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DAMPING-DEPENDENT COEFFICIENTS FOR MAXIMUM RESPONSE ESTIMATION OF ISOLATED STRUCTURES

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The equivalent linearization method (ELM) is often used to estimate the maximum displacement of isolated structures. Damping-dependent coefficients (C_D) which are a scale multiplier required to give simplified elastic acceleration design spectra (EADS) for greater damping values are proposed. The C_D is obtained from the relationship between nonlinear time history analysis (NTHA) and ELM using the standard waves from various ground types and different types of earthquakes. The proposed C_D is compared to the previous one and validated for various isolated structures under a natural earthquake and standard waves.

***Key Words** : equivalent linearization method, damping-dependent coefficients, bilinear isolators*

1. INTRODUCTION

The equivalent linearization method (ELM) is used popularly to predict a maximum displacement of complex structures using single-degree-of-freedom (SDF). Recently, the ELM is applying to the isolated structures with comparatively high damping and high nonlinearity, but the degree of accuracy for response estimation is not good since the damping-dependent coefficients (C_D) are obtained from a linear system with viscous damping under earthquakes limited. C_D is a scale multiplier required to give simplified elastic acceleration design spectra (EADS) for greater damping values used in the ELM. Thus, if C_D obtained from linear analysis apply to bilinear isolators with high nonlinearity, the previous C_D, which is obtained from limited conditions should be modified.

The description of the steady-state response of a nonlinearly damped oscillator by means of an equivalent viscous damping coefficient was first proposed by Jacobsen in 1930[1]. To determine the equivalent damping coefficient, the damping factor of a linear oscillator with the same natural period is chosen so that the nonlinearly damped oscillator and the linear oscillator dissipate the same amount of energy per cycle of response to sinusoidal excitation. Shibata discussed an equivalent linear model to simulate the maximum inelastic response of hysteretic SDF system under earthquake loadings[2]. It has been recognized that the maximum inelastic response of hysteretic yielding systems can be satisfactorily determined using equivalent linear models with reduced stiffness and increasing damping determined as a function of attained maximum displacement for a conventional structure with relatively small ductility ratio. The applications of ELM for isolated structures are described in references 3) and 5).

In this paper, the C_D for the isolated structures with bilinear isolators are obtained from the relationship between nonlinear time history analysis (NTHA) and ELM using the 18 standard waves from various ground types (hard, medium, and soft) and different types of earthquakes (hypocenter under sea and hypocenter directly below urban areas).

The fact that a maximum displacement of a bilinear SDF is equal to that of an equivalent linear system is assumed. The 456 bilinear models are selected to obtain C_D for the given conditions. Two kinds of formulas for C_D are proposed. One is the detailed formula which consists of two isolator parameters (elastic period T_{bl} and yield-force ratio Q_y/W) , the other is the enveloped formula which consist of equivalent damping ratio h_{eq}.

2. ELM using EADS[1]

It is assumed that design-earthquake motions are available in terms of displacement response spectra. Often design motions are specified in terms of 2% or 5% damped EADS. These may be converted to the required form by using Eq.(1). The C_D may be obtained from various formulas. The estimation of the seismic response for a structure with bilinear hysteretic isolation may proceed through Step 1 to Step 7.

$$S_D(T,h)=\frac{T^2}{4\pi^2}C_D(h_{eq})S_A(T,h_b) \qquad (1)$$

In Eq.(1), S_D is converted relative displacement design spectrum, T is the period for liner systems, h is the total viscous damping ratio (= h_{eq} + h_b), h_{eq} is the equivalent viscous damping ratio corresponding to hysteretic damping, h_b is the velocity-damping ratio for isolators, and S_A is EADS. The h_b is assumed as 0.05.

Step 1 : Assume an earthquake displacement (X_b)
Step 2 : Calculate yield-force ratio (Q_y/W)
Step 3 : Calculate base shear ratio (S_b/W)

$$\frac{S_b}{W}=\frac{Q_y}{W}\left(1-\frac{T_{b1}^2}{T_{b2}^2}\right)+\frac{4\pi^2 X_b}{gT_{b2}^2} \qquad (2)$$

Step 4 : Calculate equivalent liner period (T_B)

$$T_B=2\pi\sqrt{\frac{X_b}{\left(\frac{S_b}{W}\right)g}} \qquad (3)$$

Step 5 : Calculate equivalent viscous damping (h_{eq})

$$h_{eq}=\frac{2}{\pi}\frac{(Q_y/W)}{(S_b/W)}\left(1-\frac{T_{b1}^2}{T_B^2}\right) \qquad (4)$$

Step 6 : Compare X_b and S_D (within the given error)
Step 7 : Obtain S_D

In Eq.(2), S_b is the maximum base-level shear, W is the total weight of structures, Q_y is the yield force of isolators, T_{b1} is the elastic period of isolators, T_{b2} is the plastic period of isolators, X_b is the assumed earthquake displacement, and g is gravity acceleration. In Eq.(3), T_B is the equivalent period of isolators. In this paper, EADS in references 4) and 5) are used for standard waves and El Centro NS 1940 respectively in the analysis.

3. THE PREVIOUS FORMULAS FOR C_D

Generally, the previous formulas are obtained using Eq.(5), which consider linear systems, viscous damping, and linear response spectra. In Eq.(5), n is the number of linear system, $S(T_i, h)$ is the linear response spectra for period T_i and damping ratio h, and $S(T_i, h_c)$ is the linear response spectra for period T_i and a given damping ratio h_c. The h_c is the constant damping ratio (0 (undamped) or 0.05 are used commonly).

$$C_D(h_{eq})=\frac{1}{n}\sum_{i=1}^{n}\frac{S(T_i,h)}{S(T_i,h_c)} \qquad (5)$$

This equation can not consider the various hysteresis characteristics. In this paper, two kinds of formulas for obtaining C_D are proposed considering the various hysteresis models and earthquake characteristics. The various formulas for C_D to give EADS for greater damping values were proposed. Eq.(6) is used in reference 5) for the isolated structures. These formulas have a different formula for different damping ranges and are used with EADS. The formulas Eq.(6) are obtained from linear systems under limited earthquakes (not consider soil type, earthquake type, and nonlinear).

$$\left.\begin{aligned} C_D(h_{eq})&=\frac{1}{\sqrt{30h_{eq}+1}} & (h_{eq}<0.1) \\ C_D(h_{eq})&=\frac{1}{\sqrt{10h_{eq}+3}} & (h_{eq}\ge 0.1) \end{aligned}\right\} \qquad (6)$$

Eq.(7) is used in reference 4) and is similar to the approximated values of Eq.(8). These formulas have a constant value for different damping ranges and are used with the 5% damped EADS. Eq.(7) is applied to the seismic isolation design for highway bridges(see reference 4)). Eq.(7) can not consider the C_D precisely according to h_{eq} because it has a constant value for a damping range and has comparatively large values.

$$\left.\begin{aligned} C_D(h_{eq})&=1.0 & (h_{eq}<0.1) \\ C_D(h_{eq})&=0.9 & (0.1\le h_{eq}<0.12) \\ C_D(h_{eq})&=0.8 & (0.12\le h_{eq}<0.15) \\ C_D(h_{eq})&=0.7 & (h_{eq}\ge 0.15) \end{aligned}\right\} \qquad (7)$$

Eq.(8) is used in reference 4) to obtain EADS with higher damping ratio. Eq.(8) is not used at the seismic isolation design stage directly but the checking for isolated structures designed are conducted using Eq.(8) proposed by K. Kawasima et al. 1984 in dynamic analysis[6]. The formula Eq.(8) is obtained from linear systems and is also used with EADS.

$$C_D(h_{eq})=\frac{1.5}{40h_{eq}+1}+0.5 \qquad (8)$$

In this paper, the three kinds of formulas for C_D mentioned above are examined for the accuracy of maximum response estimation for various isolator types under various kinds of earthquake loadings and are compared to the two proposed formulas (the detailed and the enveloped formula).

4. METHEDOLOGY FOR OBTAINING NEW C_D

(1) Selected 18 Standard Waves

The 18 standard waves are selected to obtain the new C_D. These waves include various ground types (hard (Soil 1), medium (Soil 2), and soft (Soil 3)) and two kinds of earthquake loadings (hypocenter under sea (Type 1) and hypocenter directly below urban areas (Type 2)). Type 1 is the plate boundary

Table 1 18 Standard Waves

Ty.	Name	Year	Direc.	ST	M
1	Kaihoku Brg.	1978	LG.	1	7.4
1	Kaihoku Brg.	1978	TR.	1	7.4
1	Shichihou Brg.	1993	LG.	1	7.8
1	Itajima Brg.	1968	LG.	2	7.5
1	Itajima Brg.	1968	TR.	2	7.5
1	Onnetto Brg.	1994	TR.	2	8.1
1	Tsugaru Brg.	1983	TR.	3	7.7
1	Tsugaru Brg.	1983	LG.	3	7.7
1	Kushirogawa Emb.	1994	LG.	3	8.1
2	Jma Kobe Obs.	1995	N-S	1	7.2
2	Jma Kobe Obs.	1995	E-W	1	7.2
2	Hepc Inagawa	1995	N-S	1	7.2
2	Jr Takatori Sta.	1995	N-S	2	7.2
2	Jr Takatori Sta.	1995	E-W	2	7.2
2	Ogas Fukiai	1995	N27W	2	7.2
2	Hepc Higashi Kobe	1995	N12W	3	7.2
2	Kobe Port Island	1995	N-S	3	7.2
2	Kobe Port Island	1995	E-W	3	7.2

type earthquakes and the large amplitude of waves repeat with a long duration time. Type 2 is near field earthquakes and has very large amplitude in a short duration time. The distance of hypocenter for Type 2 is between about 10 km and 24 km. These waves are obtained from the modification of amplitude for the natural earthquake loadings in **Table 1**. In **Table 1**, Ty. stands for type, Direc. stands for direction, ST stands for soil type, M stands for magnitude, LG. stands for longitudinal, TR. stands for transverse, Brg. stands for bridges, Emb. stands for embankments, Obs. stands for observation, and Sta. stands for station. These waves are used in reference 4).

(2) Selected Analysis Models

Fig.1 shows the selected single degree-of-freedom (SDF) isolated structures with bilinear isolators. The isolators are modeled as a bilinear shear spring and do not consider the flexibility of structures. In **Fig.1**, a_g is ground acceleration, W is the total weight of structures, S_b is maximum shear force of isolators, Q_y is yield force of isolators, T_{b1} is elastic periods of isolators, T_{b2} is plastic periods of isolators, T_B is the equivalent periods of isolators, X_y is yield displacement of isolators, and X_b is maximum displacement of isolators.

Table 2 shows the values used in the 456 selected models. The total weight of structures is the same value for all selected models as 9,800 N. These models can represent the bilinear isolated structures to date. 19 elastic periods of isolators, 4 plastic periods of isolators, and 6 yield ratio of isolators are selected for analysis. We assume that these models can represent the isolated structures with a rigid body.

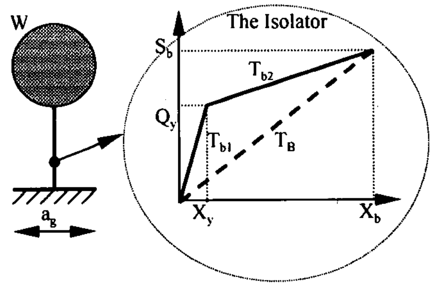


Fig.1 SDF Model of Isolated Structures with Bilinear Isolators

Table 2 The Selected Models

Parameters	Symbols	Values
Total Weight	W	9,800 N
Elastic Periods	Tb1	0.1～1.0 (Δ= 0.05) sec
Plastic Periods	Tb2	1.5, 3.0, 4.5, 6.0 sec
Yield Ratios	Qy/W	0.02～0.22 (Δ= 0.04)

(3) Flow Chart for obtaining the New C_D

The new C_D consider earthquake characteristics and various bilinear models as shown in **Table 1** and 2. Eq.(9) represents the formula for obtaining C_D. In Eq.(9), n is the number of earthquakes, $D_{amax}(T_{b1}, T_{b2}, Q_y/W)_{NTHA}$ is absolute maximum displacement for a model with parameters (elastic period T_{b1}, plastic period T_{b2}, and yield-force ratio Q_y/W). $S_D(T_B, h_c)$ is displacement response spectra for equivalent period T_B and damping ratio h_c (= 0.05). The C_D is obtained if the ratio of NTHA and ELM is within the given error ε. Eq.(9) consider the NTHA and ELM directly. From the results of analysis, the $C_D - T_{b1}$ relationship and the $C_D - h_{eq}$ relationship can be obtained. The detailed formulas are obtained from $C_D - T_{b1}$ relationship and the enveloped formulas are obtained from $C_D - h_{eq}$ relationship.

$$\frac{\frac{1}{n} D_{a\max}\left(T_{b1}, T_{b2}, Q_y / W\right)_{NTHA}}{\left(C_D\left(h_{eq}\right) \cdot S_D\left(T_B, h_c\right)\right)_{ELM}} \leq \varepsilon \qquad (9)$$

Fig.2 shows the flow chart for obtaining C_D. At first, the average absolute maximum displacements (D_{amax}/n) are obtained for the selected models and earthquakes by NTHA. n is the number of earthquakes for each case. Next, the design displacements S_D are obtained by ELM using EADS in reference 4) for the same models and earthquakes. The S_D is the design response spectra converted from EADS. If the ratio of average D_{amax} and S_D agree with a given error ε, the C_D are obtained. The error ε is assumed as 0.05. These C_D are associated with the hysteresis characteristics (T_{b1}, T_{b2}, and Q_y/W) and damping ratio (see Chapter 5).

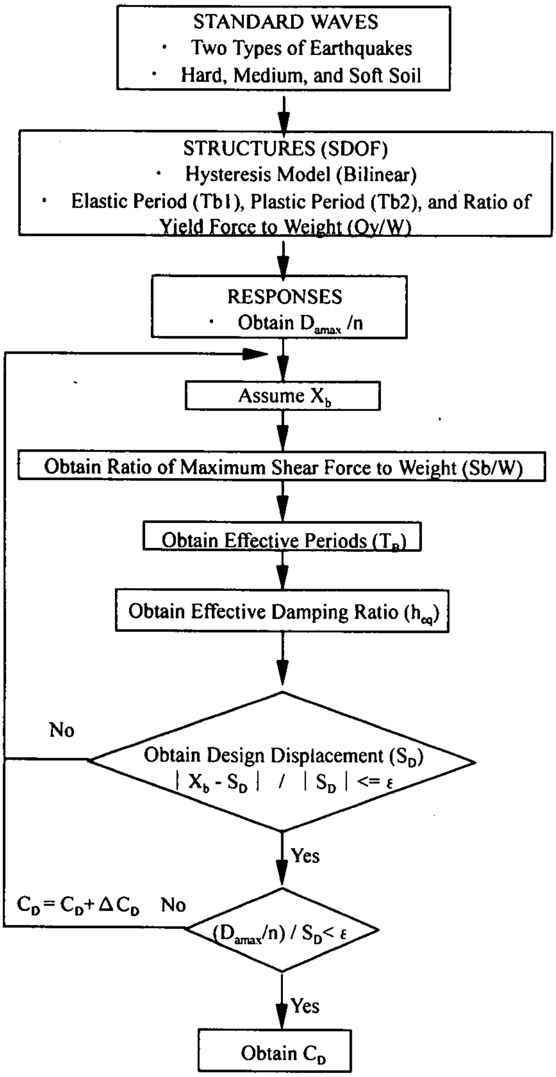
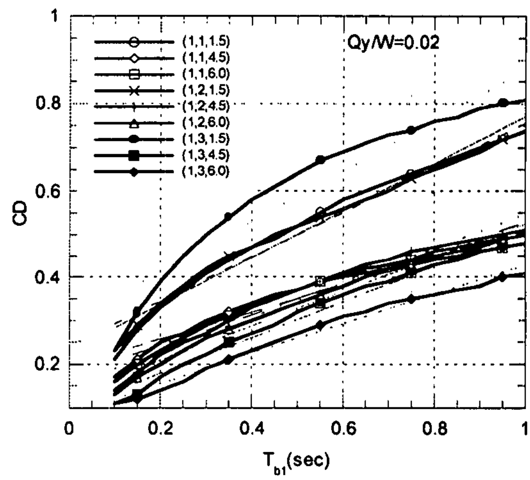


Fig.2 Flow Chart for Obtaining C_D

5. THE PROPOSED C_D

In this paper, two kinds of formulas are proposed; the detailed formulas and the enveloped formulas. The detailed formulas consist of two parameters (T_{b1} and Q_y/W) and can be applied only to the given isolator type and earthquake waves (standard waves). These detailed formulas can predict the response of structures more precisely for the given models but do not permit an interpolation between cases. The detailed formulas have a special formula for each case described in the Appendix. The enveloped formulas consist of the equivalent damping ratio of isolators (h_{eq}) and can be applied



(a) $C_D - T_{b1}$ (Type 1, $Q_y/W = 0.02$)

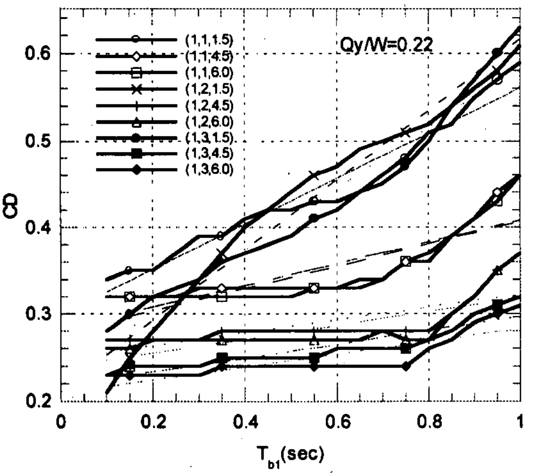
to the isolated structures with various bilinear isolators. The enveloped formulas have three kinds of formulas according to different ranges of damping ratios. These two kinds of formulas are compared to the previous formulas C_D (Eq.(6), (7), and (8)).

(1) The Detailed Formulas for C_D

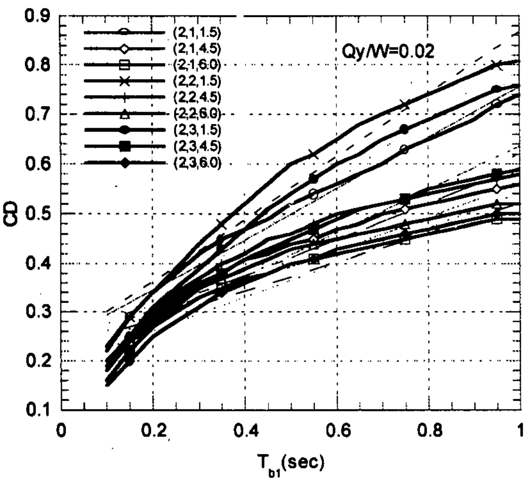
The detailed formulas can be obtained from the relationship between T_{b1} and C_D. Generally, the C_D increases as the T_{b1} increases. These relationships may be approximated by linear equations with high correlation factor (average 0.95 over). Eq.(10) shows the basic form for the various linear equations of C_D. The more detailed equations for the given cases are described in the Appendix at the end of this paper.

$$C_D(T_{b1}, r) = M1(r) + M2(r)T_{b1} \tag{10}$$

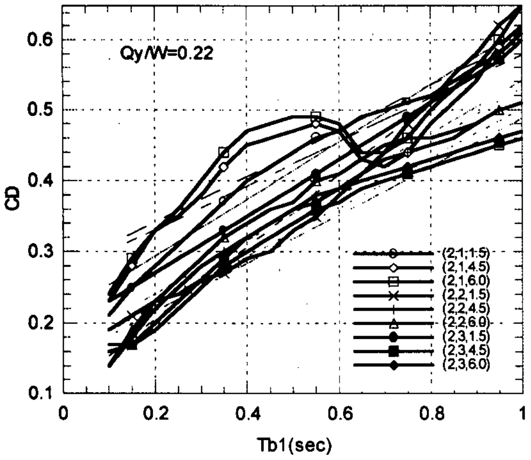
Fig.3 shows the relationship between C_D and T_{b1} for the representative models (Q_y/W = 0.02, 0.22 and T_{b2} = 1.5, 4.5, 6.0 sec) among the selected models. From **Fig.3**, several facts can be recognized as follows. First, the variation of values of C_D for small yield-force ratios Q_y/W (= 0.02) is more regular than large yield-force ratios Q_y/W (= 0.22). Secondly, the models with short period of T_{b2} (= 1.5 sec) have a large value of C_D compared to the models with long period of T_{b2} (= 4.5, 6.0 sec). Thirdly, the ELM without C_D evaluates mostly the responses of structures with respect to NTHA. The ELM without C_D for the bilinear isolator with short T_{b1} evaluate displacements largely in comparison to the bilinear isolator with long T_{b1}. The numbers in ( ) of **Fig.3** mean (Earthquake Type, Soil Type, Plastic Period).



(b) $C_D - T_{b1}$ (Type 1, $Q_y/W = 0.22$)

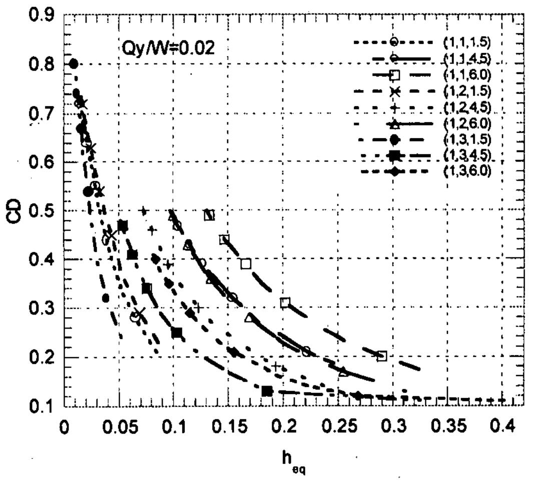


(c) $C_D - T_{b1}$ (Type 2, $Q_y/W = 0.02$)

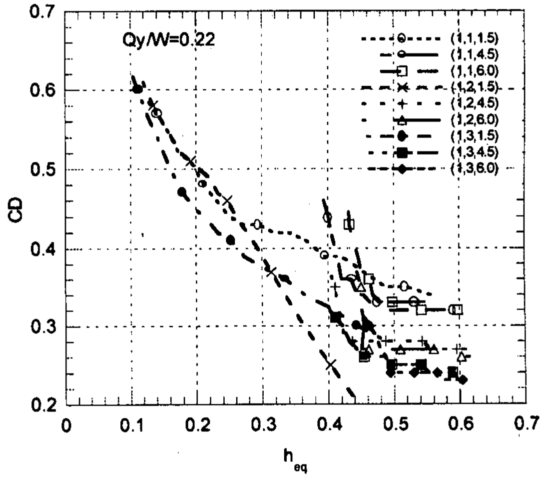


(d) $C_D - T_{b1}$ (Type 2, $Q_y/W = 0.22$)

Fig. 3 $C_D - T_{b1}$ Relationship



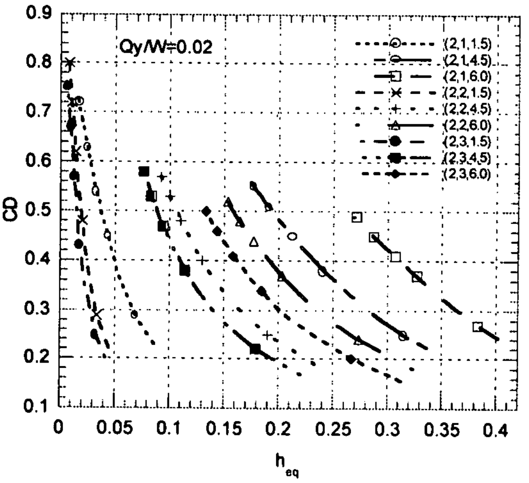
(a) C_D - h_{eq} (Type 1, $Q_y/W = 0.02$)



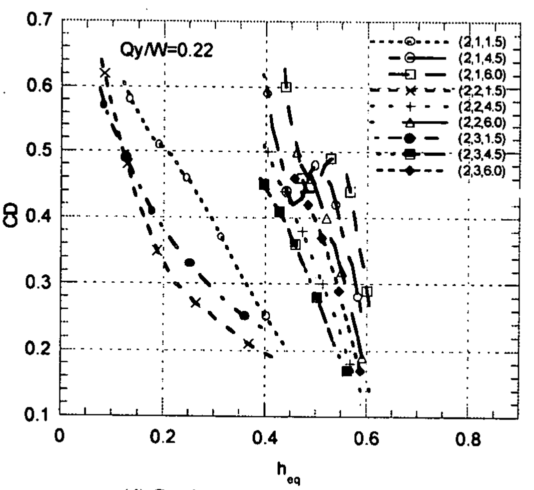
(b) C_D - h_{eq} (Type 1, $Q_y/W = 0.22$)

(2) The Enveloped Formulas for C_D

The enveloped formulas can be obtained from the relationship h_{eq} and C_D for all selected models in **Table 2. Fig.4** shows the relationship between h_{eq} and C_D for the representative models ($Q_y/W = 0.02$, 0.22 and T_{b2} = 1.5, 4.5, 6.0) among the selected models. From **Fig.4**, several facts can be recognized as follows. First, the C_D decreases as the h_{eq} increases. Second, the variation of C_D for the small yield-force ratio Q_y/W (= 0.02) is more regular than the large yield-force ratio Q_y/W (= 0.22). Third, the models with short periods of T_{b2} (= 1.5 sec) have a low damping ratio compared to the models with long periods of T_{b2} (= 4.5, 6.0 sec). The numbers in ( ) of **Fig.4** mean (Earthquake Type, Soil Type, Plastic Period).



(c) C_D - h_{eq} (Type 2, $Q_y/W = 0.02$)



(d) C_D - h_{eq} (Type 2, $Q_y/W = 0.22$)

Fig.4 C_D - h_{eq} Relationship

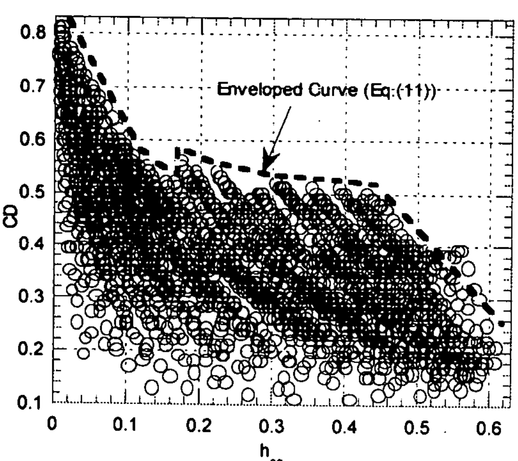


Fig.5 The Enveloped Curve

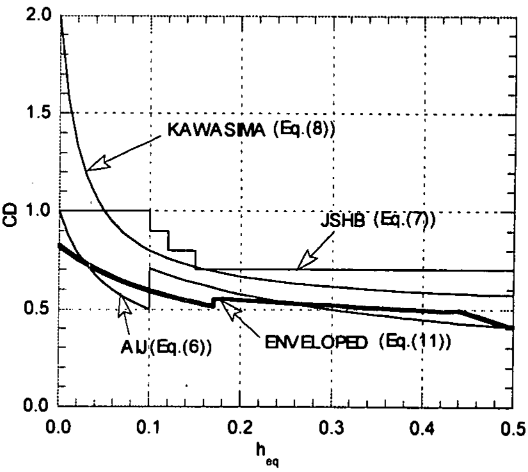


Fig.6 Comparison between The Previous and The Proposed Formulas

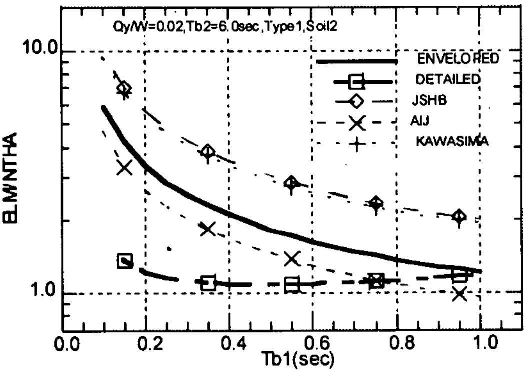
Fig.5 shows all analyzed C_D with respect to each h_{eq} for all selected models. The dashed line in **Fig.5** represents the enveloped curve. The enveloped curve can expressed by three kinds of formulas according to different ranges of damping ratio as shown in Eq.(11).

Eq.(11) shows the enveloped formulas of C_D. These formulas are the maximum values of C_D for each damping ratio and can envelop all values of C_D as safe values. These formulas may be used for all bilinear isolator to date. Eq.(11) is nonlinear, and considers two kinds of earthquake characteristics and various soil conditions. It also has three kinds of formulas due to the given damping ranges.

$$\left.\begin{aligned} C_D(h_{eq}) &= \frac{0.825}{\sqrt{9.2h_{eq}+1}} \quad (0 < h_{eq} <= 0.17) \\ C_D(h_{eq}) &= \frac{0.616}{\sqrt{1.346h_{eq}+1}} \quad (0.17 < h_{eq} <= 0.43) \\ C_D(h_{eq}) &= -1.434h_{eq} + 1.124 \quad (h_{eq} > 0.43) \end{aligned}\right\} \quad (11)$$

(3) The Comparison Between The Previous and The Proposed C_D

Fig.6 shows the plotting for the each formula of C_D mentioned above. In **Fig.6**, JSHB shows Japan Specification for Highway Bridges and AIJ is Architecture Institute of Japan. The formula JSHB is used in reference 4) and the formula AIJ is used in reference 5). We can see that the formulas Kawasima and JSHB evaluate largely the values of C_D comparing the formulas AIJ and ENVELOPED. The AIJ and the proposed B show similar curve but the ENVELOPED has large C_D in the range of 0.025 to 0.1 and 0.25 to 0.5 of h_{eq}.



(a) case 1

Table 3 Validations for Standard Waves

CASE	Qy/W	Tb2	TYPE	SOIL	WAVE
1	0.02	6.0	1	2	Standard
2	0.14	6.0	1	2	Standard
3	0.02	6.0	1	3	Standard
4	0.14	6.0	1	3	Standard
5	0.02	6.0	2	2	Standard
6	0.14	6.0	2	2	Standard
7	0.02	6.0	2	3	Standard
8	0.14	6.0	2	3	Standard

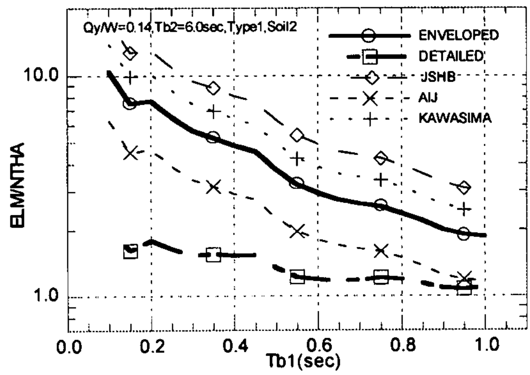
6. APPLICATIONS AND VALIDATIONS

The 14 cases are selected to validate the proposed formulas. case 1 to case 8 for the standard waves and case 9 to case 14 are for a natural earthquake (El Centro). The two kinds of proposed formulas (the detailed and the enveloped) are compared to the previous formulas (Eq.(6), (7), and (8)). In the cases of the detailed, the estimated values are those multiplied by safety factor 1.2 to avoid 'dangerous estimation'. The detailed formulas can be applied to only standard waves.

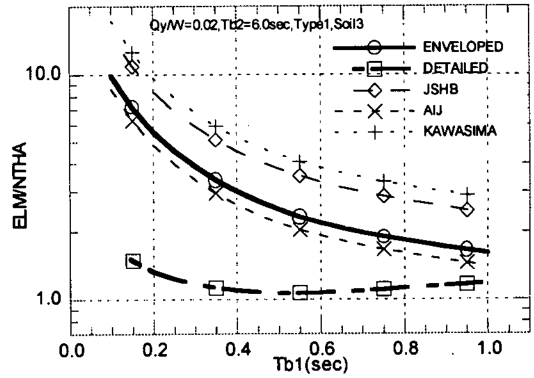
(1) Validations for Standard Waves

Table 3 shows the representative 8 cases (Q_y/W(= 0.02, 0.14)), Type1, Type 2, Soil 1, Soil 2, and Soil 3).

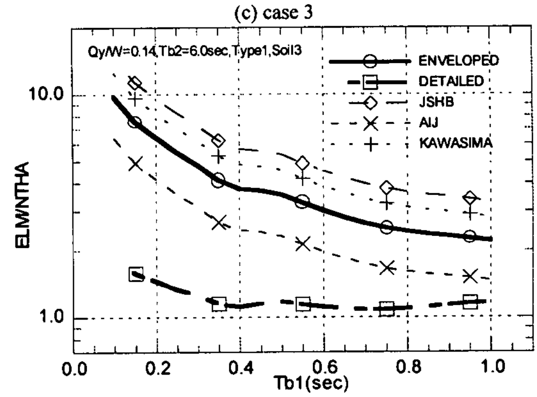
Fig.7 shows the degree of accuracy for the absolute maximum response estimation for the selected cases (see **Table 3**). Generally, JSHB and KAWASIMA evaluate largely the response comparing the detailed, the enveloped, and AIJ. The detailed formulas have a good estimation for the given condition. The AIJ has 'dangerous estimation' (ELM/NTHA is 1.0 below) in case (5), (6), (7), and (8). In the range of short periods of T_{b1}, the degree of accuracy of estimation is very bad (10 times over in cases (2), (3), and (4)).



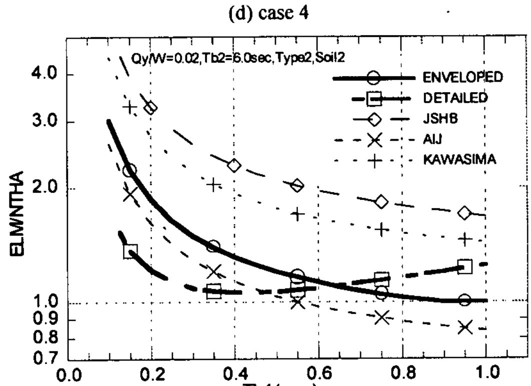
(b) case 2



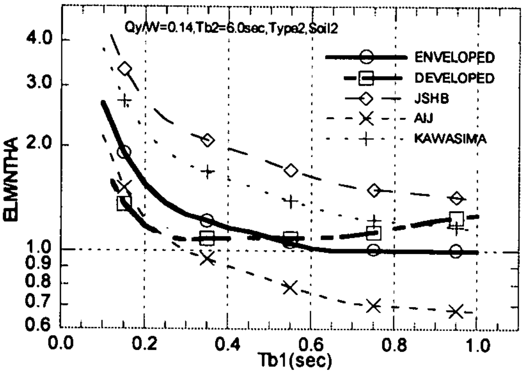
(c) case 3



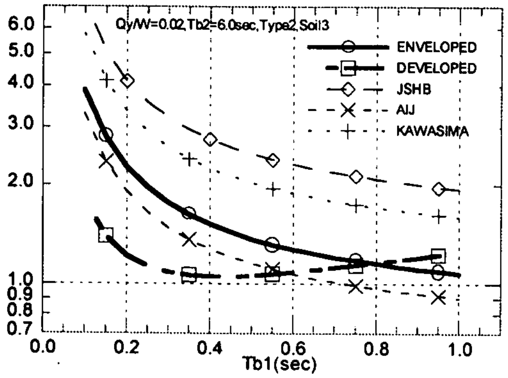
(d) case 4



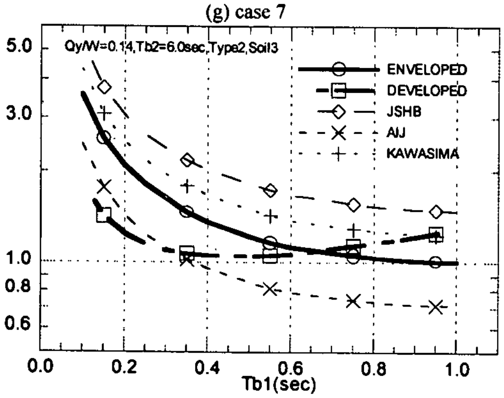
(e) case 5



(f) case 6



(g) case 7



(h) case 8

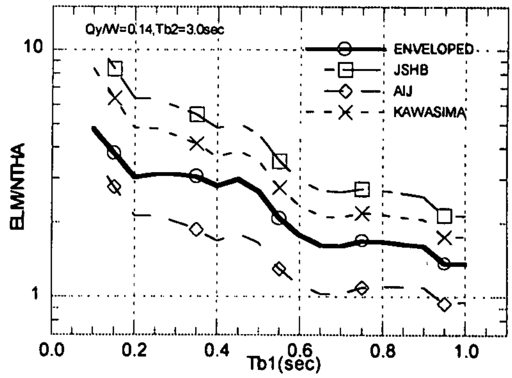
Fig.7 Validations for Standard Waves

(2) Validations for Natural Earthquake

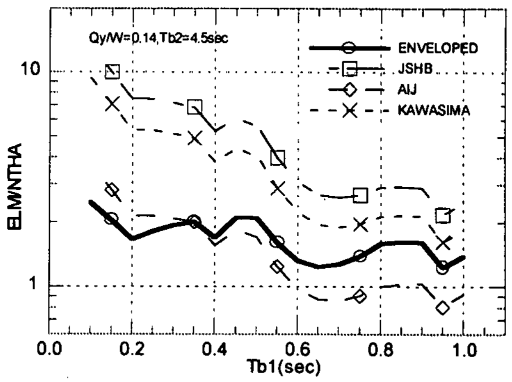
Table 4 shows the six representative cases (Q_y/W (= 0.14, 0.22), T_{b2}(= 3.0, 4.5, 6.0 sec)). **Fig.8** shows the degree of accuracy for the absolute maximum response estimation for the selected cases (see **Table 4**). The AIJ has 'dangerous estimation' in all cases. JSHB and KAWASIMA have very bad accuracy of estimation in the range of short periods of T_{b1} (error with 10 times over), thus these two formulas can not be applied to the bilinear isolated structures for the response estimations and validations of the isolated structures designed without a modification.

Table 4 Validations for Natural Earthquake (El Centro)

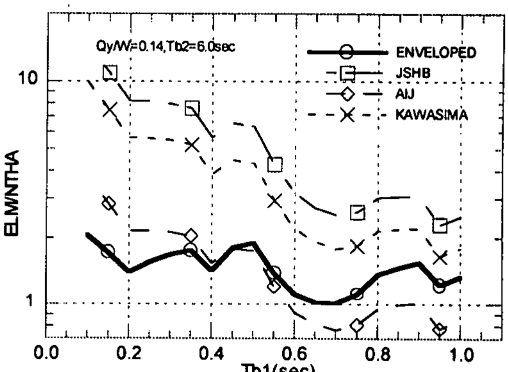
CASE	Qy/W	Tb2	WAVE
9	0.14	3.0	El Centro
10	0.14	4.5	El Centro
11	0.14	6.0	El Centro
12	0.22	3.0	El Centro
13	0.22	4.5	El Centro
14	0.22	6.0	El Centro



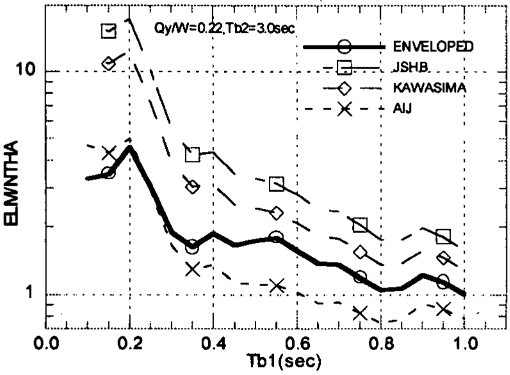
(i) case 9



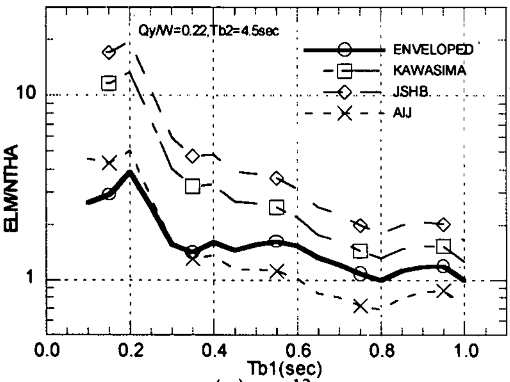
(j) case 10



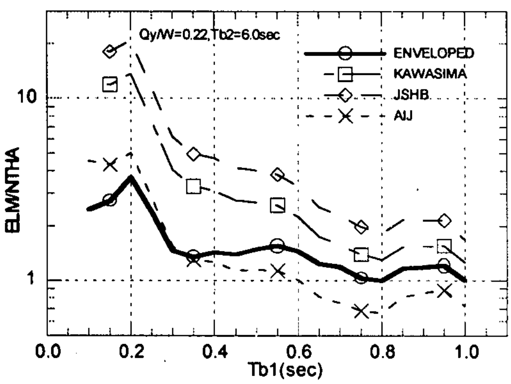
(k) case 11



(l) case 12



(m) case 13

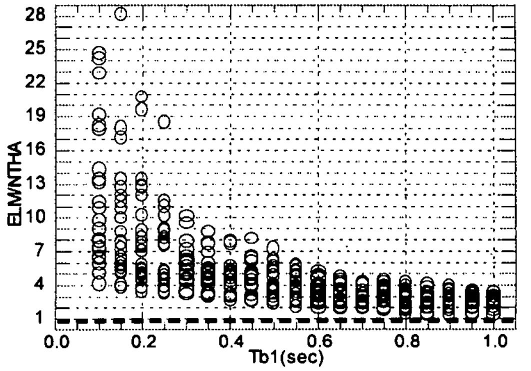


(n) case 14

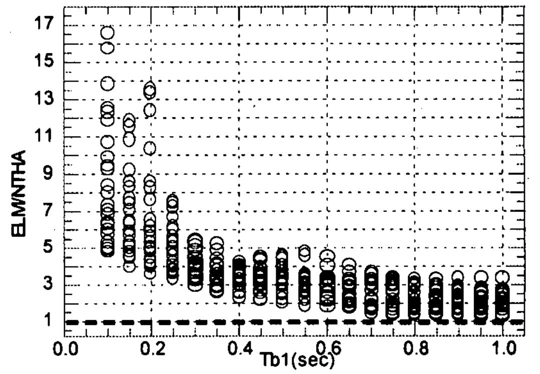
Fig.8 Validations for Natural Earthquake

(3) Validations for All Selected Models

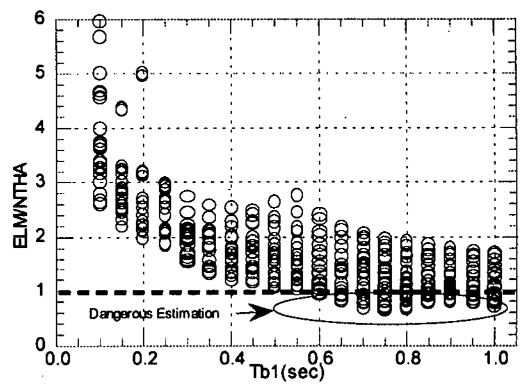
Fig.9 shows the degree of accuracy of the estimation for all the selected models under the El Centro earthquake. The enveloped formulas are only compared to the previous formulas since the detailed formulas can be used for the given models described in Appendix under standard waves. The formula JHSB and KAWASIMA are not good for estimations. The AIJ has a good degree of accuracy but has 'dangerous estimation' in the range of long T_{b1}.



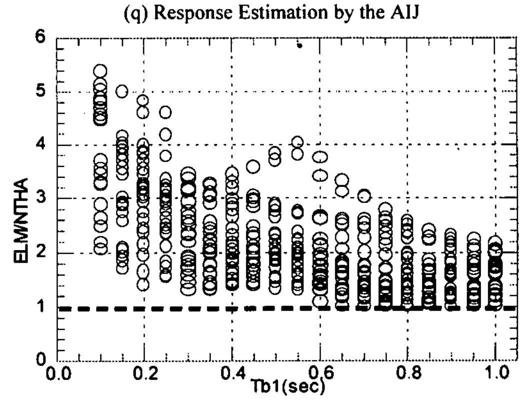
(o) Response Estimation by the JSHB



(p) Response Estimation by the KAWASIMA



(q) Response Estimation by the AIJ



(r) Response Estimation by the ENVELOPED

Fig.9 Validations for All Selected Models

7. CONCLUSIONS

(1) Two kinds of formulas for damping-dependent coefficients (C_D) (the detailed and enveloped formula) are proposed considering various bilinear isolators and earthquake characteristics.
(2) Eq.(6) and (7) can not be applied to the design of bilinear isolated structures or the checking of the isolated structures designed without a modification.
(3) The elastic period (T_{bl}) and the yield ratio (Q_y/W) of isolators are closely related with C_D.

APPENDIX

Damping-Dependent Coefficients

$$C_D(T_{b1}, r) = M1(r) + M2(r)T_{b1}$$

$$r = Qy/W$$

Hypocenter under Sea Type

M1(r)

T1S1[1.5] : $M1=0.238-0.369r+2.446r^2+1.973r^3$
T1S1[3.0] : $M1=0.208-1.004r+7.562r^2-6.392r^3$
T1S1[4.5] : $M1=0.226-1.348r+8.561r^2-6.589r^3$
T1S1[6.0] : $M1=0.199-0.930r+6.020r^2-1.855r^3$
T1S2[1.5] : $M1=0.232-0.830r+5.735r^2-5.879r^3$
T1S2[3.0] : $M1=0.194-1.451r+10.980r^2-14.520r^3$
T1S2[4.5] : $M1=0.175-1.122r+8.395r^2-8.917r^3$
T1S2[6.0] : $M1=0.149-0.704r+5.678r^2-3.591r^3$
T1S3[1.5] : $M1=0.308-0.437r-1.959r^2+10.614r^3$
T1S3[3.0] : $M1=0.135-0.161r+3.064r^2-2.407r^3$
T1S3[4.5] : $M1=0.0916+0.321r+0.334^2+3.188r^3$
T1S3[6.0] : $M1=0.0785+0.465r-0.639r^2+5.181r^3$

M2(r)

T1S1[1.5] : $M2=0.618-4.616r+21.894r^2-36.971r^3$
T1S1[3.0] : $M2=0.286-0.621r+0.378r^2-2.407r^3$
T1S1[4.5] : $M2=0.320-1.812r+9.105r^2-20.376r^3$
T1S1[6.0] : $M2=0.372-2.422r+12.227r^2-25.939r^3$
T1S2[1.5] : $M2=0.703-3.273r+5.642r^2-1.065r^3$
T1S2[3.0] : $M2=0.378-1.998r+4.322r^2-4.545r^3$
T1S2[4.5] : $M2=0.446-3.605r+13.926r^2-22.064r^3$
T1S2[6.0] : $M2=0.433-3.165r+11.713r^2-19.362r^3$
T1S3[1.5] : $M2=0.602-1.054r-0.268r^2+0.0395r^3$
T1S3[3.0] : $M2=0.502-3.854r+13.474r^2-17.653r^3$
T1S3[4.5] : $M2=0.478-3.867r+13.949r^2-20.017r^3$
T1S3[6.0] : $M2=0.391-2.825r+9.772r^2-15.021r^3$

Hypocenter Directly Below Urban Areas Type

M1(r)

T2S1[1.5] : $M1=0.239+0.111r-0.671r^2-1.618r^3$
T2S1[3.0] : $M1=0.241+0.659r-3.143r^2+2.052r^3$
T2S1[4.5] : $M1=0.203+1.258r-5.352r^2+4.656r^3$
T2S1[6.0] : $M1=0.194+1.276r-4.583r^2+2.604r^3$
T2S2[1.5] : $M1=0.258-0.962r-0.853r^2+9.194r^3$
T2S2[3.0] : $M1=0.259+0.565r-9.055r^2+18.229r^3$
T2S2[4.5] : $M1=0.222+0.789r-7.942r^2+13.336r^3$
T2S2[6.0] : $M1=0.208+1.004r-7.887r^2+11.285r^3$
T2S3[1.5] : $M1=0.197+0.048r-0.824r^2+2.367r^3$
T2S3[3.0] : $M1=0.224+0.312r-6.973r^2+17.558r^3$
T2S3[4.5] : $M1=0.173+1.390r-11.902r^2+23.122r^3$
T2S3[6.0] : $M1=0.162+1.491r-11.273r^2+20.005r^3$

M2(r)

T2S1[1.5] : $M2=0.590-4.084r+19.626r^2-23.161r^3$
T2S1[3.0] : $M2=0.516-7.282r+44.009r^2-69.287r^3$
T2S1[4.5] : $M2=0.506-7.290r+44.163r^2-69.050r^3$
T2S1[6.0] : $M2=0.420-5.653r+35.724r^2-55.832r^3$
T2S2[1.5] : $M2=0.634-0.273r+0.238r^2-6.905r^3$
T2S2[3.0] : $M2=0.399-2.224r+17.255r^2-33.026r^3$
T2S2[4.5] : $M2=0.424-2.136r+13.559r^2-21.938r^3$
T2S2[6.0] : $M2=0.361-1.335r+9.174r^2-13.021r^3$
T2S3[1.5] : $M2=0.653-2.157r+6.709r^2-9.312r^3$
T2S3[3.0] : $M2=0.489-2.643r+14.995r^2-29.79r^3$
T2S3[4.5] : $M2=0.501-3.512r+21.716r^2-41.312r^3$
T2S3[6.0] : $M2=0.387-1.722r+12.607r^2-25.450r^3$

where T1 = hypocenter under sea type, T2 = hypocenter directly below urban areas type, S1 = hard soil, S2 = medium soil and S3 = soft soil. The values in [ ] are plastic periods Tb2 of isolastor.

REFERENCES

1) JSCE : *Dynamic Analysis and Earthquake-Resistant Design*, Gihoudou, 1989.
2) Shibata, A. : Equivalent linear models to determine maximum inelastic response of nonlinear structures for earthquake motions, *Proc. of the 4th JSCE Earthquake Engineering Symposium*, pp. 831-838, 1975.
3) Skinner, R.I., Robinson, W.H., and McVerry, G.H., : *An Introduction to Seismic Isolation*, John Wiley & Sons, 1996.
4) Japan Load Association, *Specifications for Highway Bridges-Part V: Seismic Design*, Maruzen, 1996.
5) Architectural Institute of Japan : *Recommendation for the Design of Base Isolated Buildings*, Maruzen, 1993.
6) Kawashima, K., and Aizawa, K., Modification of earthquake response spectra with respect to damping, Journal of Structural Engineering and Earthquake Engineering, JSCE, 1984.
7) Paul C. Jennings : Equivalent viscous damping for yielding structures, *Proc. of the ASCE*, Vol. 94, No. EM1, pp. 103-116, Feb. 1968.

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免震構造物の応答推定のための減衰補正係数の提案

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等価線形化法はバイリニア形の免震構造物の設計において，構造物の最大変位を推定するためによく用いられる方法である．従って，等価線形化法で免震構造物の応答を精度よく推定するのは大事なことである．本論文では，等価線形化法を利用し，より正確な免震構造物の最大変位を求めるための，減衰補正係数を提案した．この減衰補正係数を求めるために，さまざまな地盤と地震波形の特性を有する１８種類の標準波形を用いた．ここで，等価線形化法を利用した応答推定精度は免震措置の弾性周期と，降伏力と構造物の総重量との比に関係があることを確認した．