# A Study on Damping Correction of Response Spectrum for Long Period and High Damping Range

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#### **SUMMARY:**

The purpose of this study is to propose the response reduction factor for the long period and high damping range, focusing on damping characteristics to evaluate the effect of reducing the building response. In this study, the response reduction effect is evaluated by using response spectra of earthquake ground motions with a different damping ratio. It is found that the response reduction effect reduces over the predominant periods of strong ground motions. In other words, the response reduction effect is smaller than the current estimation in long period range. The tendency is conspicuous in the pulse-like ground motions. The degree of decrease has tendency to depend on phase characteristics. The proposal of the response reduction factor is made based on the spectral analysis results. A time history analysis of the seismically isolated buildings is carried out to confirm the validity of the proposed equation of the damping correction.

Keywords: Response reduction factor, Response Spectrum Method, Damping

# **1. INTRODUCTION**

There is a Response Spectrum Method as an efficient method to predict the maximum seismic response without a time history analysis. As methods using a Response Spectrum Method, there are the Calculation Method of Response and Limit Strength and the Calculation Method for Seismically Isolated Buildings in Japanese seismic code.

Seismic force in the Japanese these methods is calculated by multiplying lumped mass of structures, the site amplification factor, the seismic hazard zone factor, the design acceleration spectrum and the response reduction factor. In particular, the response reduction factor is considered an important element in assessing damping of structures in these methods. The response reduction factor  $F_h$  in Japanese seismic code (from now on, we will abbreviate this to  $F_{h(JSC)}$ ) is equivalent to the damping correction factor in United States (IBC2003), China (GB50011-2001), and Eurocode 8.  $F_{h(JSC)}$  is smaller than the other countries factors given similar values, when the effective damping is larger. The  $F_{h(JSC)}$  is considered to overestimate the damping effect in designing seismically isolated buildings with the high damping ratio. In the actual design, the seismic isolated layer has various combinations of material configuration, thus damping of structures can be higher. It is difficult to respond all cases in  $F_{h(JSC)}$ . In addition long period ground motions and pulse-like ground motions have a significant impact on seismically isolated buildings having the long natural period. In Japan, earthquakes occur on various types. Actually Tohoku-Chiho Taiheiyo-Oki Earthquake occurred March 11, 2011. Strong motion records with maximum acceleration in excess of  $1,000 \text{ cm/s}^2$  were observed in several places. This earthquake lasted for a long time, and the aftershock occurred frequently. From these, damping of structures should be properly evaluated.

The response reduction factor is also very important in the widely used Equivalent Linearization Analysis Method. The seismically isolated buildings having the long natural period and the high damping ratio are special construction methods. Therefore, in order to evaluate the seismic response of such buildings, it is necessary for an accurate estimation. The purpose of this study is the proposal of the response reduction factor for the long period and high damping range.

#### 2. RESPONSE REDUCTION FACTOR

Seismic force  $Q_0$  in the Calculation Method of Response and Limit Strength and the Calculation Method for Seismically Isolated Buildings in Japanese seismic code is calculated by multiplying lumped mass of structures M, the site amplification factor  $G_s$ , the seismic hazard zone factor Z, the design acceleration spectrum at engineering bedrock  $S_0$  and the response reduction factor  $F_h$ . Seismic force is defined in Eqn. 2.1.  $F_{h(ISC)}$  is defined in Eqn. 2.2 by using the effective damping h. The conceptual scheme of a Response Spectrum Method in Japanese seismic code is shown in Fig. 2.1.

$$Q_0 = M \times G_S \times Z \times S_0 \times F_h \tag{2.1}$$

$$F_h = \frac{1.5}{1+10h} \ge 0.4 \tag{2.2}$$



Figure 2.1. Conceptual scheme of Response Spectrum Method in Japan

 $F_{h(JSC)}$  is considered to overestimate the damping effect in designing seismically isolated buildings having the high damping ratio. In Table 2.1, the numerical coefficients related to effective damping of the isolation system design displacement  $B_D$  or  $B_M$  in United States (IBC2003) are given, which shall be based on linear interpolation for effective damping values other than those given. The damping coefficient *B* in United States (FEMA 440) is Eqn. 2.3. The response reduction factor  $\eta_2$  in China (GB50011-2001) is Eqn. 2.4. The value of the damping correction factor  $\eta$  in Eurocode 8 is Eqn. 2.5. These equations are equivalent to  $F_{h(JSC)}$ .

**Table 2.1** Damping coefficients  $B_D$  or  $B_M$ 

Tuble 2.1 Dumping coefficients $D_D$ of $D_M$									
Effective Damping $\beta$ [%]	$\leq 2$	5	10	20	30	40	≥50		
$B_D$ or $B_M$ Factor	0.8	1.0	1.2	1.5	1.7	1.9	2.0		

$$B = \frac{4}{5.6 - \ln(100\beta)} \tag{2.3}$$

$$\eta_2 = 1 + \frac{0.05 - \xi}{0.06 + 1.7\xi} \ge 0.55 \tag{2.4}$$

$$\eta = \sqrt{\frac{0.1}{0.05 + \xi}} \ge 0.55 \tag{2.5}$$

where,  $\beta$ ,  $\xi$ : the effective damping.

As equation of previous, there are several proposed equations of the response reduction factor by Akiyama, Hanson, Kasai and Hisada. Those equations are defined in Eqns. 2.6 to 2.9. Eqn. 2.9 has also natural period parameters. It is verified that those proposed equations are applied to various earthquake ground motions.

Akiyama 
$$F_h = \frac{1+3h_0+1.2\sqrt{h_0}}{1+3h+1.2\sqrt{h}}$$
 (2.6)

Hanson

Tanson 
$$F_h = \sqrt{\frac{(1 - e^{-18h})h_0}{(1 - e^{-18h_0})h}}$$
 (2.7)  
Tasai  $F_h = \sqrt{\frac{1 + 25h_0}{(1 - e^{-18h_0})h}}$  (2.8)

Kasai 
$$F_h = \sqrt{\frac{1+25n_0}{1+25h}}$$
 (2.8)

Hisada 
$$F_h(T_i, h) = \begin{cases} 1.0 & (T = 0.02) \\ 1/\sqrt{1 + 17(1 - 0.05)} \cdot \exp(-2.5T/10^{0.31M_d - 1.2}) & (T \ge 0.07) \end{cases}$$
 (2.9)

where,  $h_0$ : the initial effective damping,  $M_d$ : the magnitude of earthquake.

The response reduction factors by Eqns. 2.2 to 2.5 and Table 2.1, by Eqns. 2.2 and 2.6 to 2.8, by Eqn. 2.9, are shown in Fig. 2.2.  $F_{h(ISC)}$  is smaller than other countries and other proposed equations given similar values, when the effective damping is higher.



Figure 2.2. Comparison of response reduction factors

# **3. EARTHQUAKE GROUND MOTION CHARACTERISTICS**

# 3. 1. Phase Difference Characteristics

A discrete time history f(t) is expressed by a finite Fourier series, is defined in Eqn. 3.1.

$$f(t) = \sum_{k=0}^{N/2} a_k \cos(\omega_k + \phi_k)$$
(3.1)

where,  $a_k$ : denote the Fourier amplitude of the kth degree,  $\phi_k$ : the Fourier phase of the kth degree,  $\omega_k$ : an angular frequency of the kth degree, N: the number of discrete data points.

The difference in the Fourier phase for any adjacent frequencies, which are arranged so as to have the value of an interval  $[0, -2\pi]$ , is defined as the phase difference. It is said that the convergence of the phase differences corresponds to the envelope of the acceleration waveform. The difference in the Fourier phase  $\Delta \phi_k$  is defined in Eqn. 3.2.

$$\Delta \phi_k = \phi_{k+1} - \phi_k, \quad (k = 1, 2, \cdots, N/2 - 1)$$
(3.2)

Examples of a distribution of the phase differences that is represented as a histogram by dividing the interval $[0, -2\pi]$  into 32 are shown in Fig. 3.1. Length of data are unified in 163.84 sec.

The duration of earthquake ground motion  $T_g$  (from now on, we will abbreviate this to 'the duration  $T_g$ ') is calculated by using the distribution of the phase differences, and is defined in Eqns. 3.3 to 3.5.

In addition, the duration of earthquake ground motion  $T_p$  (from now on, we will abbreviate this to 'the duration  $T_p$ ') is defined as cumulative duration, which is the time interval during which the central 90% of the contribution to the integral of the square of the acceleration take place (Trifunac & Brady 1975). The relationship between the duration  $T_g$  and  $T_p$  is shown in Fig. 3.2. Although the duration  $T_g$  is shorter than the duration  $T_p$ , these correlation is comparatively high. This study uses the duration  $T_g$  as an index, which will permit quantitative evaluations of the phase characteristics.

In this study, 30 artificial earthquake ground motions with various phase characteristics for design are shown in Table 3.1.

$$T_{g} = \sqrt{\frac{1}{N_{e}} \sum_{k=1}^{N_{e}} (t_{grk} - \bar{t}_{g\tau})^{2}}$$
(3.3)

$$f_{g\pi k} = -\Delta \phi_k / 2\pi \Delta f, \quad (k = 1, 2, \cdots, N/2 - 1)$$
(3.4)

$$\bar{t}_{g\tau} = \frac{1}{N_e} \sum_{k=1}^{N_e} t_{g\tau k}$$
(3.5)

where,  $t_{gt}$ : group delay time corresponding to Fourier frequency  $f_k$  of the *k*th degree,  $N_e$ : Significant frequency in the number of  $t_{gt}$ .



Figure 3.1. Comparison of phase difference distribution and envelope characteristics

**Figure 3.2.** Relationship between duration  $T_g$  and  $T_p$ 

#### 3.2. Site Amplification Characteristics

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In this study, 3 ground models shown in Fig. 3.3 are used to evalute site amplification characteristics. 30 artificial earthquake ground motions for design are amplified by using a Single Dimension Wave Propagation Theory on 3 ground models. The nonlinear dynamic soil properties used for the analysis, which are based on the study by Hardin and Drnevich (1972), is defined in Eqns. 3.6, 3.7, and is shown in Fig. 3.4. In the clay layer and the sand layer, the standard shear strain  $\gamma_{0.5}$  is 0.18% and 0.10%, the maximum effective damping  $h_{max}$  is 17% and 21%, respectively. The shear modulus ratio of soils and strain level developed in surface soils are estimated from the record by a simple method.

$$G/G_0 = \frac{1}{1 + \gamma/\gamma_{0.5}}$$
(3.6)

$$h = h_{\max} \left( 1 - G / G_0 \right) \tag{3.7}$$

where,  $G/G_0$ : shear modulus ratio,  $\gamma$ : shear strain.

In a Response Spectrum Method for seismically isolated building in Japanese seismic code, the final value of first predominant period  $T_1$ , second predominant period  $T_2$  and amplification factor  $G_{S1}$ ,  $G_{S2}$ , several convergence calculations are needed to obtain the site amplification factor  $G_S$ , because of evaluating especially natural period of the structure, about 2.0 to 5.0 sec. Ground1-2 and Ground3 corespond to the site class  $2^{nd}$  and  $3^{rd}$  in Japanese seismic code, respectively.

	Farthquake name	Observation point	Abbreviation	PGA	Duration	Duration
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	Larinquake name	Observation point	Abbieviation	$[m/s^2]$	$T_g[sec]$	$T_p[sec]$
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	Imperial Valley, 1940	El Centro	Elce	3.81	18.9	30.2
Tokachi-oki, 1964         Hachinohe         Hachi         3.25         42.1         102.2           Hyogo-ken Nanbu, 1995         JMA Kobe         Kobe         3.91         8.9         15.6           Osaka Gas Fukiai         Fuki         3.29         15.0         10.6           JR Takatori         Taka         2.91         27.4         15.8           Tottori-ken Seibu, 2000         Kik-net Hino         TTRH02         3.75         23.5         74.0           Geiyo, 2001         K-net Yurai         HRS009         4.88         16.5         38.2           Tokachi-oki, 2003         K-net Tomakomai         HKD129         3.49         27.0         88.2           Niigata-ken Chuetsu, 2004         K-net Torai         ISK005         4.19         15.4         29.6           Niigata-ken Chuetsu-oki, 2007         K-net Kashiwazaki         NIG018         4.56         9.3         16.8           Iwate Miyagi Nairiku, 2008         K-net Naruko         MYG005         3.24         14.3         36.0           Assumption Nagoya         Saphenous Fault         Cg062         3.81         16.5         52.4           Assumption Shin-Tokai         Nagoya Sannomaru         San         3.33         16.9         58.8	Kerm Country, 1952	Taft	Taft	3.87	12.6	38.0
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Tokachi-oki, 1964	Hachinohe	Hachi	3.25	42.1	102.2
$\begin{array}{c c c c c c c c c c c c c c c c c c c $		JMA Kobe	Kobe	3.91	8.9	15.6
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	Hyogo-ken Nanbu, 1995	Osaka Gas Fukiai	Fuki	3.29	15.0	10.6
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $		JR Takatori	Taka	2.91	27.4	15.8
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	Tottori-ken Seibu, 2000	Kik-net Hino	TTRH02	3.75	23.5	74.0
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Geiyo, 2001	K-net Yurai	HRS009	4.88	16.5	38.2
Niigata-ken Chuetsu, 2004K-net OjiyaNIG019 $4.06$ $25.7$ $31.8$ Noto-hanto, 2007K-net ToraiISK005 $4.19$ $15.4$ $29.6$ Niigata-ken Chuetsu-oki, 2007K-net KashiwazakiNIG018 $4.56$ $9.3$ $16.8$ Iwate Miyagi Nairiku, 2008K-net KashiwazakiNIG018 $4.56$ $9.3$ $16.8$ Iwate Miyagi Nairiku, 2008K-net NarukoMYG005 $3.24$ $14.3$ $36.0$ Assumption NagoyaOpposite FaultCg062 $3.81$ $16.5$ $52.4$ Assumption Shin-TokaiNagoya SannomaruSan $3.33$ $16.9$ $58.8$ Assumption KantoTokyo JMATOK $4.05$ $12.4$ $32.6$ Yokohama MMYKL $3.71$ $36.8$ $137.6$ Vokohama MMYKL $3.71$ $36.8$ $137.6$ Vokohama AOSK005 $3.96$ $47.3$ $180.4$ Kik-net OsakaOSK005 $3.96$ $47.3$ $180.4$ Kik-net KishiwadaOSK008 $3.35$ $33.4$ $135.6$ Envelop functions of The Building Center of Japan (BCJ) Guideline, Level.2Random phase 1Ran1 $3.71$ $34.0$ $69.4$ Random phase 3Ran3 $3.42$ $33.1$ $70.1$ Random phase 4Ran4 $3.77$ $32.7$ $69.3$	Tokachi-oki, 2003	K-net Tomakomai	HKD129	3.49	27.0	88.2
	Niigata-ken Chuetsu, 2004	K-net Ojiya	NIG019	4.06	25.7	31.8
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $		JMA Kawaguchi	Kawa	3.26	31.5	60.9
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Noto-hanto, 2007	K-net Torai	ISK005	4.19	15.4	29.6
Iwate Miyagi Nairiku, 2008K-net NarukoMYG005 $3.24$ $14.3$ $36.0$ Assumption NagoyaOpposite FaultCg062 $3.81$ $16.5$ $52.4$ Assumption Shin-TokaiSaphenous FaultFukuzai $3.33$ $16.9$ $58.8$ Assumption Shin-TokaiNagoya SannomaruSan $3.33$ $25.8$ $89.3$ Assumption KantoTokyo JMATOK $4.05$ $12.4$ $32.6$ Yokohama MMYKL $3.71$ $36.8$ $137.6$ Osaka DistrictOSA $2.48$ $57.2$ $274.9$ West OsakaWOS $2.90$ $53.1$ $201.8$ K-net OsakaOSK005 $3.96$ $47.3$ $180.4$ Kik-net KonohanaOSK005 $3.96$ $47.3$ $180.4$ Kik-net KishiwadaOSK008 $3.35$ $33.4$ $135.6$ Envelop functions of The Building Center of Japan (BCJ) Guideline, Level.2Random phase 1Ran1 $3.71$ $34.0$ $69.4$ Random phase 3Ran3 $3.42$ $33.1$ $70.1$ $70.1$ $70.1$	Niigata-ken Chuetsu-oki, 2007	K-net Kashiwazaki	NIG018	4.56	9.3	16.8
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$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$		Side Slip Fault	Yoko	5.01	12.5	33.3
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $		Saphenous Fault	Fukuzai	3.33	16.9	58.8
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Assumption Shin-Tokai	Nagoya Sannomaru	San	3.33	25.8	89.3
Assumption Kanto         Yokohama MM         YKL         3.71         36.8         137.6           Assumption Nankai         Osaka District         OSA         2.48         57.2         274.9           Mest Osaka         WOS         2.90         53.1         201.8           K-net Osaka         OSK005         3.96         47.3         180.4           Kik-net Konohana         OSKH02         3.35         48.6         176.5           Osaka Fukushima         FKS         3.33         38.7         136.4           K-net Kishiwada         OSK008         3.35         33.4         135.6           Envelop functions of The Building Center of Japan (BCJ) Guideline, Level.2         Random phase 1         Ran1         3.71         34.0         69.4           Random phase 3         Ran3         3.42         33.1         70.1           Random phase 4         Ran4         3.77         32.7         69.3	Assumption Kanto	Tokyo JMA	TOK	4.05	12.4	32.6
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$		Yokohama MM	YKL	3.71	36.8	137.6
Assumption Nankai         West Osaka         WOS         2.90         53.1         201.8           Assumption Nankai         K-net Osaka         OSK005         3.96         47.3         180.4           Kik-net Konohana         OSKH02         3.35         48.6         176.5           Osaka Fukushima         FKS         3.33         38.7         136.4           K-net Kishiwada         OSK008         3.35         33.4         135.6           Envelop functions of The Building Center of Japan (BCJ) Guideline, Level.2         Random phase 1         Ran1         3.71         34.0         69.4           Random phase 3         Ran3         3.42         33.1         70.1           Random phase 4         Ran4         3.77         32.7         69.3	Assumption Nankai	Osaka District	OSA	2.48	57.2	274.9
Assumption Nankai         K-net Osaka         OSK005         3.96         47.3         180.4           Assumption Nankai         Kik-net Konohana         OSKH02         3.35         48.6         176.5           Osaka Fukushima         FKS         3.33         38.7         136.4           K-net Kishiwada         OSK008         3.35         33.4         135.6           Envelop functions of The Building Center of Japan (BCJ) Guideline, Level.2         Random phase 1         Ran1         3.71         34.0         69.4           Random phase 2         Ran2         3.29         33.3         68.0           Random phase 3         Ran3         3.42         33.1         70.1           Random phase 4         Ran4         3.77         32.7         69.3		West Osaka	WOS	2.90	53.1	201.8
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Osaka Fukushima         FKS         3.33         38.7         136.4           K-net Kishiwada         OSK008         3.35         33.4         135.6           Envelop functions of The Building Center of Japan (BCJ) Guideline, Level.2         Random phase 1         Ran1         3.71         34.0         69.4           Random phase 2         Ran2         3.29         33.3         68.0           Random phase 3         Ran3         3.42         33.1         70.1           Random phase 4         Ran4         3.77         32.7         69.3		Kik-net Konohana	OSKH02	3.35	48.6	176.5
K-net KishiwadaOSK0083.3533.4135.6Envelop functions of The Building Center of Japan (BCJ) Guideline, Level.2Random phase 1Ran13.7134.069.4Random phase 2Ran23.2933.368.0Random phase 3Ran33.4233.170.1Random phase 4Ran43.7732.769.3		Osaka Fukushima	FKS	3.33	38.7	136.4
Envelop functions of The Building Center of Japan (BCJ) Guideline, Level.2Random phase 1 Random phase 2Ran1 Ran23.71 3.2934.0 3.3369.4 69.4Random phase 2Ran23.2933.368.0Random phase 3Ran33.4233.170.1Random phase 4Ran43.7732.769.3		K-net Kishiwada	OSK008	3.35	33.4	135.6
Envelop functions of The Building Center of Japan (BCJ) Guideline, Level.2Random phase 2Ran23.2933.368.0Random phase 3Ran33.4233.170.1Random phase 4Ran43.7732.769.3	Envelop functions of The Building Center of Japan (BCJ) Guideline, Level.2	Random phase 1	Ran1	3.71	34.0	69.4
Building Center of Japan (BCJ) Guideline, Level.2Random phase 3Ran33.4233.170.1Random phase 4Ran43.7732.769.3		Random phase 2	Ran2	3.29	33.3	68.0
Random phase 4 Ran4 3.77 32.7 69.3		Random phase 3	Ran3	3.42	33.1	70.1
		Random phase 4	Ran4	3.77	32.7	69.3

Table 3.1 List of artificial earthquake ground motions with various phase characteristics



Figure 3.3. Ground models

Figure 3.4. Nonlinear dynamic soil properties

#### 4. PROPOSAL OF RESPONSE REDUCTION FACTOR

A root mean square response displacement  $\sigma_x^2$  in a Theory of Random Processes is defined in Eqn. 4.1, when structures have an influence of white noise. Expected value of response displacement spectrum ratio is given in Eqn. 4.2.

$$\sigma_x^2 = \begin{cases} \frac{pwS_0}{4h\omega^3} (1 - e^{-2h\omega t_1}) & (h \neq 0) \\ \frac{pwS_0 t_1}{2\omega^2} & (h = 0) \end{cases}$$
(4.1)

$$S_d(h)/S_d(h=0.05) = \sqrt{\frac{1 - e^{-4\pi h(t_1/T)}}{20h(1 - e^{-0.2\pi(t_1/T)})}}$$
(4.2)

where,  $_{pw}S_0$ : power spectrum density,  $\omega$ : natural cicular frequency,  $t_1$ : duration of earthquake ground motion.

The duration of earthquake ground motion  $t_1$  is needed to convert into the equivalent duration of white noise.  $t_1/T$  would be about 3 to 5 as the damping effect of the actual earthquake ground motion. In this study, Eqns. 4.3, 4.4 are the proposed equations of the response reduction factor (from now on, we will abbreviate this to ' $F_{h(\text{propasal})}$ '). Eqn. 4.3 is improved the format of Eqn. 2.2, is attached the *R* factor. Eqn. 4.4 is approximated to Eqn. 4.2 by using a Least-Squaes Method. The natural period *T* and the duration  $T_g$  are added to Eqn. 4.4.

$$F_{h} = \frac{1.5}{1+10h} \cdot R \qquad (h > 0.05) \qquad (4.3)$$

$$R = \frac{20h-1}{2} (1 - \frac{T}{T}) + 1 \qquad (T < T_{2})$$

$$R = 1.0 (T_2 \le T \le T_1)$$

$$R = \frac{20hT_1}{T_a} (1 - \frac{T_1}{T}) + 1 (T_1 < T < 5.0)$$
(4.4)

The application range of Eqn. 4.3 is above 5% effective damping *h* to target high damping range in this study. Eqn. 4.4 is separated into predominant periods of soil  $T_1$  and  $T_2$ , the short period range are only advisory. In the predominant period range, Eqn. 4.4 has the equal damping effect of  $F_{h(JSC)}$ . Over predominant period, the natural period *T* is longer or the duration  $T_g$  is shorter, when the damping effect is lower. Eqn. 4.4 uses the duration  $T_g$  in order to evaluate the phase characteristics. In addition, the site amplification would not significantly affect the duration of earthquake ground motion.



Figure 4.1. Comparison of proposed response reduction factor and analysis values

Several comparisons of  $F_{h(\text{propasal})}$  and analysis values; the response displacement spectrum ratio  $S_d(h)/S_d(h=0.05)$ , are shown in Fig. 4.1. Analysis values have phase characteristics of Kobe, Elce and Hachi waves, amplified in Ground1, respectively. The values of  $F_{h(\text{propasal})}$  can be fitted to the analysis values. In phase characteristics with pulse-like ground motions, analysis values are uneven, thus it is necessary to evaluate earthquake ground motions characteristics from various perspectives, such as the pulse period.

### 5. TIME HISTORY ANALYSIS

A time history analysis of the seismically isolated buildings (from now on, we will abbreviate this to 'THA') is carried out to confirm the validity of  $F_{h(propasal)}$ . In this study, the seismically isolated buildings are taken up to target long period and high damping range.

#### 5.1. Outline of Analysis

Analytical model is 1-mass-system as base-isolated building with isolator and hysteresis damper or velocity-dependent fluid damper (From now on, we will abbreviate these to 'Hysteresis model' and 'Fluid model', respectively). The analysis is performed under the following terms. Stiffness of isolator  $k_f$  is decided so that the isolation period  $T_f$  is set to 3.0, 4.0 and 5.0 sec, and lumped mass of structure M. The hysteresis damper is the perfect elasto-plastic, considered only the harizontally displacement. The fluid damper is bi-linear element with a damper force relief mechanism. Analytical models are shown in Fig. 5.1.

In Hysteresis model, the yield displacement of the hysteresis damper  $\delta_y$  is 1.0cm. The yield strength of the hysteresis damper  $Q_y$  is given as the yield shear coefficient of the hysteresis damper  $\alpha_s$  set to 0.02, 0.04 and 0.06. The first stiffness  $k_1$  is  $k_1 = k_f + k_s$  ( $k_s$ : the stiffness of the hysteresis damper).

In Fluid model, the first damping coefficient of the fluid damper  $C_B$  is  $C_B = Q_{v150}/40$  ( $Q_{v150}$ : damping force at velocity of 150cm/s). The damping force at velocity of 150cm/s  $Q_{v150}$  is given as the introduction amount of the fluid damper  $\alpha_v$  set to 0.03, 0.05 and 0.07. The second damping coefficient ratio  $\rho$  is 0.0678.

THA is carried out for 1620 ( $=2\times3\times3\times30\times3$ ) SDOF systems: 2 damper types; 3 amount of the damper; 3 isolation periods; 30 artificial earthquake ground motions shown in Table 3.1; 3 ground models shown in Fig. 3.3.



Figure 5.1. Outline of analytical model

#### 5.2. Results of Analysis

The relationship between the duration  $T_g$  and analysis results of maximum displacement  $\delta_{max}$  is shown in Fig. 5.2. The fitted curves of each the yield shear coefficient of the hysteresis damper  $\alpha_s$  or the introduction amount of the fluid damper  $\alpha_v$  are also shown in Fig. 5.2.

The analysis results have a tendency that the duration  $T_g$  is shorter when the maximum displacement  $\delta_{max}$  increases. These results suggest the possibility that the maximum displacement  $\delta_{max}$  depends on the phase characteristics of input earthquake ground motions.

Several comparisons of the maximum displacement  $\delta_{max}$  using a Equivalent Linearization Analysis Method (from now on, we will abbreviate this to 'ELM') and THA, are shown in Fig. 5.3. In results of the ELM, the response values using  $F_{h(\text{propasal})}$  and  $F_{h(\text{JSC})}$  are superimposed in Fig. 5.3. ELM is adopted in seismically isolated buildings based on Japanese design standard. The response values using  $F_{h(\text{JSC})}$  is somewhere smaller than the analysis results in the long period and high damping range, thus the equation of current  $F_{h(\text{JSC})}$  is considered to overestimate the damping effect in designing seismically isolated buildings having the long natural period and high damping. On the other hand, the response values using  $F_{h(\text{propasal})}$  agree well with the analysis results in the long period and high damping range, and evaluate as the safe side. The damping effect can be properly evaluated by using  $F_{h(\text{propasal})}$ .



Figure 5.2. Relationship between duration  $T_g$  and maximum displacement  $\delta_{max}$ 

Figure 5.3. Comparison of Estimated and Numerical maximum displacement  $\delta_{max}$ 

## 6. CONCLUSIONS

In this study, the response reduction factor  $F_h$  for the long period and high damping range is proposed by considering phase and period characteristics of earthquake ground motions.

The response reduction factor in the Japanese seismic code is smaller than the other countries codes factors. The spectral analysis and the time history analysis of the seismically isolated buildings are carried out to confirm the validity of the proposed equation in this study. The relationship between phase characteristics of earthquake ground motions and the seismic response of buildings is shown from analysis results. Several comparisons of the maximum displacement using a Equivalent Linearization Analysis Method and a time history analysis are shown, and the validity of the proposed equation is confirmed on buildings having the the long natural period and high damping. In future, the followings are considered to improve the precision of the proposed equation to be tackled: considering more building types and more earthquake ground motion characteristics; defining clearly the duration of the earthquake ground motion.

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