A STUDY ON CHARACTERISTICS OF STRUCTURAL ELASTO-PLASTIC RESPONSE BASED ON "3-D VIEW OF NONLINEAR RESPONSE SPECTRUM"

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SUMMARY

In this paper, as of an index of comprehensive effects of ground motions to nonlinear structural response, a "3-D view of nonlinear response spectrum (3D spectrum)" is newly proposed. Firstly, The 3D spectrum is introduced as a comprehensive index by comparing with several conventional spectra. Then, using the 3D spectrum, response characteristics of simply made artificial ground motions are studied, and a basic concept of the 3D spectrum characteristics is proposed. Finally, a parametric study of structural nonlinear response using the 3D spectrum is carried out. In the parametric study, some typical parameters of structural nonlinear systems are selected and by combining the input motion characteristics, dominant factors and conditions are investigated. Although this study is in a principle phase, these results may highly expected to be applied to seismic safety evaluation of actual structures.

INTRODUCTION

Structural damage due to strong ground motions has come to peoples' concern from long time ago. Recently, several kinds of evaluation methods have been studied and proposed for seismic design of structures. Until now, most of popular evaluation methods are based on linear systems, such as an elastic response spectrum. As long as structures behave within or close to linear regions, these kinds of evaluation methods are useful.

On the other hand, recent developments of new structural systems such as seismic isolation devices and elast-plastic seismic damper systems may make nonlinear structural systems. In addition, some recent big earthquakes unfortunately show that evaluation methods based on linear systems cannot always available for understanding structures' response characteristics if a large ground motion is applied.

In this paper, as of an index of comprehensive effects of ground motions to nonlinear structural response, a "3-D view of nonlinear response spectrum" is newly proposed. Using the spectrum, parametric study, where system's nonlinear characteristics and input motion characteristics are considered, is carried out for structure's nonlinear behavior.

A 3-D VIEW OF NONLINEAR RESPONSE SPECTRUM

2.1 Introduction of the 3-D View of Nonlinear Response Spectrum

As a nonlinear structure system has several characteristics that may affect its dynamic responses, comprehensive understanding of such systems by a 2D spectrum may not always be appropriate. In this paper, we propose a 3-D view of nonlinear response spectrum (hereafter, it will be named 3D spectrum).

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Fig.1 shows a principle concept of the 3D spectrum. The 3D spectrum has three axes; a period axis, a response axis and a strength axis. The former two axes are also used in conventional 2D spectra, and the last axis is

unique factor for nonlinear systems, a principal characteristics of which is shown in Fig.2. Each axis may apply any unit as long as it can be classified to the axis type. An example of applied units of this spectrum is as follows;

1) The period axis : natural period in second

2) The response axis : δ_{max}/δ_L where δ_{max} is a maximum response displacement of elast-plastic system, whereas δ_L is that of linear system under same input motion.

3) The strength axis : β is a ratio given by the following equation.

$$\beta = \frac{a_{max}}{a_y} = \frac{\alpha(T)}{C_y g}$$

Where, $\alpha(T)$ is a dynamic amplification factor ($Sa(T)/a_{max}$), Sa(T) is a maximum acceleration of the linear system; a_{max} is a maximum response acceleration of elast-plastic system; a_y is that of linear system under same input motion. C_y is normalised yield strength, and g is a gravity factor.

One example of the 3D spectrum using above units is shown in Fig.3; used ground motion data is JMA Kobe NS component at 1995 Hyogoken Nanbu Earthquake. There are three parameters for the nonlinear system. Critical damping ratio (h) is 0.05, stiffness reduction ratio after yielding (γ) is 0.1, and type of restoring force characteristics (RFC) is Normal Bi Linear.

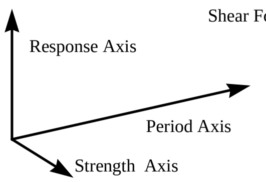


Fig.1 Concept of 3D Spectrum

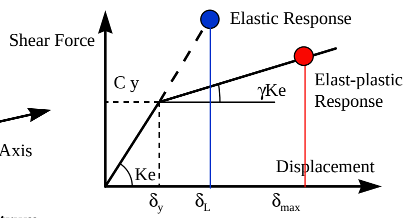


Fig.2 Restoring Foce Characteristics

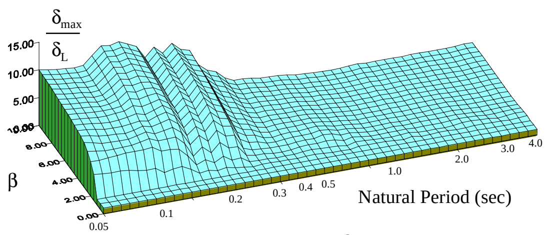


Fig.3 An Example of 3D Spectrum

Selection of axis units and comparison to conventional spectra

As mentioned above, each axis of the 3D spectrum may apply any unit as long as it can be classified to the axis type, and the selection of axis units may results different kind of 3D views. Examples of selection are shown in Fig.4(a) to Fig.4(c). In these figures, the following equations are used.

$$\mu = \frac{\delta_{max}}{\delta_y} \quad \beta(T) = \frac{a_{max}}{a_y} = \frac{\delta_L}{\delta_y} \quad \delta_L = T^2 \frac{Sa(T)}{4\pi^2} \quad a_y \alpha(T) = C_y g$$

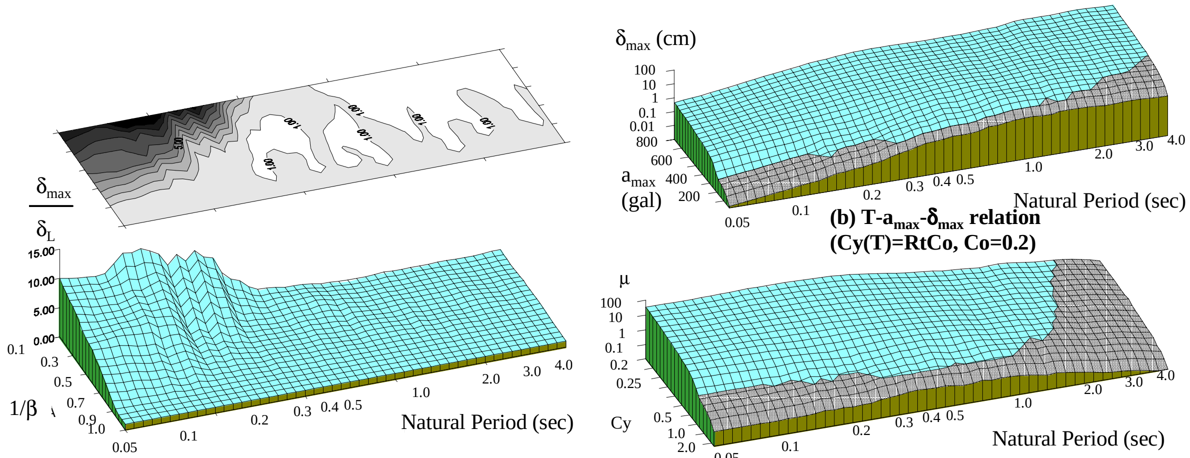
Where, μ is ductility ratio, and δ_y is yield displacement of the structure.

For the purpose of focusing a small ductility region, Fig.4(a) is a good selection because the strength unit $1/\beta$ shows more precise characteristics in the small ductility region. This type of 3D spectrum is a kind of period-integration of a yield level-displacement relation. Fig.5 shows a concept of this relation, where selected 2D plane (shown as a grey rectangular) in the 3D spectrum is the yield level-displacement relation.

When structural strength is defined, an elast-plastic displacement response spectrum shows actual response of the structure. If we need to know response variation due to change of input motion level, Fig.4(b) is a useful solution. This 3D spectrum is a kind of input-level-integration of an elast-plastic displacement response spectrum. As mentioned above, structural strength (C_y) must be set, and in the Fig.4(b), it is set to be a RtCo type with Co=0.2. The grey zone in the spectrum shows elastic region. Fig. 6 shows a concept of this relation, where selected 2D plane (shown as a grey rectangular) in the 3D spectrum is the elast-plastic displacement response spectrum.

If we need to know a required structural strength to satisfy a certain ductility ratio, Fig.4(c) is useful. This 3D spectrum is a kind of ductility-ratio-integration of a strength demand spectrum. Fig. 7 shows a concept of this relation, where selected 2D plane (shown as a grey rectangular) in the 3D spectrum is the strength demand spectrum.

Thus, the introduced 3D spectrum can vary to several types by selecting units in each axis, and be used for several design evaluations.



(a) T-1/β-δ_{max}/δ_L Relation

(b) T-a_{max}-δ_{max} relation (Cy(T)=RtCo, Co=0.2)

(c) T-Cy-μ Relation (a_{max}=800gal)

Fig.4 Combination of Sterngth Axis and Response Axis (JMA-Kobe NS, h=0.01, Normal Bi-linear)

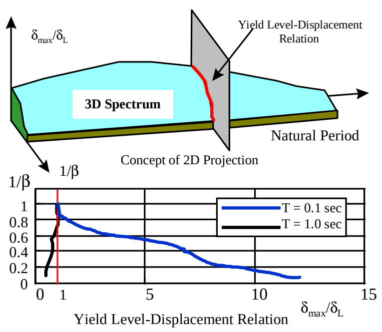


Fig.5 Comparison of 3D Spectrum to Yield Level-Displacement Relation

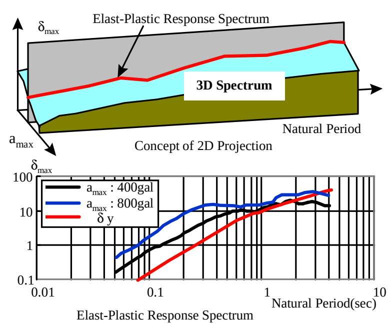


Fig.6 Comparison of 3D Spectrum to Elast-Plastic Response Spectrum

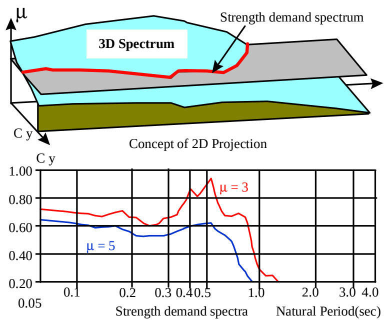


Fig.7 Comparison of 3D Spectrum to Strength Demand Spectrum

RESPONSE CHARACTERISTICS OF SIMPLY MADE ARTIFICIAL GROUND MOTIONS

3.1 Displacements after yielding by fourier amplitude constant waves

A structure may change its harmonic period after yielding. As observed ground motions usually have different response amplitude by period, the response after yielding are quite complicated. In order to understand the displacement characteristics ignoring such complication, artificial ground motions with constant fourier amplitude are used. There are two waves; we call them SV constant wave and SA constant wave, as expressed below. Fig.8 shows linear amplification factors of these waves with h=0.05.

1) SV constant wave : fourier amplitude spectrum F(ω) is constant along the angular frequency ω. This wave is considered to maintain a constant response velocity spectrum with no damping.

2) SA constant wave : ω times F(ω) is constant along ω. This wave is considered to maintain a constant response acceleration spectrum with no damping.

Using the 3D spectra (Fig.4(a) type), a normalised elast-plastic displacement responses (hereafter, it is called NED) of these waves are calculated as shown in Fig.9. Critical damping ratio (h) is 0.05, stiffness reduction ratio after yielding (γ) is 0.1, and type of restoring force characteristics (RFC) is Normal Bi Linear.

The 3D spectrum of SV constant wave shows that the normalised elast-plastic displacement response does not differ much, and keeps similar to that of linear response displacement. This is so called "Displacement constant law", previously mentioned as one of the typical elast-plastic characteristics. On the other hand, The 3D spectrum of SA constant wave shows that normalised elast-plastic displacement increases according to strength reduction of the structure.

For quantitative evaluation, average of the displacement in period (0.05sec to 1.0 sec) is calculated, and is shown in Fig.10. In the case of SV constant wave, the NED is similar to 1.0 when $1/\beta > 0.3$; it seems to matches with the displacement constant law. In the case of SA constant wave, the NED is similar to the stress constant law, it means that the displacement is coincide with what of static loading.

3.2 Comparing amplitude constant waves and an observed wave

As an example of actually observed wave, average of the displacement in period of JMA Kobe NS wave is calculated. As usual, spectral intensity of this wave fluctuates and getting an average overall the period may eliminate important characteristics, therefore we set three period ranges as shown in Fig.11. In this figure, the results of SV and SA constant waves and theoretical values are also shown for comparison.

In the shortest range (0.05sec to 0.1 sec), response of JMA Kobe NS wave is larger than that of SA constant wave and is similar to the stress constant law. In the middle range (0.1 sec to 0.2 sec), condition of $1/\beta > 0.5$ shows the response is similar to the energy constant law; however as $1/\beta$ decreases, the response is apt to increase, and sometimes lager than stress constant law. In the longer range (0.2 sec to 0.4 sec), condition of $1/\beta > 0.3$ shows that the response is similar to the displacement constant law; however as $1/\beta$ decreases, the response is apt to increase, and sometimes lager than energy constant law. In the longest range (more than 0.4 sec), the response is almost always close to the displacement constant law, and not is affected by other parameters.

In general, elastic acceleration response spectra of observed ground motions may have a typical shape that the acceleration response increases along with period in the shortest range, then it keeps certain level with some fluctuation, and lastly, it increases along with period in the longest range. Comparing this trend with the nonlinear displacement response mentioned above, the large displacement after yielding might match with a range that spectral power increases as period increases. Thus, the elast-plastic response displacement of structure after yielding is strongly affected by the power of long period range.

3.3 Resonance period change due to yielding by 1hz sinusoid wave

As the fourier spectrum constant waves are not suitable for a study of resonance period change because such waves do not have a clear spectral peak, a 1Hz sinusoid wave is prepared and the 3D spectrum is calculated. Fig. 12 shows the 3D spectrum. The peak in this spectrum is not that of sinusoid wave (1hz, T), but that calculated as an equivalent resonance period (T_{eq}). As a ductility of the structure increases, the ratio of linear and nonlinear resonance period (T/T_{eq}) converges to a square root of γ. One example is shown in Fig. 13, where γ is set to 0.1, therefore T/T_{eq}= 0.32 and this is same as the peak of Fig.12.

3.4 A concept of 3D nonlinear spectrum

Based of the study mentioned above, we propose a concept of 3D nonlinear spectrum. Fig. 14 is the conceptual draw of the 3D nonlinear spectrum. When natural period is short enough, the response is close to the force constant law, and as natural period increases, the 3D response once increases up to a certain peak whose period can be predicted using T/T_{eq}. Then the 3D response decreases crossing the energy constant law, and finally it converses to that of displacement constant law.

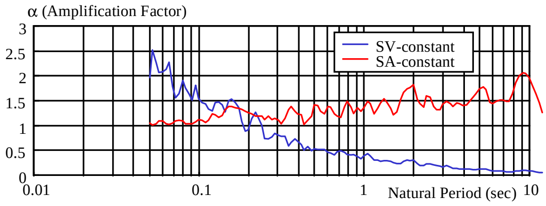


Fig.8 Acceleration Amplification Factor of Synthesized Waves

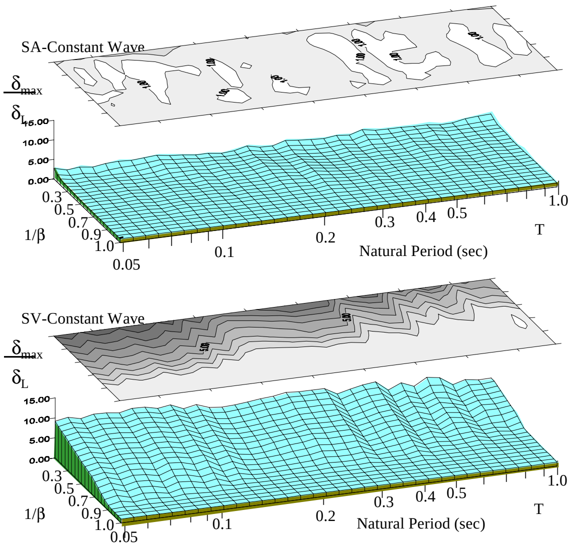


Fig.9 3D Response Spectra by Synthesized Waves

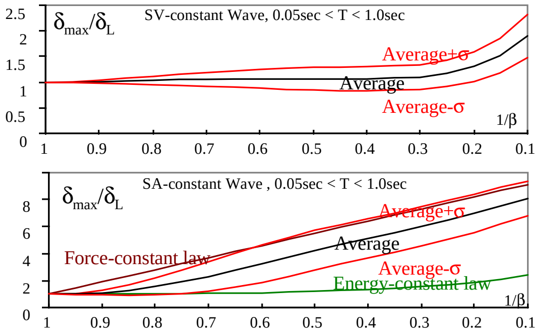


Fig.10 1/β-δ_{max}/δ_L Relations of Synthesized Waves
(h = 0.05, γ = 0.1, Normal-Bi-Linear)

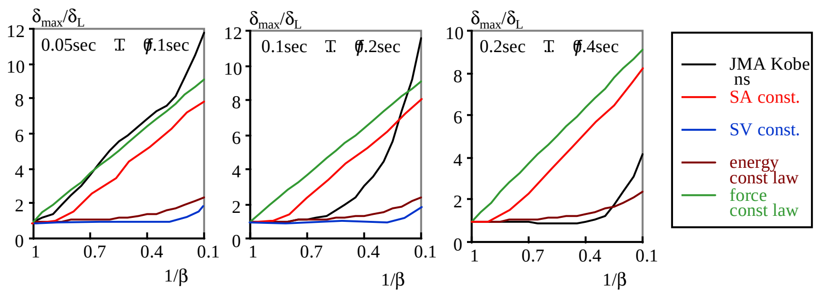


Fig.11 1/β-δ_{max}/δ_L Relations Comparison by Period Range

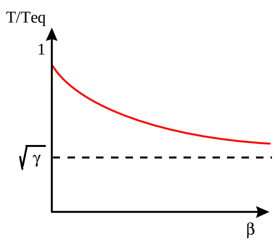


Fig.13 Concept of Teq Change due to β

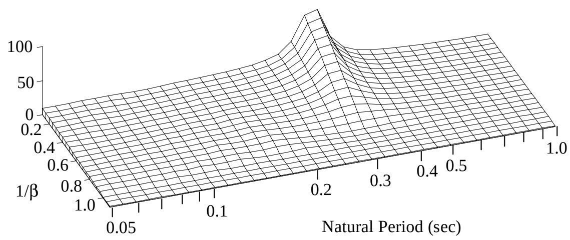


Fig.12 3D Response Spectrum by 1Hz Sinusoid Wave

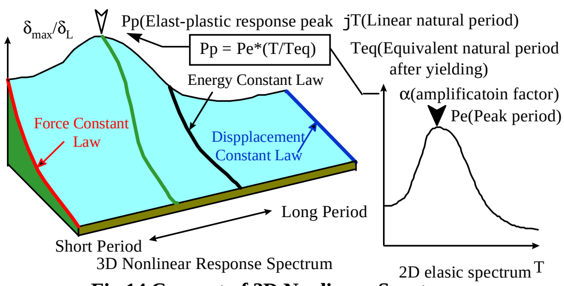


Fig.14 Concept of 3D Nonlinear Spectrum

PARAMETRIC STUDY OF STRUCTURAL NONLINEAR RESPONSE USING THE 3D SPECTRUM

4.1 Conditions of the parametric study

As the proposed 3D spectrum may be able to evaluate structure's nonlinear response characteristics, it is used for the parametric study on nonlinear response characteristics of structures. There are mainly three parameters. Stiffness reduction ratio γ as used before, critical damping ratio h, and type of restoring force characteristics (RFC)

In this study, each parameter is set as follows.

γ : 0.3, 0.1, 0.01, and 0.001

h : 0.01, 0.05, and 0.10

RFC : Normal type and Origin oriented type

Applied ground motions are the SA constant wave, the SV constant wave, and the 1hz sinusoid wave. These waves are compared using a period average of the 3D spectrum (hereafter, it is called average spectrum), the concept of which is shown in Fig. 15.

4.2 Effects due to change of stiffness reduction ratio γ

The average spectrum of the SA constant wave (SACT) and the SV constant wave (SVCT) are shown in Fig. 16(a) to (d). The averaging is set to cover the period range that responses do not differ so much. Namely, the period range is 0.05sec. to 1.0sec. for the case of $\gamma = 0.3$ and 0.1, 0.05sec. to 0.4sec. for the case of $\gamma = 0.01$, and 0.05sec. to 0.2sec. for the case of $\gamma = 0.001$.

Table 1 shows these average values with theoretical results by the force constant law and the energy constant law. In the case of the SA constant wave, δ_{max}/δ_L increases as β becomes larger. On the other hand, in the case of the SV constant wave, δ_{max}/δ_L does not differ so much; especially, when h is little and γ is large, it even decreases. Comparing to the theoretical values at $\beta = 10$, the SA constant wave displacement is similar to that of the force constant law, and the SV constant wave displacement is similar to that of the energy constant law. The effect of γ is clear in the case of the SA constant wave, but not clear in the case of the SV constant wave. These characteristics are qualitatively same in both the case of h = 0.01 and h = 0.05.

4.3 Effects due to critical damping ratio

The average spectrum of the SA constant wave (SACT) and the SV constant wave (SVCT) are shown in Fig. 17(a) to (d) with theoretical results by the force constant law and the energy constant law. In the case of the SA constant wave, δ_{max}/δ_L is smaller than the force constant law. When $\gamma = 0.1$, smaller h makes smaller δ_{max}/δ_L, but this trend reverses when $\gamma = 0.001$. In the case of the SV constant wave, δ_{max}/δ_L is generally small and less than that of the energy constant law; but it increases as h becomes large; it goes up to close to the energy constant law when $\gamma = 0.1$ and it excesses the law when $\gamma = 0.001$.

4.4 Effects due to the type of restoring force characteristics RFC

Until here, all studies are based on the Normal Type RFC. In addition, the Origin Oriented RFC is studied to study the effects due to the type of RFC. Fig. 18 shows comparison of the both RFC with $\gamma = 0.1$. In general, the Origin Oriented RFC shows larger displacement than the Normal Type RFC, but the differences are small in the case of the SA constant wave.

The comparison of the both RFC by 1hz sinusoid is shown in Fig.19. In the contours of the figure, a peak curve of theoretical equivalent resonance period (T_{eq}) is written under assumption that the T_{eq} is calculated by the tangent modulus of nonlinear stress strain relation. In the case of the Origin Oriented RFC, the nonlinear system behave relatively parallel to the assumption mentioned above, the identified equivalent peak curve coordinates with the theoretical one. On the other hand, in the case of the Normal RFC, the nonlinear system does not have the tangent modulus stiffness and not have a clear peak curve when β is small.

TABLE 1 NORMALIZED DISPLACEMENT AT β=10

γ	SACT		SVCT		Theory	
	h=0.01	h=0.05	h=0.01	h=0.05	F-const	E-const
0.3	2.490	2.911	0.715	1.256	3.100	1.613
0.1	7.134	8.056	1.079	1.900	9.100	2.402
0.01	73.49	68.92	1.556	3.503	90.10	4.207
0.001	599.2	398.5	2.679	6.279	900.1	4.933

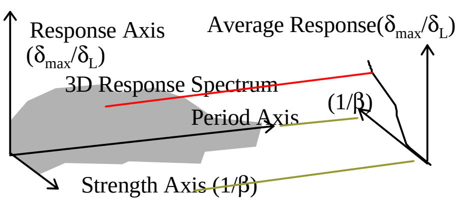


Fig.15 Concept of Period-average of 3D Spectrum

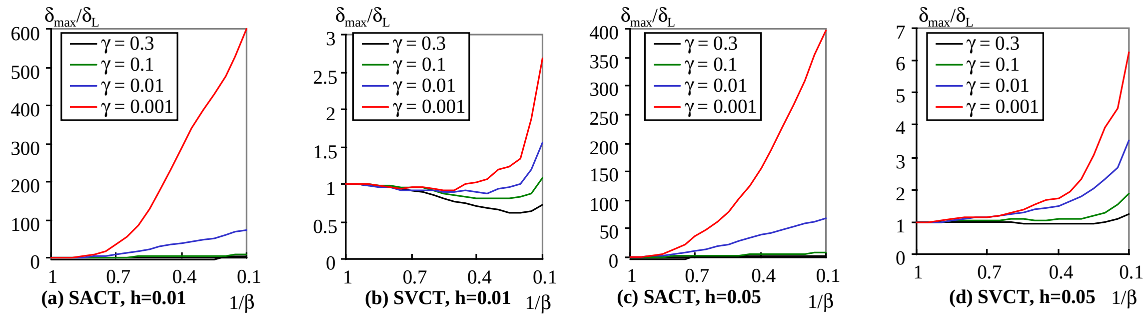
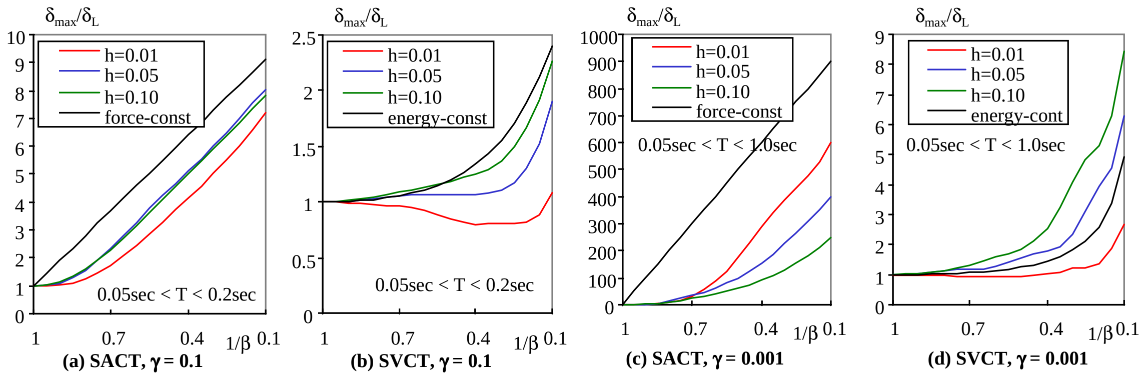


Fig.16 Comparison of γ-different cases (RFC:Normal Bi-linear)



(a) SACT, γ = 0.1 (b) SVCT, γ = 0.1 (c) SACT, γ = 0.001 (d) SVCT, γ = 0.001

Fig.17 Comparison of h-different cases (RFC:Normal Bi-linear)

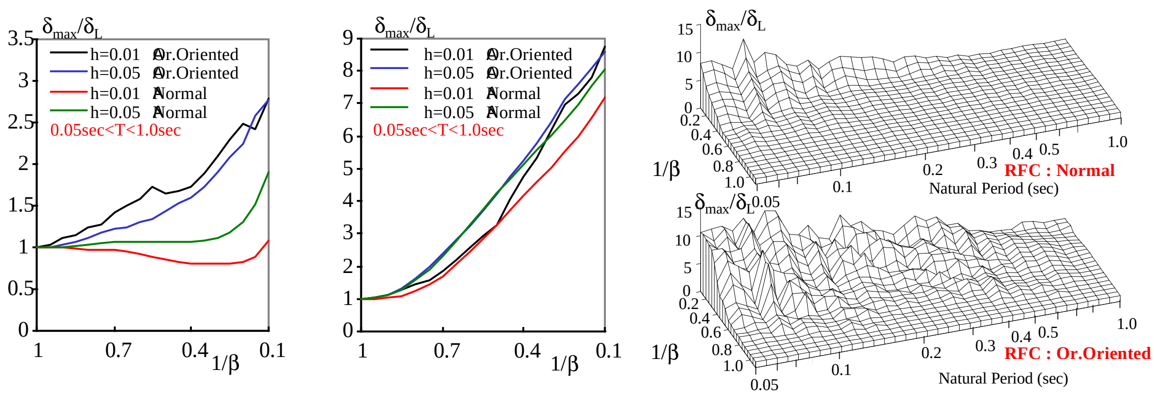


Fig.18 Comparison of h & RFC different cases (γ = 0.1)

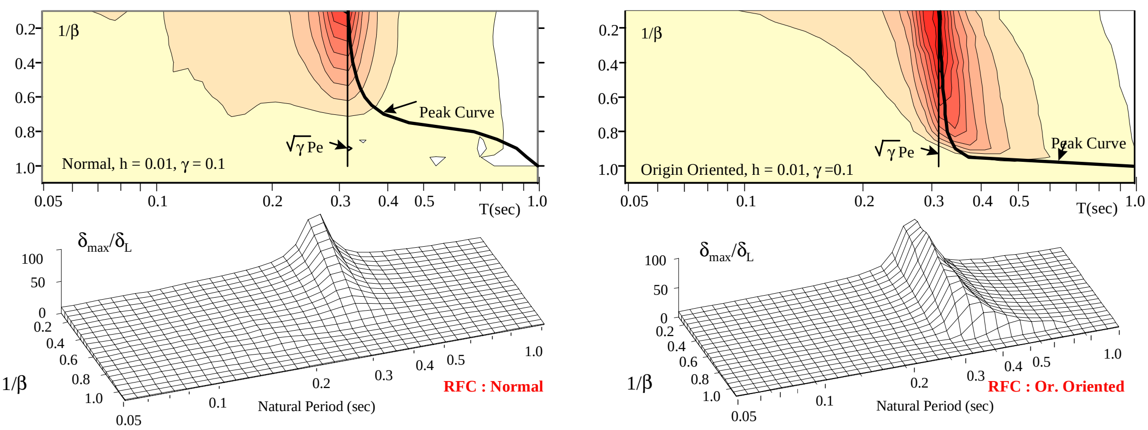


Fig.19 Comparison of RFC by 1hz sinusoid wave

CONCLUDING REMARKS

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