield shear force coefficient distribution. It is a characteristic point compared with the standard of other countries, this standard is enable to design SI-buildings up to 60meters in height. However, it has been pointed out that the above-mentioned method likely underestimates the seismic response (M.Takayama et al. 2002). The following cases are more possibility; 1) Superstructure doesn't behave as rigid-body. 2) Seismic isolator has high-stiffness, it has been confirmed that higher-mode responses is generated. In other words, seismic forces and floor accelerations of the superstructure are amplified more than ideal isolation system. This phenomenon counteracts the purpose of isolation system. Thus, this paper proposes a response amplification factor β_i considering higher-mode responses to evaluate the seismic response properly.

2. VERTICAL DISTRIBUTION OF LATERAL SHEAR FORCE COEEFICIENT

This section shows an evaluation method for the response amplification of shear force coefficient distribution of SI-building. The degree of amplification is calculated from a large number of Non-linearity Time History Analyses (NTHA) and is formulated by measure which evaluates the structural characteristics. The proposed method shows suitable correspondence compared with the results of NTHA.

2.1. Non-linear Time History Analysis

A large number of NTHA is carried out on 10-story shear-type model with Bi-linear restoring force model as seismic isolation layer. Firstly, superstructure is decided as base fixed model, the mass at each story is set to 1,000 tons, story stiffness distribution is decided as 1/2 ratio trapezoid. The first natural period T_0 is set to 0.2-1.6sec. Resisting force characteristics of superstructure is linear. The initial structural damping is applied using stiffness-proportional damping and the first mode damping ratio is set to 0.02. Then, as isolated model, the position of isolation layer is set to first story. Isolation layer which is composed of elastomeric isolator and elasto-plastic hysteresis dampers. Lateral stiffness of elastomeric isolator k_f is calculated from the isolation period T_f which is set to 4.0sec. Lateral stiffness of hysteresis damper is k_s ($k_s=Q_y/\delta_y$), Q_y as the yield strength of hysteresis damper is given by shear coefficient of damper α_s which is set to 0.01-0.10 by each 0.01. δ_y as the yield displacement of hysteresis damper is 0.1, 1.0 and 3.0 cm. These models and parameters are shown in Table.2.1 and Fig.2.1. Then input earthquakes are artificial earthquake ground motions for design which considered site amplification factor Gs corresponds to 1.23(const.), 1st class and 2nd class in Japanese seismic code. Fig.2.2 shows acceleration response spectrum of artificial earthquake ground motions when Gs is assumed 2nd class. The analysis results are shown in Fig.2.3. As the amount of dampers α_s and the natural periods of the superstructure are increasing, the distribution of shear coefficient is amplified. Especially, it is remarkable in the middle floors over the 4-th floor.

Table 2.1. Structure model and analysis parameters.

Structure model		Analysis parameters (5,940 patterns)	
Analysis model	10-story shear model	Shear coefficient of damper α_s	0.01-0.10 (by each 0.01)
Mass distribution	Each 1,000 [ton]	Yield displacement of hysteresis damper δ_y	0.1, 1.0, 3.0 [cm]
Stiffness distribution	1/2 ratio trapezoid.	Natural periods of superstructure base-fixed condition T_o	0.2, 0.24, 0.28, 0.32, 0.36, 0.4, 0.5, 0.6, 0.8, 1.2, 1.6 [sec]
Restoring characteristics	Elastic (h=2%)	Input earthquakes	Artificial earthquake ground motions for design
Restoring characteristics of Isolation devises	Isolator: elastic Damper: Normal Bi-linear	Phase characteristics	Ramdom pahse×3, Elcentro (1940) NS phase, Hahinohe (1968) EW phase, Kobe (1995) NS phase
Periods of Isolation	4.0 [sec]	Site amplification factor Gs	1.23(const.), 1st class, 2nd class,

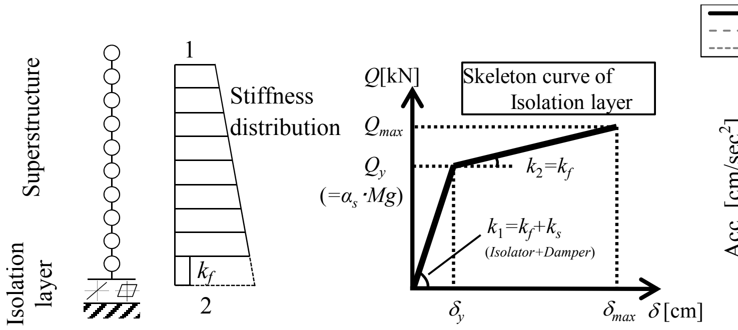

Figure 2.1. Structure model and characteristics of isolation layer

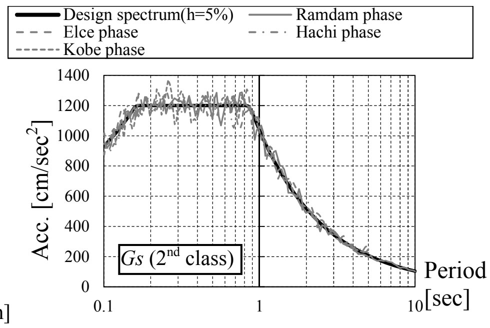

Figure 2.2. Response spectrum (Acc.)

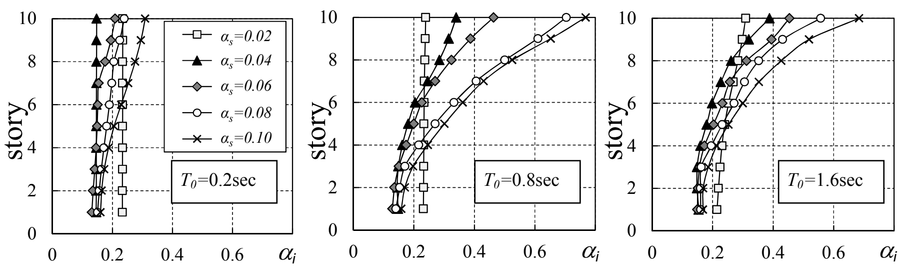

Figure 2.3. Maximum response of shear force coefficient

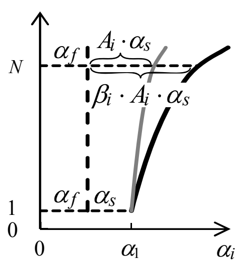

Figure 2.4. Composition of α_i

2.2. Amplification Factor β_i

In the cases of using hysteresis damper, shear coefficient distribution is represented by the following equation which is adopted by the form of Eq.1.5:

$$\alpha_i = \alpha_f + \beta_i \cdot A_i \cdot \alpha_s \tag{2.1}$$

where β_i is a amplification factor for A_i distribution which gives a correct distribution of response amplification by hysteresis damper. If β_i equals 1, Eq.2.1 is identical to Eq.1.5 (It don't use fluid damper; Qv=0). If β_i is given by Eqs.1.3-1.4, Eq.2.1 is identical to Eq.1.2. Fig.2.4 shows the composition of Eq.2.1. If the distribution of shear force coefficient is calculated by Eq.2.1, response amplification of the shear force can be perceived by evaluating of the amplification factor β_i. Thereby Eq.2.2 is replaced by Eq.2.1 and substitutes the results of NTHA to analyze the distribution of β_i.

$$\beta_i = \frac{\alpha_i - \alpha_f}{A_i \cdot \alpha_s} \tag{2.2}$$

Fig.2.5 shows the distribution of β_i. In these cases, β_i is greater than 1. In other words, evaluation method by using A_i distribution only is insufficient in association with the representation of response amplification for the height direction. Here, approximation method of β_i into a linear line is as follows:

$$\beta_i = \left\{\left(\overline{\beta} - 1\right)/(N-1)\right\}\, i + \left(N - \overline{\beta}\right)/(N-1) \tag{2.3}$$

where $\overline{\beta}$ is the value of β_i on the top story which is obtained from a linear approximation of β_i distribution shown in Fig.2.5 by the method of least squares. But $\overline{\beta}$ is set that the first layer of the approximation line (β_1) equals 1. This approximation method is shown in Fig 2.6.

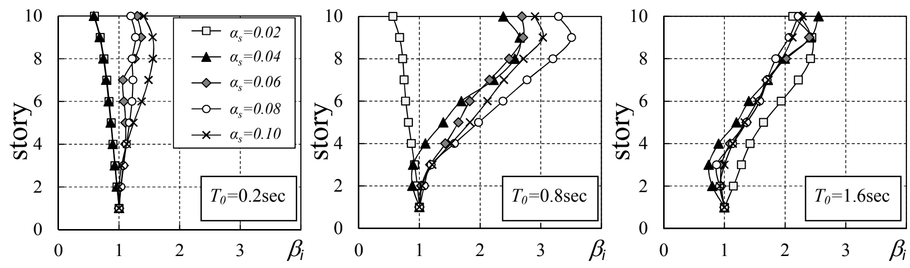

Figure 2.5. Distribution of amplification factor β_i

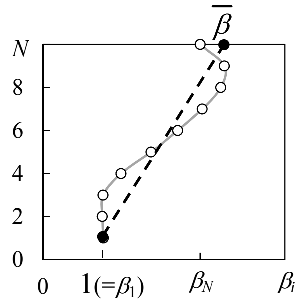

Figure 2.6. Approximation method of β_i

2.3. Isolation ratio *I* and Non-linearity factor *NL*

β_i is calculated from the results of NTHA and is formulized by Isolation-ratio I and Non-Linearity factor NL which are proposed by Skinner (skinner et al. 1993). I is the ratio between the natural period of the superstructure in the fixed-base condition (T_0) to that of seismic isolation layer corresponding to the initial stiffness (T_{b1}). The Isolation ratio I, which governs so many aspects of seismic response, is a measure of period shift produced by isolation.

$$I = T_{b1}/T_0 \tag{2.2}$$

NL defines Non-linearity of Isolation layer as quantitative. NL is the ratio of the maximum loop offset, from the secant line joining the points, to the maximum offset of axis-parallel rectangle through these points, i.e. P_1/P_2. Hence NL increases from 0 to 1 as the loop changes from zero-area shapes to a rectangular shape. For a Bi-linear isolator, this is equivalent to the ratio of loop area A_h to that of the rectangle. Definition of NL is given as follows:

$$\underline{NL} = P_1/P_2 = A_h/4 \cdot \delta_b \cdot Q_b = \pi \cdot h_{eq}/2 \tag{2.3}$$

NL is proportional to the hysteretic damping factor h_{eq} for Bi-linear hysteretic loops. Fig.2.7 shows hysteresis loop defines Non-linearity factor NL. In this paper, consideration of generality, NL replaces with the equivalent viscous damping ratio h_{eq}.

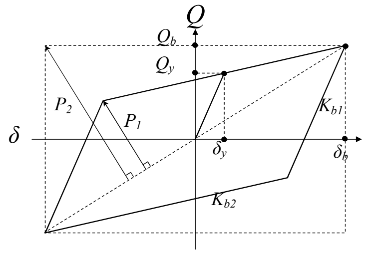

Figure 2.7. Hysteresis loop defines Non-linearity factor *NL*

The relationship between isolation ratio I and $\overline{\beta}$ is shown in Fig.2.8 which is classified by each equivalent viscous damping ratio h_{eq}. Diamond-shaped mark is moving average $\overline{\beta}_{MA}$ which is average of $\overline{\beta}$ in the range of Isolation ratio I from 0 to 0.8, then moved by each 0.4. $\overline{\beta}$ is distributed nearby 3 and scattering of $\overline{\beta}$ is very widely in the range of $0 < I \leq 1.5$. As the increasing of Isolation ratio I, $\overline{\beta}$ and scattering of $\overline{\beta}$ becomes smaller. $\overline{\beta}$ is formulized by Isolation ratio I as follows:

$$\overline{\beta} = \frac{s}{I^2} + t \quad \text{(Upper limit is } \overline{\beta} = u \text{)} \tag{2.4}$$

where s, t are obtained from the method of least squares of $\overline{\beta}$ in the range of $1.5 < I$. u is a simple average of $\overline{\beta}$ in the range of $0 < I \leq 1.5$. Fig.2.9 shows the relationship s, t, u and h_{eq}.

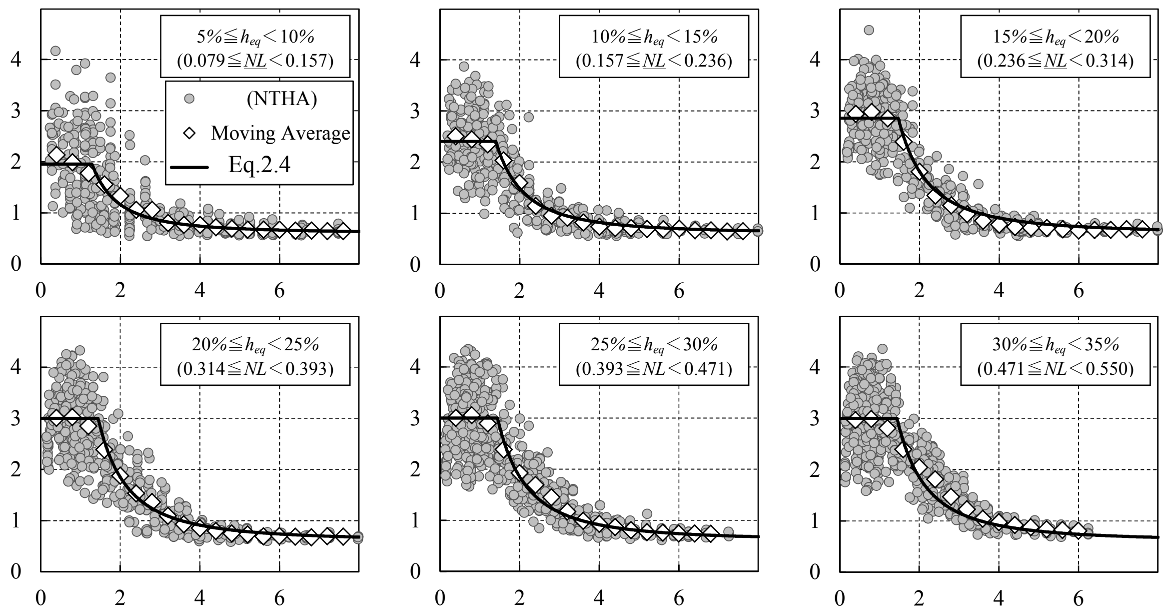

Figure 2.8. Relationship between amplification factor $\overline{\beta}$ and Isolation ratio I

By regression analysis based on Fig. 2.9, each coefficient s, t, u are formulized by equivalent viscous damping ratio. h_{eq} is represented in percent on Eq.2.5-2.7.

$$s = 0.26 h_{eq} + 0.29 \quad \text{(Upper limit is } s = 5.0 \text{)} \tag{2.5}$$

$$t = 0.60 \tag{2.6}$$

$$u = 0.09 h_{eq} + 1.28 \quad \text{(Upper limit is } u = 3.0 \text{)} \tag{2.7}$$

A solid line of Fig.2.8 shows evaluation of $\overline{\beta}$ calculated by Eqs.2.4-2.7. This line is corresponding to moving average $\overline{\beta}_{MA}$. Fig.2.10 shows correspondence of prediction value of shear force coefficient on the 4-th and top story calculated by Eq.2.1 and the results of NTHA. The prediction of Eq.2.1 can evaluate properly average value on 4-th story and 10-th story compared with the results of NTHA.

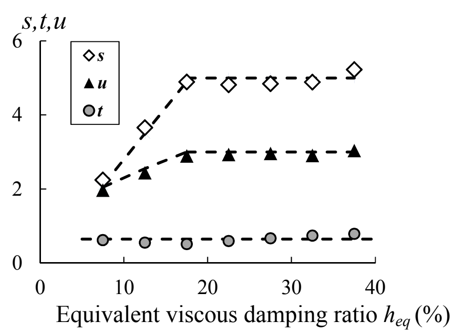

Figure 2.9. Relationship between s,t,u and h_{eq}

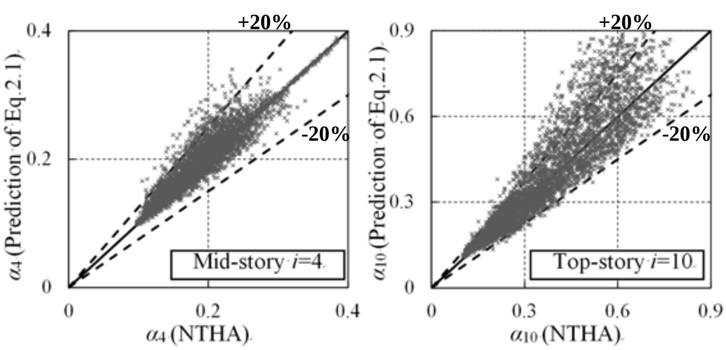

Figure 2.10. Corresponding to the results of NTHA

2.4. Variation Correction Factor for Scattering of $\overline{\beta}$

Distribution of $\overline{\beta}$ tends to dispersion for input earthquake and structural characteristics such as damper and superstructure. Then variation correction factor ν is set for scattering of $\overline{\beta}$. Variation correction coefficient ν is set to $\nu_{1\sigma}$ and $\nu_{2\sigma}$ correspond to $\overline{\beta}_{MA+1\sigma}$ and $\overline{\beta}_{MA+2\sigma}$ using standard deviation σ of $\overline{\beta}$. Fig.2.11 shows coefficient of variance $\underline{CV}$ of $\overline{\beta}$ on each range of Isolation ratio I. Based on the data of equivalent viscous damping ratio h_{eq} are 10%-30%, $\underline{CV}$ is given by as follows:

$$\begin{cases} \underline{CV} = 0.25 & (0 \le I < 3) \\ \underline{CV} = -0.06I + 0.43 & (3 \le I < 6) \\ \underline{CV} = 0.07 & (6 \le I) \end{cases} \tag{2.8}$$

Variation correction factor $\nu_{1\sigma}$ and $\nu_{2\sigma}$ which multiplying for amplification factor $\overline{\beta}$ is given by as follows:

$$\nu_{1\sigma} = (1 + \underline{CV}) \tag{2.9}$$

$$\nu_{2\sigma} = (1 + 2\underline{CV}) \tag{2.10}$$

Fig.2.12 shows correspondence of the prediction of Eq.2.1 considering Eq.2.9 and the results of NTHA of the shear force coefficient on the 4-th and top story. In these cases, almost prediction value of Eq.2.1 evaluates a safe side corresponding to the results of NTHA.

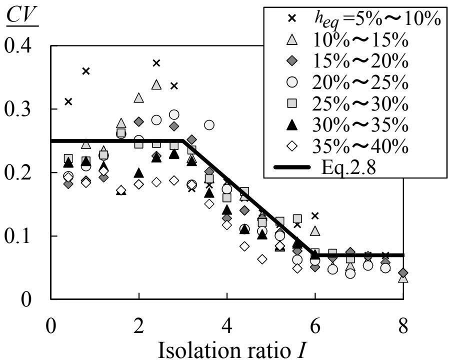

Figure 2.11. Relationship between $\underline{CV}$ and I

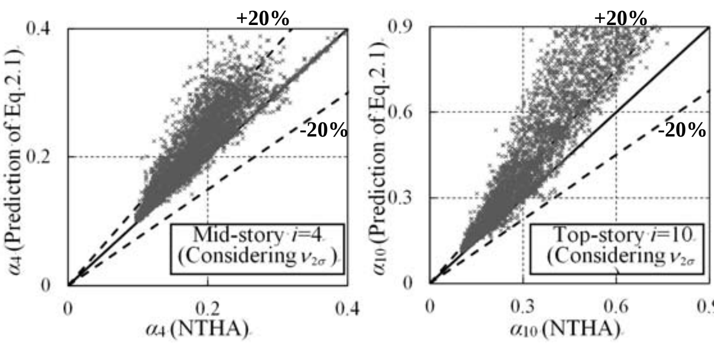

Figure 2.12. Corresponding to NTHA (considering Eq.2.10)

3. ANALYSIS OF HIGHER MODAL RESPONSE

R.I.skinner has revealed the contribution of higher mode is explained by earthquake response of seismically isolated buildings by free-free mode shape vector (skinner et al. 1993). In this study the influence of higher mode, which gives response amplification of shear force coefficient, is revealed by non-linearity modal analysis using free-free mode. By this analysis method, the fluctuation of amplification factor β_i for Isolation ratio I and characteristics of proposed method is explained.

3.1. Modal Analysis with Free-Free Mode Vibration

An appropriate set of mode shapes to represent the response of an isolated structure is set of free-free mode. These mode shapes is obtained when stiffness of isolation story is zero. The s-th ($s \leqq n$) mode shapes and frequencies for free-free mode vibration are defined by Eq.3.1. where $\mathbf{K}_{FF}$ and $\mathbf{M}$ are the stiffness and mass matrix of the structure, ${}_s\mathbf{u}_{FF}$ is s-th mode shape, ${}_s\omega_{FF}$ is s-th natural circular frequency, respectively as the stiffness of isolation story is zero.

$$\mathbf{K}_{FF} \cdot {}_s\mathbf{u}_{FF} = {}_s\omega_{FF}^2 \cdot \mathbf{M} \cdot {}_s\mathbf{u}_{FF} \tag{3.1}$$

Fig.3.1 shows natural periods and mode shapes vector of base fixed condition mode and free-free mode (normalized ${}_s\mathbf{u}_{FF}^T \cdot \mathbf{M} \cdot {}_s\mathbf{u}_{FF} = 1$). The equation of motion about relative displacement vector $\mathbf{y}$ becomes as follows:

$$\mathbf{M} \cdot \ddot{\mathbf{y}} + \mathbf{C} \cdot \dot{\mathbf{y}} + \mathbf{K}_{FF} \cdot \mathbf{y} + \left(\mathbf{0}_{n-1} \quad F_b\right)^T = -\mathbf{M} \cdot \mathbf{1} \cdot \ddot{y}_g \tag{3.2}$$

where **C** is damping matrix, **0** and **1** are n-th zero vector and column vector of which all element are 1. F_b is the isolator force arising from Bi-linear resistance to displacement. Eq.3.2 becomes as follows using mode shape vector ${}_s\mathbf{u}_{FF}$:

$${}_s\ddot{\mathbf{y}} + 2 \cdot {}_s h \cdot {}_s\omega_{FF} \cdot {}_s\dot{\mathbf{y}} + {}_s\omega_{FF}^2 \cdot {}_s\mathbf{y} + \frac{{}_s\mathbf{u}_{FF}\, {}_s u_{FF,1} \cdot F_b}{{}_s\mathbf{u}_{FF}^T \cdot \mathbf{M} \cdot {}_s\mathbf{u}_{FF}} = -{}_s\Gamma_{FF} \cdot {}_s\mathbf{u}_{FF} \cdot \ddot{y}_g \tag{3.3}$$

where ${}_s h$ is s-th damping ratio, ${}_s\Gamma_{FF}$ is s-th participation factor, ${}_s u_{FF,1}$ is the element above isolation story of s-th mode shape vector. For the fundamental mode (s=1), the frequency ${}_s\omega_{FF}$=0, the participation factor ${}_s\Gamma_{FF}$ =1, Eq.3.3 become as follows:

$${}_1\ddot{\mathbf{y}} + \mathbf{1} \cdot \ddot{y}_g = -\mathbf{1} \cdot F_b / m_T \tag{3.4}$$

where m_T is the total mass of the structure. For higher modes (s>1), the participation factor ${}_s\Gamma_{FF}$ =0, the equation of motion become as follows:

$${}_s\ddot{\mathbf{y}} + 2 \cdot {}_s h \cdot {}_s\omega_{FF} \cdot {}_s\dot{\mathbf{y}} + {}_s\omega_{FF}^2 \cdot {}_s\mathbf{y} = -\frac{{}_s\mathbf{u}_{FF} \cdot {}_s u_{FF,1} \cdot F_b}{{}_s\mathbf{u}_{FF}^T \cdot \mathbf{M} \cdot {}_s\mathbf{u}_{FF}} \tag{3.5}$$

From Eq.3.4 and Eq.3.5, higher mode response is occurred by the force of isolation story F_b. Time history of F_b is reflected by input earthquake and characteristics of each isolation device, hence analysis of F_b is able to evaluate the influence of each mode response. To calculate the maximum response of higher mode using relative acceleration response spectrum for F_b/m_t, relationship between Eq.3.4 and Eq.3.5, as follows:

$${}_s\ddot{\mathbf{y}}_{max} = \frac{{}_s\mathbf{u}_{FF} \cdot {}_s u_{FF,1}}{{}_s\mathbf{u}_{FF}^T \cdot \mathbf{M} \cdot {}_s\mathbf{u}_{FF}} \cdot m_T \cdot {}_1S_{a(rel)}({}_sT, {}_sh) \tag{3.6}$$

Furthermore, the maximum response of higher modal shear force coefficient by using Eq.3.5 is calculated by Eq.3.6, it calculates relative acceleration response. The response of the first mode is including the ground acceleration. Calculation of the maximum response of shear force coefficient by using Square Root of Sum of Square (*SRSS*) is represented by Eq.3.7-3.9.

$${}_1\alpha_i = \sum_{i=1}^{N} m_i \left({}_1\ddot{y}_i + \ddot{y}_g\right) / \sum_{i=1}^{N} m_i \cdot g = F_b / m_T g \qquad (s=1) \tag{3.7}$$

$${}_s\alpha_i = \sum_{i=1}^{N} m_i \cdot {}_s\ddot{y}_{max,i} / \sum_{i=1}^{N} m_i \cdot g \qquad (s \geqq 2) \tag{3.8}$$

$$\alpha_{i(SRSS)} = \sqrt{\sum_{s=1}^{N} {}_s\alpha_i^2} \tag{3.9}$$

3.2. Amplification of Shear Force Coefficient

Shear force coefficient of each vibration mode and maximum response of shear force coefficient by using *SRSS* is calculated by the results of NTHA. Analysis model is same to chapter 2. Type of damper is elasto-plastic hysteresis dampers. The yield displacement of hysteresis damper δ_y is fixed at 1.0 cm, yield shear coefficient of dampers α_s is fixed at 0.04. Fig.3.2 shows relative acceleration response spectrum ${}_1S_{a(rel)}$ for F_b/m_t. Relative acceleration response spectrum shows that the peak-period corresponds to the seismic isolation period 4.0sec. Further, Short-period range near the natural period of free-free mode vibration in Fig.3.1, response spectrum is amplified. This range directly affects to the higher mode response.

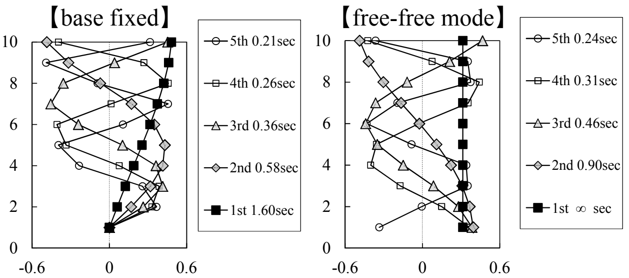

Figure 3.1. Mode shape vector

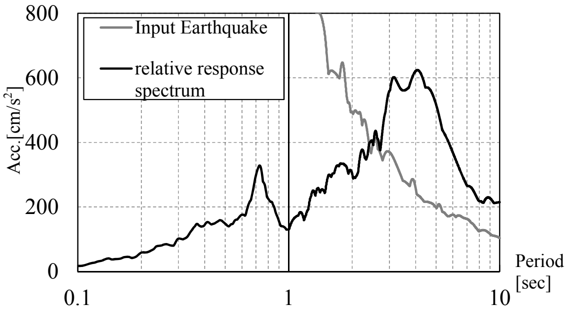

Figure 3.2. Relative acceleration response spectrum

Fig.3.3 shows shear force distribution of *SRSS* (considering 5th mode), the results of NTHA, the prediction of Japanese design code Eq.1.5 and proposed method Eq.2.1. *SRSS* is corresponding to NTHA (i.e. each mode response evaluated by Eq.3.4 and Eq.3.6 is valid for response characteristics of SI-buildings). Further, proposed method Eq.2.1 is corresponding to the results of NTHA. Fig.3.4 shows variation of each mode response for the fluctuation of Isolation ratio *I*. In the cases of $I \le 3.0$, the influence of higher mode is more amplified. In this range, Eq.1.5 underestimated earthquake response. The proposed method Eq.2.1 represents adequately the amplification of shear force coefficient caused by higher mode response.

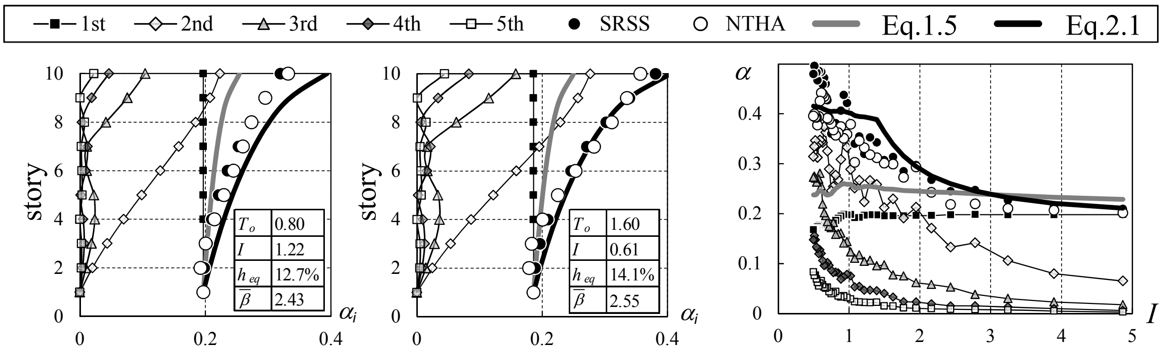

Figure 3.3. Shear force coefficient distribution of each mode

Figure 3.4. Variation of each mode response for the fluctuation of Isolation ratio *I*

4. EFFECTS OF AMPLIFICATION FACTOR

Evaluation methods of shear force coefficient and amplification factor are determined by seismically isolated buildings with Bi-linear restoring characteristics. The characteristics of isolation layer are not necessarily Bi-linear restoring characteristics. Therefore we propose a method of obtaining Bi-Linear approximation for various restoring force model such as Tri-Linear or Ramberg-Osgood characteristics. Hence the proposed method Eq.2.1 can be adapted to various kinds of SI-buildings. And it is confirmed that the evaluation method of shear force coefficient is sufficient to evaluate the Overturning Moment.

4.1. Adaption for Another Characteristics Model

The characteristics of isolation layer is not Bi-linear restoring characteristics, a method of obtaining Bi-Linear approximation for various restoring force model such as Tri-Linear or Ramberg-Osgood characteristics is set as follows:

1. Second stiffness k_2 of Bi-linear (Bi_{eq}) is set tangent stiffness of the original model in the maximum displacement δ_{max}.
2. Initial stiffness k_1 of Bi-linear (Bi_{eq}) is determined as equivalent viscous damping factor h_{eq} is equal to the original model in the maximum displacement δ_{max}.

Fig.4.1 shows approximation method for Tri-linear model and Ramberg-Osgood model.

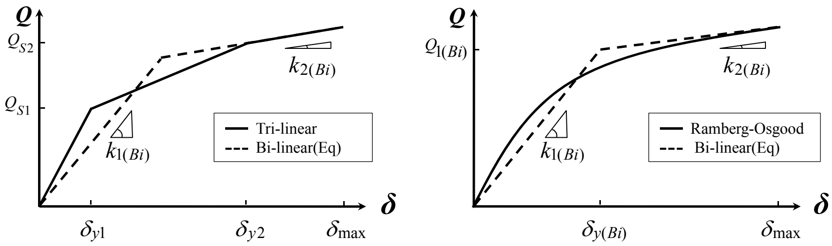

Figure 4.1. Approximation methods for Tri-linear model and Ramberg-Osgood model

To confirm that evaluation of shear force coefficient using above method is effective, NTHA carried out on 10-sotry mass shear model with Tri-linear and R-O model characteristics for isolation layer. Parameters of NTHA are shown in table 4.1. Before and After approximation, shear force coefficient of 10-th story is calculated by Eq.2.1. Before approximation, Tri-linear model is initial stiffness and R-O model is Tangent stiffness of starting point for evaluation of isolation ratio *I,* respectively. Then prediction value of Eq.2.1 evaluates fairly on the safe side shown is Fig.4.2. After approximation, On the other hand, approximation method for Bi-linear model is approaching the appropriate evaluation.

Table 4.1. Characteristics of isolation story for analysis model

Tri-linear model						Ramberg-Osgood model			
Original Tri-linear				Bi-linear (eq)		Original R-O		Bi-linear (eq)	
Bi-linear damper①		Bi-linear damper②							
δy_1[cm]	αs_1[%]	δy_2[cm]	αs_2[%]	$\delta y(Bi)$[cm]	$\alpha s(Bi)$	δy	αs	$\delta y(Bi)$	$\alpha\ s(Bi)$
0.1	0.3	1.0	2.7	0.9	0.03	—	—	20cm	0.075
0.1	0.3	3.0	2.7	2.7					
1.0	1.2	3.0	1.8	2.2					
1.0	1.8	3.0	1.2	1.8					
0.1	0.5	1.0	4.5	0.9	0.05				
0.1	0.5	3.0	4.5	2.7					
1.0	2.0	3.0	3.0	2.2					
1.0	3.0	3.0	2.0	1.8					
0.1	1.0	1.0	6.0	0.9	0.07				
0.1	1.0	3.0	6.0	2.7					
1.0	3.0	3.0	4.0	2.2					
1.0	4.0	3.0	3.0	1.8					

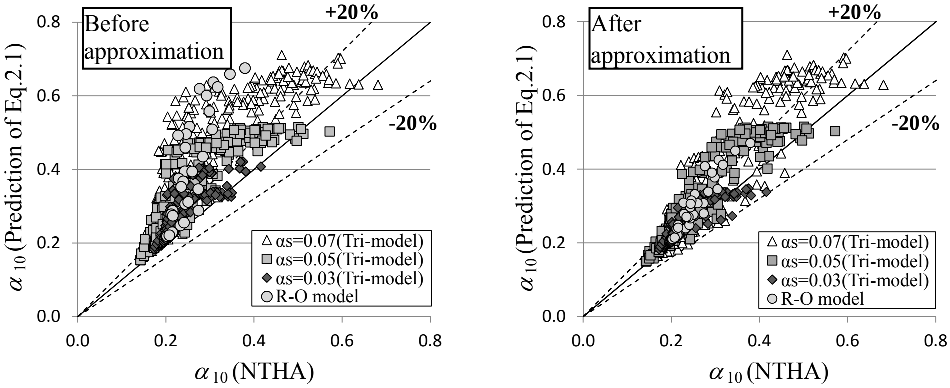

Figure 4.2. The evaluation of shear force coefficient considering approximation method

4.2. Evaluation of Overturning Moment

It is necessary for high-rise SI-buildings to be careful with uplift of Isolator caused by Overturning Moment. Analysis model is same to chapter 2. Overturning Moment on the isolation story is calculated by as follows:

$$OTM_i = \sum_{i=1}^{Nu} W_i \cdot \alpha_i \cdot H_i \tag{4.1}$$

Where α_i is calculated by Eq. 1.5 or Eq.2.1, *Nu* is the top story. Fig.4.3 shows comparison overturning moment by using each evaluation method and that of NTHA. Proposed method introducing β_i is also sufficient to evaluate of Overturning Moments.

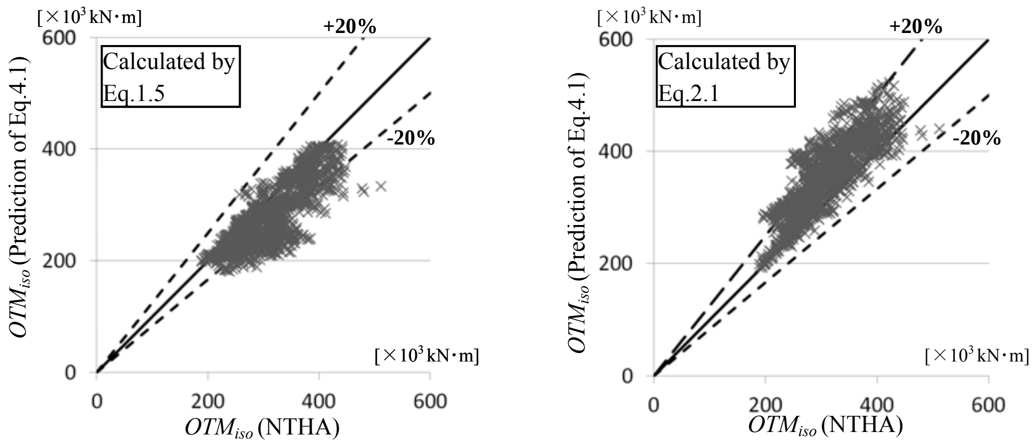

Figure 4.3. Corresponding to the results of NTHA (Overturning Moment on the isolation story)

5. CONCLUSION

This paper proposed an evaluation method of shear force coefficient for SI-buildings. The results obtained by analytical studies are as follows; 1) It is confirmed that the prediction of the proposed method can evaluate properly or safe side corresponding to the results of NTHA. 2) Response amplification of shear force coefficient is explained by non-linearity modal analysis with free-free mode vibration. 3) We proposed an approximation method Tri-linear and Ramberg-osgood into Bi-linear. By using this approximation, the proposed method is adopted to various kinds of SI-buildings. 4) Proposed method of shear force coefficient is sufficient to evaluation of overturning moment. On these studies, proposed methods are corresponding to results of NTHA.

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