DERIVATION OF A DISPLACEMENT RESPONSE PREDICTION FOR RC STRUCTURES BASED ON THE CAPACITY SPECTRUM METHOD

Y. Ito[1], K. Kusunoki[2], T. Yeow[3]

[1] *Joint Researcher, Earthquake Research Institute, The University of Tokyo, i10-44@eri.u-tokyo.ac.jp*
[2] *Professor, Earthquake Research Institute, The University of Tokyo, kusunoki@eri.u-tokyo.ac.jp*
[3] *Project Researcher, Earthquake Research Institute, The University of Tokyo, trevoryeow@eri.u-tokyo.ac.jp*

Abstract

The capacity spectrum method was permitted for use in Japanese structural engineering practice in the 2000 revision of the Japanese Building Standards Law, and is widely used in practice as the building's displacement can be predicted without the need for more complex time-history analysis. Based on the standard, structural performance need only be considered at serviceability, damage-control and life-safety limit states by comparing the capacity curve of the structure and design demand spectrums representative of these limit-states. However, for seismic performance evaluations, other shaking intensities would need to be considered. As code-specified demand spectrums have not been provided for these cases, the use of the capacity spectrum method is limited for these cases. In order to perform seismic performance evaluations, it is necessary to clarify the relationship between the level of the input ground motion and the displacement response.

In this paper, a prediction formula for predicting the displacement response for middle to low-rise reinforced concrete (RC) structures considering the average velocity response spectrum was proposed as a simple alternative. This equation was derived using capacity spectrum concepts but assuming (i) structural strength does not increase after yielding had occurred, and (ii) the spectral velocity is reasonably constant at the natural frequencies corresponding to the secant stiffnesses of interest. Based on these assumptions, the damage prediction equation can be represented as follows:

$$_v\delta_{\max} = F_h\sqrt{\mu_{eq}} \cdot \frac{T_y}{2\pi} \cdot \left(\frac{1}{bT_y - aT_y} \cdot \int_{aT_y}^{bT_y} S_v(\mathrm{h}_{0.05}, T).\,\mathrm{dT}\right)$$

Where $_v\delta_{\max}$ is the maximum predicted displacement response, F_h is the reduction factor accounting for additional damping due to inelastic behavior, μ_{eq} is the ductility factor at the building's response, T_y is the period corresponding to secant yield stiffness, $S_v(h_{0.05}, T)$ is the spectral velocity of the ground motion at period T and with 5% damping.

It was found that $F_h\sqrt{\mu_{eq}}$ was approximately 1.0 for μ_{eq} between 1.0 and 5.0 (maximum allowed in Japanese Building Standard). Furthermore, based on frequency response function, the optimum a and b factors to use in the equation was 0.9 and 1.1, respectively.

In order to verify the proposed method, inelastic response analysis is carried out using observed ground motion records. Predictions of the displacements were then made using the proposed prediction equation and the capacity spectrum method, which were then compared to those from the earthquake response analysis. It was observed that the proposed prediction equation could be estimate the displacement response with the same accuracy as the capacity spectrum method. Based on these results, the proposed prediction equation as follows can be used to reliably predict the building's displacement response.

$$_v\delta_{\max} = 0.16\left(\frac{1}{0.2} \cdot \int_{0.9T_y}^{1.1T_y} S_v(\mathrm{h}_{0.05}, T).\,\mathrm{dT}\right)$$

Keywords: displacement response prediction, velocity response spectrum, reinforced concrete, capacity spectrum method

1. Introduction

1.1 Background

In recent years, there is an increased need for certain buildings to be continuously usable after a major seismic event, such as disaster management centers or emergency shelters. To judge the residual seismic capacity of structures after a major earthquake, it is necessary to evaluate the building's displacement response caused by the earthquake. One such method proposed by (Kusunoki et.al [1]) is to use acceleration sensor readings to calculate a performance curve, which is the relationship between the representative restoring force and deformation, to evaluate the extent of inelastic response in the building and the remaining displacement capacity before reaching the building's safety limit.

In an earthquake damage survey, research has been conducted to estimate the damage level and/or displacement response by correlating this to some parameter which quantifies the seismic event's shaking intensity (referred to as the intensity measure, hereinafter). Various factors (e.g. peak ground acceleration, spectral acceleration, and spectrum intensity) have been adopted for the intensity measure. If the maximum displacement response during an earthquake can be expressed in relation to the intensity measure, a simple response prediction method can be made possible. However, since these factors on their own do not provide sufficient information on all parameters which may influence building response, the correlation with the displacement response and these factors are not always high. Additionally, the physical explanation for the relationship between the factors and the maximum displacement response are not clear since the factors used for the intensity measure are typically determined by regression analysis.

Due to the significant socioeconomic influence of major seismic events, there is rising demand for buildings to be more resilient rather than being designed to minimum standards such as "collapse prevention". Therefore, even if existing buildings satisfy current prescription-based seismic standards, it may be necessary to re-evaluate its seismic performance considering its likely displacement response and residual capacity.

1.2 Purpose of this research

In the Japanese building Standards law, the capacity spectrum method may be used for buildings shorter than 60 m to estimate the maximum displacement response as an alternative to more resource-demanding time-history response analysis. In the capacity spectrum method, the response spectrum of acceleration and displacement is used as the "capacity curve", and the "demand curves" are specified in stepwise states to check various performance objectives (i.e. serviceability, damage-control, and life-safety). The intersect of these curves is the estimated response. If one considers a different performance objective, it is necessary to recalculate the response point due to potential changes in effect (or secant) period, T_{eq}. Hence, the response process from a small earthquake to a large earthquake cannot be evaluated like a continuous function using this method. Furthermore, according the capacity spectrum method, the demand curve may be reduced by a factor, F_h, which considers the hysteretic energy absorbed through deformation of plastic hinges. Thus, the response estimation using the capacity spectrum method is highly dependent on the accuracy of F_h. Therefore, if the maximum displacement response can be evaluated from the elastic response spectrum using a reliable intensity measure which can consider the plasticity of the building without needing to consider F_h and T_{eq}, one could derive a simpler prediction method to use instead of the capacity spectrum method.

In this paper, a formula to predict the peak displacement response of middle-to-low rise reinforced concrete (RC) structures considering a intensity measure is proposed. This equation was derived using capacity spectrum concepts by simplifying the calculation of various parameters (i.e. F_h and T_{eq}) and considering the velocity response spectrum. The accuracy of this prediction equation will then be evaluated against inelastic response history analyses. Besides, the authors have been examining the qualitative tendency of the maximum displacement response using the inelastic response history analyses results (Ito and Kusunoki [2], [3]). However, it was examined by the relation between the maximum displacement response and the average velocity spectrum based on the regression analysis. So, we think it is necessary to discuss the proposed prediction equation in perspective of physical significance.

2. Average spectral velocity consideration

2.1 Importance of spectral velocity

Peak ground acceleration and velocity are physical values which is one measure used to represent the shaking intensity of the ground motion, and are no dependent on the characteristics of the building. Because of its easy in quantifying these parameters, it was often used in the past as the intensity measure for verifying the displacement response of buildings. Generally, short-period buildings have a high correlation with between the displacement response and the maximum acceleration. However, the correlation decreases as the natural period of the building increases, while the correlation with the maximum velocity increases (Kobayashi at.al [4]). In addition, the effective period of buildings may increase due to inelastic action, even for short-period buildings. Therefore, the intensity measure associated with the response of the building may be better represented by a velocity-based parameter rather than an acceleration-based parameter.

On the other hand, response spectra are often used in seismic design, and the velocity response spectrum S_v can be treated as a measure of the maximum potential energy that the ground motion inputs into a building. Housner expressed this as $mS_v^2(\mathrm{h}_{0.00},\mathrm{t})/2$ using the undamped velocity response spectrum $S_v(\mathrm{h}_{0.00},\mathrm{t})$ (Housner [5]), where m is the total mass of building. Based on this, S_v has a physical significance on the building's response, and thus will be further considered as the intensity measure for evaluating displacement response.

2.2 Difference between spectral intensity and average velocity response spectrum

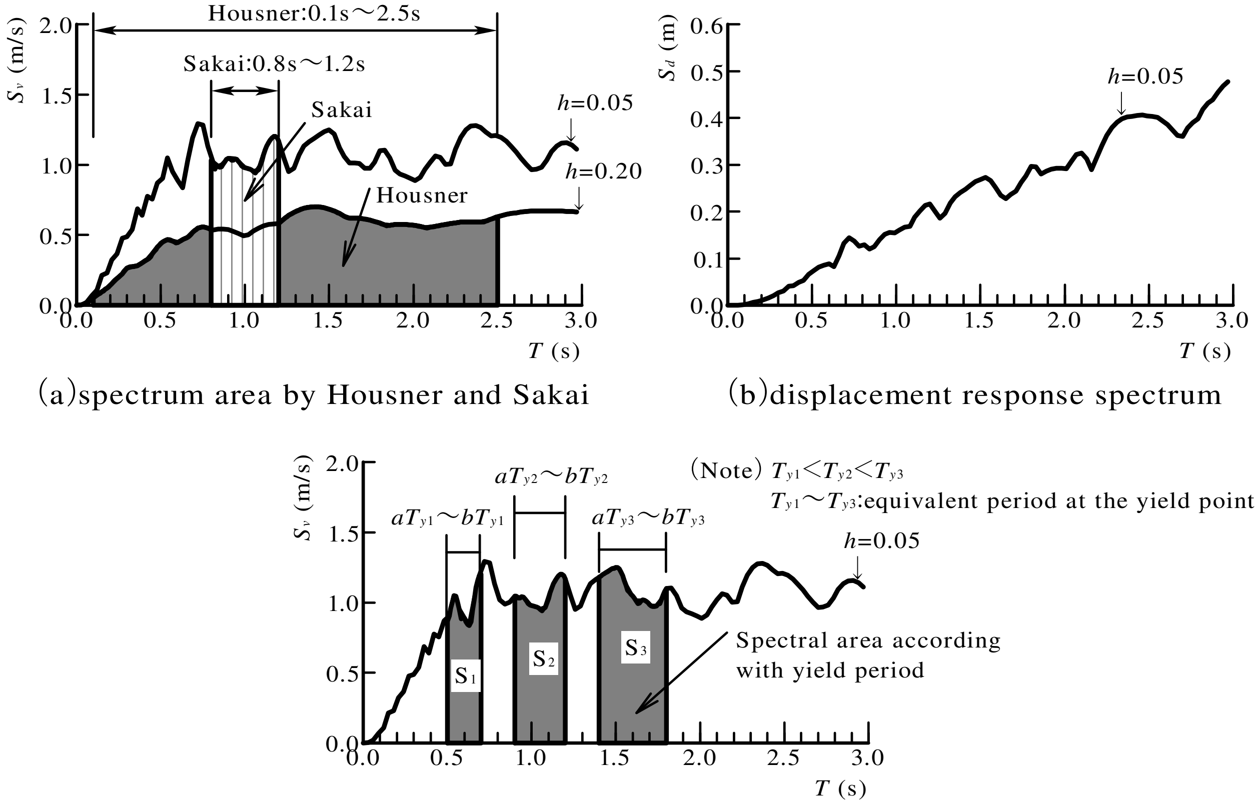
Fig.1 (a) shows an example of the velocity response spectrum. The spectrum shape obtained from actual ground motion has irregularities, and the spectrum value may vary significantly with only a slight change in the period. Consideration of an average value can reduce this variation. One measure proposed by Housner was termed the "spectrum intensity", *SI*, as shown in Fig.1(a). *SI* is the area under the velocity spectra within the period range of 0.1 to 2.5 sec (Housner [6]).

One limitation of *SI* was that it considered a wide range of periods, some of which may not be relevant to the building of interest. For this reason, Sakai proposed a period range of 0.8 to 1.2 sec for the middle-to-low rise RC buildings for which the natural period was assumed to be about 0.5 sec as shown in Fig.1(a) (Sakai at.al [7]). Since there is no certainty that the natural period of an actual middle-to-low rise RC building with would be 0.5 sec, there is still a necessary to validate the use of this period range. An additional complexity is that both approaches considered different damping ratios, h, (i.e. Housner used h = 0.2 while Sakai used h = 0.05).

One consideration which can be made is that S_v can be regarded not only as a measure of input energy, but also by the product of spectral displacement, S_d, and the natural frequency, ω. At the same time, S_d generally increases as the period increases, even when S_v is relatively constant as shown in Fig.1(b).

Therefore, S_v is more likely to show engineering significance than spectral area as the intensity measure. To reduce the effect of local variation of S_v, the average value of S_v could be determined following Eq. (1) considering a small period range close to the fundamental building period, aT_y to bT_y, where T_y is the period corresponding to yield, and a and b are factors determining lower and upper bound of the period range. As h = 0.05 is often used in structural engineering practice, this value was adopted. A demonstration of this approach is shown Fig.1(c).

$$ {}_{\mathrm{ave}}S''_v = \frac{1}{bT_y - aT_y} \cdot \int_{aT_y}^{bT_y} S_v(\mathrm{h}_{0.05}, T).\,\mathrm{dT} \tag{1} $$



(a)spectrum area by Housner and Sakai

(b)displacement response spectrum

(c)spectrum area considered in this paper

Fig. 1 – Various consideration of the velocity response spectrum

3. Consideration of velocity response spectrum in the Capacity Spectrum Method

As discussed previously, the capacity spectrum method involves simplifying the building's capacity down to an equivalent single-degree-of-freedom system and compare it with the response acceleration and displacement "demand" spectra. Since S_v/S_d and S_a/S_v is ω, applying F_h to one parameter would result in another decreasing by the same amount. With this consideration, one could determine the reduced S_v value at T_{eq} following the steps shown in Fig.2, and relate it back to spectral displacement as shown in Eq. (2), where ${}_pS_d$ (h_{eq}, T_{eq}) is the pseudo displacement response spectrum.

$${}_{\mathrm{p}}S_d\left(h_{eq}, T_{eq}\right) = F_h \cdot S_v\left(\mathrm{h}_{0.05}, T_{eq}\right)/\omega_{eq} \tag{2}$$

According the Japanese Building Standards Law, the design-spectra had a constant spectral acceleration region at short periods and a constant velocity region for a mid-range of periods as shown in Fig.3. If a building had a secant-yield period of between 0.5 to 1.5 sec and a ductility response factor of 3, the equivalent period elongates to 0.87 to 2.60 sec. As this range of period falls within the constant velocity region of the design spectra, only this region was considered further.

The velocity response spectrum S_v at the yield point T_y shifts to the equivalent period point T_{eq}, and assuming that the maximum displacement response point obtained in consideration of the damping effect is ${}_v\delta_{\max} = F_h \cdot {}_v\delta_m$, and then, Eq. (3) was obtained as follows:

$${}_v\delta_{\max} = F_h\sqrt{\mu_{eq}} \cdot {}_v\delta_e \tag{3}$$

Where ${}_v\delta_m = \sqrt{\mu_{eq}} \cdot {}_v\delta_e$, ${}_v\delta_m / {}_v\delta_e = (S_v / {}_v\omega_{eq}) / (S_v / {}_v\omega_y)$

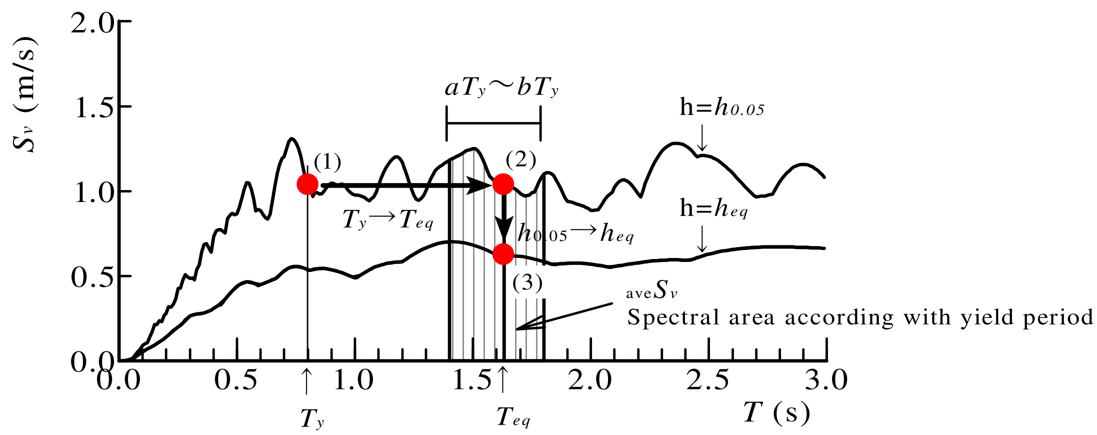
F_h is damping reduction factor, ${}_v\delta_{max}$ is maximum displacement response of structure, ${}_v\delta_e$ is elastic maximum displacement response, μ_{eq} is ductility factor, ${}_v\delta_m$ is elastic maximum displacement response for the equivalent frequency, δ_y is yield displacement of structure, ${}_v\omega_y$ is equivalent frequency at the yield point, ${}_v\omega_{eq}$ is equivalent frequency at the maximum displacement response point.

The maximum displacement response assuming fully-elastic behavior, ${}_v\delta_e$, can be calculated by $S_v(\mathrm{h}_{0.05}, T_y)/\ {}_v\omega_y$. By substituting this into Eq. (3), Eq. (4) was obtained.

$$ {}_v\delta_{\max} = F_h\sqrt{\mu_{eq}} \cdot \frac{T_y}{2\pi} \cdot S_v(\mathrm{h}_{0.05}, T) \tag{4} $$

Substituting Eq. (1) into Eq. (4), Eq. (5) can be obtained.

$$ {}_v\delta_{\max} = F_h\sqrt{\mu_{eq}} \cdot \frac{T_y}{2\pi} \cdot \left(\frac{1}{bT_y - aT_y} \cdot \int_{aT_y}^{bT_y} S_v(\mathrm{h}_{0.05}, T).\mathrm{dT} \right) \tag{5} $$



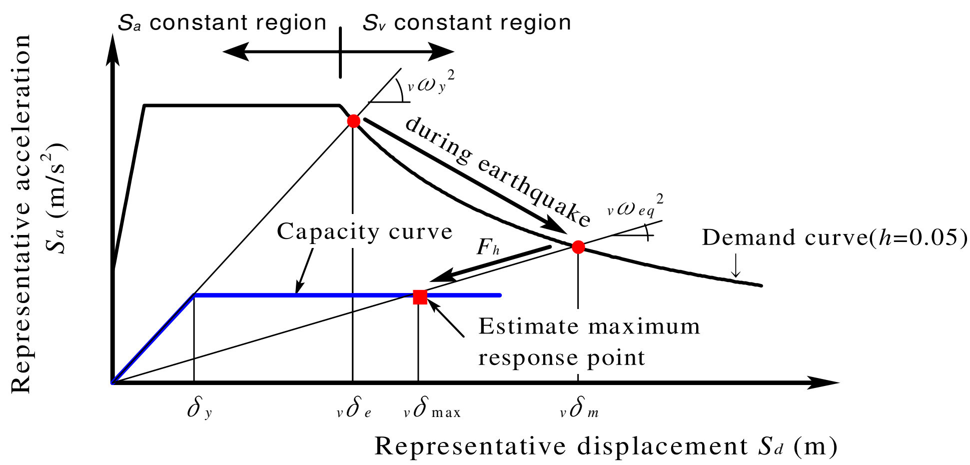
(1) For elastic response, the spectral value is given by the point $S_v(\mathrm{h}_{0.05}, T_y)$

(2) At peak response of displaement, the equivalent period becomes T_{eq}, and the point shifts to $S_v(h_{eq}, T_{eq})$

(3) Taking into account hysteretic damping from inelastic action, spectral velocity decreases to $S_v(h_{eq}, T_{eq})$

Note: This paper assumed that the initial period is defined as the period corresponding to secant-yield stiffness T_y

Fig. 2 – Determining spectral velocity demand following the Capacity Spectrum Method



Note : Subscript "v" indicates S_v for the constant range

Fig. 3 –Outline of Capacity Spectrum Method for the S_v constant region

4. Further simplification of Eq. (5)

4.1 Determination of *a* and *b* parameters

In general, the maximum displacement response is mostly affected by resonance, which occurs when a certain frequency component the earthquake ground motion and the natural frequency of the building coincide. For the resonance phenomenon, the relationship between input and response can be represented by the transfer characteristics shown in Fig.4. The transfer characteristics can be handled on a time axis (impact response function) or a frequency axis (frequency response function). A Fourier transform can be used to convert from the time axis to the frequency axis, and the square of the Fourier amplitude becomes a power spectrum (Crandall [8]). Although the ground motion is given by a response spectrum in the capacity spectrum method, but the ground motion in the frequency axis is given by a power spectrum. Here, the power spectrum is multiplied by a frequency response function to obtain a displacement response.

When Euler's law is applied to equation of vibration motion according to the single-degree-of-freedom system, where real part was denoted as $\mathrm{Re}\{e^{i\omega_{ex}t}\} = \cos\omega_{ex}$ and the imaginary part was denoted as $Im\{e^{i\omega_{ex}t}\} = \sin\omega_{ex}$, the equation of vibration motion can be written as follows:

$$\ddot{y}(y) + 2h\omega_{eq}\dot{y}(t) + \omega_{eq}{}^2 y(t) = e^{i\omega_{ex}t} \tag{6}$$

Where ω_{ex} is frequency of input, $e^{i\omega_{ex}t}$ is input motion

From Eq. (6), if the frequency response function related to the velocity response spectrum is represented by the symbol $H_v(h_{eq}, \omega_{ex})$, the frequency transfer function for velocity, which is defined as $(i\omega_{ex})H_y(i\omega_{ex})\, e^{i\omega_{ex}t}$, can be obtained as follows:

$$H_v(h_{eq}, \omega_{ex}) = \frac{i\omega_{ex}}{\omega_{eq}{}^2 - \omega_{ex}{}^2 + 2hi\omega_{eq}\omega_{ex}} \tag{7}$$

The frequency response function was defined as the Fourier transform of the response. For this case, the mean square $E[y(t)^2]$ of displacement response, in case of the response process of the steady state solution for complex form, can be obtained by relation between the spectral density of input and the spectral density of response. Therefore, Eq. (7) can be expressed as that shown in Eq. (8).

$$H_v(h_{eq}, \omega_{ex}) = \sqrt{\frac{\omega_{ex}{}^2}{\left(\omega_{eq}{}^2 - \omega_{ex}{}^2\right)^2 + \left(2h\omega_{eq}\omega_{ex}\right)^2}} \tag{8}$$

Fig.5 shows the relationship between the calculated value of the frequency response function by Eq. (8) and the period. The natural periods of building considered, $T_y = 2\pi/\omega_{eq}$, varied between 0.5sec, 1.0sec and 1.5sec (assumed representative of medium-to-low-rise RC buildings), and the initial damping ratio h was taken as 0.05. Although $H_v(h_{eq}, \omega_{ex})$ has only the point where the resonance point, so $\omega_{eq} = \omega_{ex}$ is considered. However, considering that the equivalent period during earthquake changes due to pre-yield cracking or inelastic response, the response would also be affected by the frequencies both lower and larger than that corresponding to T_y. Thus, the resonance phenomenon occurs within a certain periodic range. If it is assumed that any transfer function values which is less than half the maximum point of $H_v(h_{eq}, \omega_{ex})$ has little influence on building response, the period range corresponding to values greater than 0.5 $H_v(h_{eq}, \omega_{ex})$ can be adopted as the period range which is influenced by resonance effects.

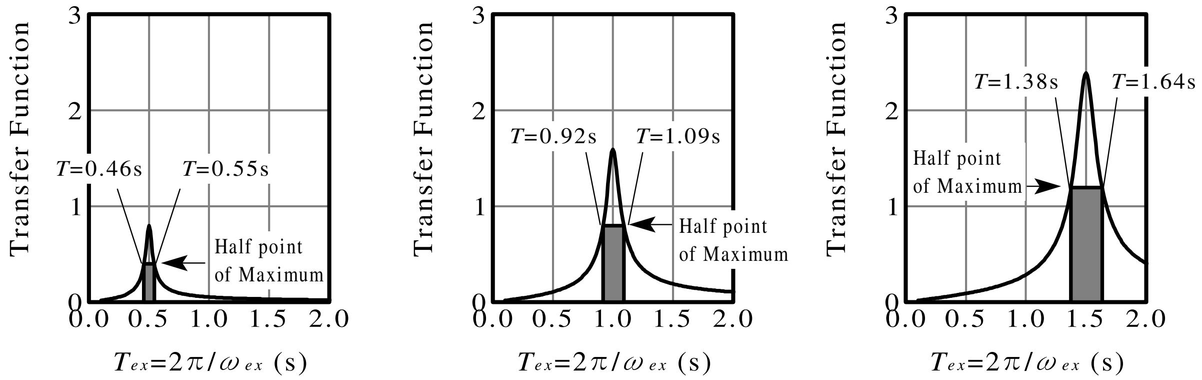
In Fig.5, when the frequency at the point that is half of the maximum value is determined, $\omega_a = 0.92T_y$ and $\omega_b = 1.09T_y$ are obtained, respectively. Based on this, the period range could be defined as $0.9T_y$ to $1.1T_y$. Therefore, *a* and *b* in Eq. (5) can be taken as 0.9 and 1.1, respectively.

Input Wave	Transfer Function	Response Wave
$\ddot{z}(t)$	$h(t)$	$y(t) = h(t) \cdot \ddot{z}(t)$
$\ddot{Z}(i\omega)$	$H(i\omega)$	$Y(i\omega) = H(i\omega) \cdot \ddot{Z}(i\omega)$

$\ddot{z}(t)$, $h(t)$, $y(t)$: process for the time-varying

$\ddot{Z}(i\omega)$, $H(i\omega)$, $Y(i\omega)$: process for the frequency-varying

Fig. 4 –Transfer characteristic between input and output



(a) T_y=0.5s ; ω_{eq}=12.6(rad/s) (b) T_y=1.0s ; ω_{eq}=6.3(rad/s) (c) T_y=1.5s ; ω_{eq}=4.3(rad/s)

Fig. 5 – Relation between calculation result of Eq. (8) and period

4.2 Simplification of damping reduction factor

Eq. (9) shows the equation for calculating the damping reduction factor given in the Japanese building standards law.

$$F_h = 1.5/(1 + 10h_{eq}) \tag{9}$$

Where h_{eq} is the effective damping ratio, and is given in the Japanese building standards law as shown in Eq. (10) for RC frame buildings, where the 0.05 represents the elastic damping ratio.

$$h_{eq} = 0.25\left(1 - 1/\sqrt{\mu_{eq}}\right) + 0.05 \tag{10}$$

The value of $F_h\sqrt{\mu_{eq}}$, which is a key parameter of Eq. (5), was calculated for a range of μ_{eq} values using the Eq. (9) and Eq. (10) and is shown in Fig.6. μ_{eq} was varied between 1 to 5 in increments of 0.1. According to the calculated result, $F_h\sqrt{\mu_{eq}}$ was in the range of 0.98 to 1.15, with an average value of 1.0. Based on this, $F_h\sqrt{\mu_{eq}} \fallingdotseq 1$ was assumed, and Eq. (5) could be simplified to Eq. (11) assuming 1/2π was approximately 0.16.

$${}_v\delta_{\max} = 0.16\left(\frac{1}{0.2}\cdot\int_{0.9T_y}^{1.1T_y} S_v(\mathrm{h}_{0.05}, T).\mathrm{dT}\right) \tag{11}$$

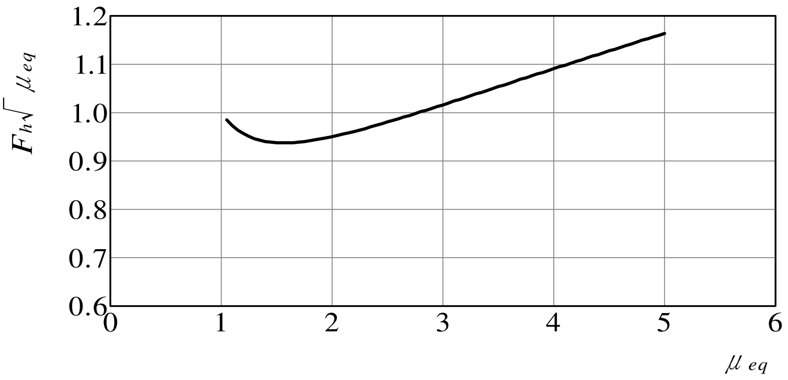


Fig. 6 – Relation of between calculated factor $F_h\sqrt{\mu_{eq}}$ and ductility factor μ_{eq}

5. Verification using response history analyses

5.1 Inelastic response history analysis description

Inelastic response history analysis was performed to verify the validity of Eq. (11). The building was assumed to behavior as an RC structure with a flexural deformation mode. Analysis parameters are shown in Table.1. The adopted hysteretic model follows the degrading type, and consisted of crack points and yield points shown in Fig.7. The yield strength of each floor, Q_{yi}, was obtained from $Q_{yi} = A_i C_{yb} \Sigma W_i$. Here, C_{yb} is the yield shear coefficient of the first floor, ΣW_i is the total weight of the building above the i^{th} floor, and A_i is vertical distribution factor of story shear coefficients.

The response analysis method adopted was the Wilson's θ method with a step time of 0.001 s. The damping factor is of the instantaneous rigidity proportional type with an initial damping ratio of h = 0.05.

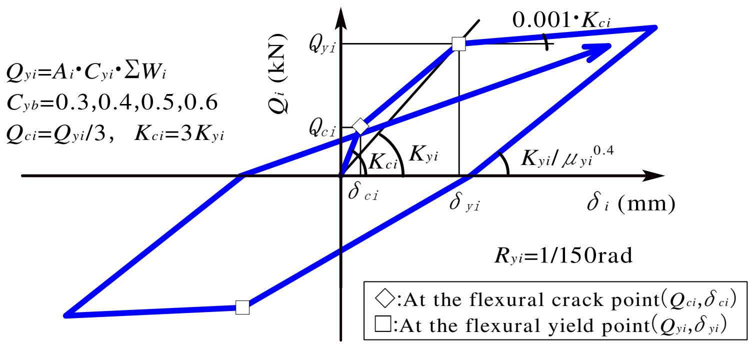


Fig. 7 –Hysteretic model for response analysis

Table 1 –Analysis parameters

Parameter	
Yield seismic coefficient (C_{yb})	0.3, 0.4, 0.5, 0.6
Story of building (N)	3-Story, 7-Story, 11-Story
Yield displacement angle (R_{yi})	1/150rad is constant

(Note)Plan: 10m×20m (is Constant), Weight: 3600kN (is Constant), Height: 3300mm (is Constant),
The Mass of the system: Multi-Degree of Freedom System

Ground motions from sixteen different seismic events were also applied and are listed in Table 3 (94 waves total considering different recording stations and horizontal components). The observed records were standardized to a maximum PGV of 50 kine. Velocity Response Spectrum shown in Fig.8.

Table 2 – Input ground motion of the observed waves

No.	Earthquake Name	Total Number	t_d/T_d
1	1940 Imperial Valley Earthquake	2	0.49
2	1952 Kern Country Earthquake	2	0.54
3	1963 Sendai Earthquake	2	0.72
4	1968 Tokachi-oki Earthquake	2	0.73
5	1978 Miyagi-oki Earthquake	2	0.51
6	1993 Kushiro-oki Earthquake	2	0.17
7	1994 Los Angeles Earthquake	2	0.13
8	1995 Hyōgo Prefecture Great Hanshin Earthquake	10	0.33
9	1999Taiwan's ChiChi Earthquake	8	0.29
10	2000Tottori Prefecture of Western Region Earthquake	10	0.17
11	2001 Geiyo Earthquake	10	0.16
12	2005 Fukuoka Prefecture of Western-oki Earthquake	8	0.15
13	2004 Niigata Prefecture Chūetsu-oki Earthquake	6	0.21
14	2008 Iwate-Miyagi Nairiku Earthquake	8	0.25
15	2011Tohoku Region Pacific Coast Earthquake	6	0.45
16	2011New Zealand's Christchurch Earthquake	14	0.20

(Note) Ratio of t_d/T_d is expressed as the effective duration time. It is recogniezed that t_d/T_d is more in case of resonat type such as No.15, t_d/T_d is less in case of shock type such as No.8.

t_d : The duration time which defined from 5% to 95% of the mean square ground acceleration.

T_d : Total duration time of ground acceleration.

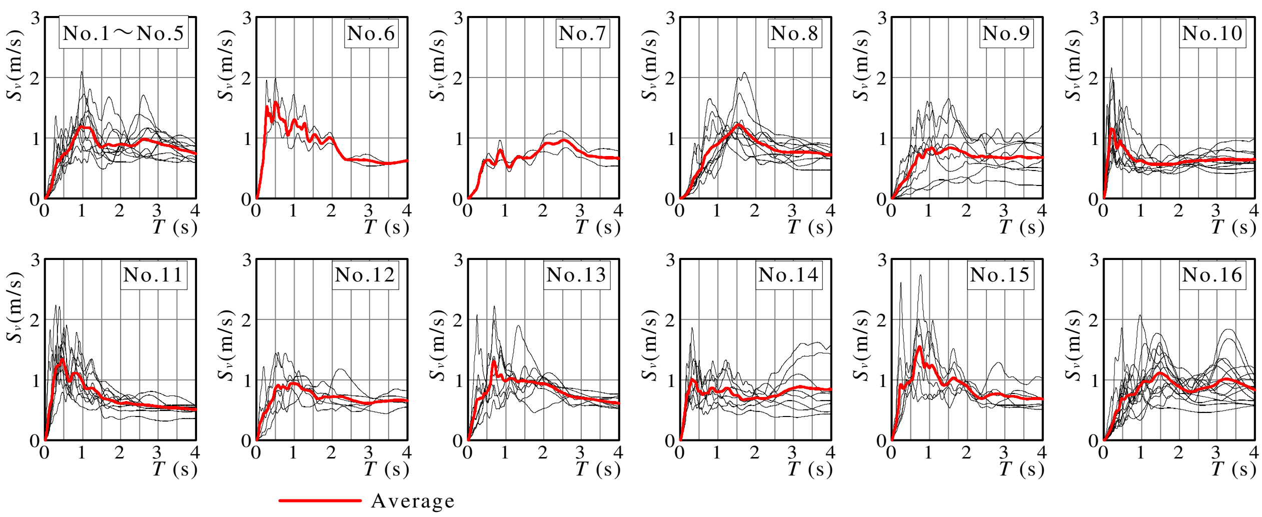


Fig. 8 –Velocity response spectrum

5.2 Accuracy of proposed prediction equation

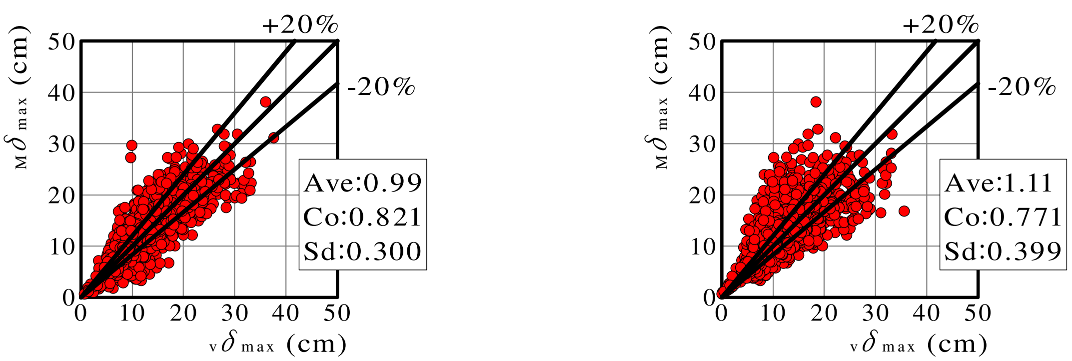
In the multi degree of freedom system for a N-Story, representative displacement of equivalent single degree of freedom system, ${}_{M}\delta_{max}$, can be derived from Eq. (12). Namely, ${}_{M}\delta_{max}$ is the maximum displacement response of building.

$$ {}_{M}\delta_{max} = \frac{\sum_{n=1}^{N} m_i \cdot \delta_i^2}{\sum_{n=1}^{N} m_i \cdot \delta_i} \tag{12} $$

Where m_i is the mass at i^{th} floor, δ_i is i^{th} floor relative displacement which was obtained from the peak point of each floor based on inelastic response history analysis

Fig. 9 shows the relationship between the maximum displacement response ${}_{M}\delta_{max}$ by Eq. (12) and the calculated value ${}_{v}\delta_{max}$ by Eq. (11). Predictions of the displacements were then made using the proposed equation and the capacity spectrum method by Eq. (2) using Eq. (9) of F_h, which were then compared to those from the response analysis. Where, ω_{eq} = 2π / T_{eq} in the Eq. (2), T_{eq} is equivalent period at the maximum displacement response of Eq. (12).

Although there is some variation, the prediction formula of Eq. (11) generally evaluated the response results reasonably. So, it was observed that the proposed prediction equation had better accuracy compared to the capacity spectrum method by Eq. (2). Based on these results, the proposed prediction equation can be used to reliably predict the building's displacement response. If the proposed prediction equation is used, the maximum displacement response can be easily predicted without using the damping reduction factor F_h.



(Note)Ave: average, Co: correlation coefficient, Sd: standard deviation

(a) Calculated results using Eq.(11)   (b) Calculated results using Eq.(2)

Fig. 9 –Comparison of the relationship between maximum displacement response ${}_{M}\delta_{max}$ of inelastic response analysis and calculated results ${}_{v}\delta_{max}$

6. Conclusion

In this paper, a formula for predicting the displacement response for middle to low-rise R/C structures using an average velocity spectrum and simplifying the capacity spectrum method procedure was proposed. In the proposed prediction equation, functions of both the damping reduction factor F_h and the equivalent period T_{eq} used in the capacity spectrum method are replaced with the simplified coefficient of 0.16 as follows:

$$ {}_{v}\delta_{\max} = 0.16\left(\frac{1}{0.2}\cdot\int_{0.9T_y}^{1.1T_y} S_v(\mathrm{h}_{0.05}, T).\,\mathrm{dT}\right) \tag{11} $$

According to the inelastic response analysis, it was observed that the proposed prediction equation could estimate the displacement response with the same accuracy as the capacity spectrum method. Based on these results, the proposed prediction equation can be used to reliably predict the building's displacement response.

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