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Input energy spectrum and its application to response prediction considering large deformation characteristics of seismic isolation

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ABSTRACT : A method for simple prediction of seismic response was established to evaluate maximum displacement and shear force of a base isolated Fast Breeder Reactor (FBR) plant building, whose foundations incorporated laminated rubber bearings with hardening characteristics and steel dampers with elasto-plastic characteristics.

The general features of the energy spectrum for base isolated buildings were studied and it was found that the seismic response could be estimated easily from the energy spectrum.

1. INTRODUCTION

A simple method of predicting the seismic responses of structures has been studied. This method utilizes the amount of energy applied to a structure during a seismic motion (H. Akiyama 1985). In applying it to the response evaluation of a base isolated structure up to ultimate, an input energy spectrum that takes account of elasto-plastic restoring force characteristics and the hardening stiffness of natural rubber bearings (NRB) was used. The relationships among the input energy, the maximum response displacement and the maximum response base shear coefficient of the isolation layer were examined. Also, a trial was conducted to develop a method for simple prediction of maximum response using the input energy spectrum.

2. SUMMARY OF ENERGY SPECTRUM

The energy spectra indicate the relationships between input energy acting on a structure during a seismic motion and the structure's natural period. The equilibrium of the total energy of a single degree of freedom system is expressed by :

$$1/2M\dot{x}^2 + \int_0^t C\dot{x}^2 dt + \int_0^t F(x)\dot{x}dt = \int_0^t -M\ddot{Z}\dot{x}dt \tag{1}$$

where,

M : Mass, C : Coefficient of viscous damping, F(x) : Restoring force,

X : Relative displacement, $\dot{X}$: Relative velocity, $\ddot{Z}$: Acceleration of ground motion

The right side of this equation is the input energy acting on a structure from time 0 to time t under a seismic motion. The first term on the left side is the kinetic energy at time t, the second term is the energy absorption of the viscous damping from time 0 to time t, and the third term is the sum of the elastic potential energy at time t and the hysteresis energy absorption from time 0 to time t.

Two kinds of input spectra, the total input energy spectrum and the momental energy spectrum, are used in this paper. The total input energy spectrum is the total input energy acting on the structures till the end of the seismic motion. In this case, the duration of the right side of Eq.(1) is from 0 to the end of the seismic motion. The momental input energy is the maximum input energy incremented during the time span Δt from time t to time $t+\Delta t$.

In this paper, the equivalent velocity by the transfer of input energy is represented by Ve as:

$$Ve = \sqrt{\frac{2E}{M}} \qquad (2)$$

where, Ve : Equivalent velocity, E : Input energy, M : Mass of single-degree-of-freedom system

3. SEISMIC ANALYSIS MODEL AND INPUT SEISMIC MOTIONS

A non-linear seismic response analysis for the base isolated FBR plant building was conducted by preparing a single degree of freedom system model as shown in Fig.2, that possesses weight, NRB with hardening and viscous damping (and a steel damper with elasto-plastic restoring force characteristics as shown in Fig.3). The energy spectra were analyzed by using two models: one without a damper and the other with a damper. Hereafter, analysis results of the former are represented by 'no damper' and results of the latter by 'damper'. There are 33 kinds of natural vibration period (T) for both models, from 0.3 to 3.5 seconds, that can be determined by K1. The natural periods are used to indicate each vibration period value of the spectra. The values for the hardening point P1,P2 in Fig.2 are assumed to be constant. After K1 is determined, Kd1 is assumed to be such that the natural vibration period of the damper model by (K1+Kd1) becomes 0.5T. Furthermore, the model with the natural vibration period of 2 seconds corresponds to the base isolated FBR building model for the series of studies herein.

Three seismic motions were applied; El Centro 1940(NS), Hachinohe 1968(NS), and Design basis earthquake motion(DBE) which was used in this series of studies (M. Kato et al. 1991). Three input levels, S2 level, two times S2 level($2\times$S2), and three times S2 level($3\times$S2), were applied. Also, for the El Centro and Hachinohe waves, the maximum velocity value of 50cm/sec was determined as the S2 level. For the DBE, a maximum acceleration 831 Gal and a maximum velocity 152cm/sec were determined as S2 level.

4. RESULTS OF SEISMIC RESPONSE ANALYSIS

4.1 Total input energy spectrum

The total input energy spectrum obtained from the results of the seismic response analysis is shown in Fig.4. In both cases of with and without the damper, the values of total input energy are about the same. However, in the case with the damper, a considerable smoothing tendency is noticed.

4.2 Relative displacement spectrum

The relative displacement spectrum(DBE) is shown in Fig.5. With the levels of S2 and 2×S2, it is noticed that the relative displacement with the damper is about one half of that without the damper.

4.3 Base shear coefficient spectra

Base shear coefficient spectra(DBE) are shown in Fig.6. At the S2 level, it is noticed that the value with the damper in the long vibration period range is considerably smaller than that without the damper.

4.4 Momental input energy spectrum

A significant correlation was recognized between the maximum response of the isolation layer and the momental input energy (A.I.J 1989). Fig.7 shows the momental input energy spectra (DBE) where Δt is assumed to be structure's natural vibration period (T). It can be seen that for S2 and 2×S2 the spectra are stable.

4.5 Comparison of total input energy spectra by elastic viscous damping model

The total input energy spectrum can be calculated rather easily by the elastic viscous damping model. If the input energy spectrum by the hysteresis model spectrum can be replaced by the viscous damping model it is possible to make a simple prediction. Fig.8 compares the spectra by the hysteresis model and by the elastic viscous damping model. By adjusting the damping constants of the elastic viscous damping model, it is noticed that the hysteresis model can be approximated. This indicates that the spectra of the no-damper model are approximated by the spectra for damping constant h=2%, and the damper model by the spectra for h=20%

5. RELATIONSHIP OF INPUT ENERGY AND RESPONSE

Regarding the base isolated building as an actual FBR plant, as considered in the series of studies conducted herewith, the review results indicated hereafter are for the case of a damper model whose natural vibration period is 2.0-2.5 seconds.

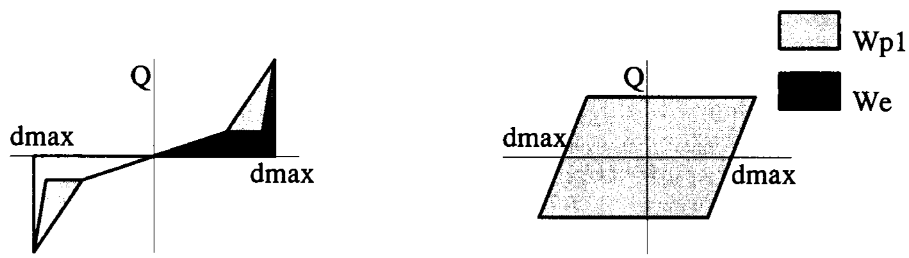
Fig.9 shows the relationship between the total input energy and the maximum response displacement. Fig.10 shows the relationship between the momental input energy and the maximum response displacement. This shows that the total input energy and the maximum response displacement correlate closely. It also indicates that the momental input energy has a higher correlation than the total input energy. Fig.11 shows the relationship between the total input energy and the maximum response base shear coefficient. Fig.12 shows the relationship between the momental input energy and the maximum response base shear coefficient. From these figures it can be seen that in the case of displacement response, the input energy and the base shear coefficient correlate closely. Also, bilinear relationship is observed. The main reason for this is thought to be that, when the input level is small the base shear coefficient is also small due to the damper effect, but as an input increases, the base shear coefficient becomes larger under the influence of hardening stiffness of the rubber bearing.

6. SIMPLIFIED PREDICTION OF RESPONSE AND ITS APPLICABILITY

The response is predicted by Equation (3) below, which assumes that the total input energy is consumed by repeating the maximum displacement d max of the base isolation layer n times. Wp1 and We are illustrated in Fig.1.

$$n \times Wp1 + We = Eall \qquad (3)$$

where,
Eall: Total input energy (=1/2MVe^2), Wp1 : Hysteresis absorption energy of 1 cycle at time of maximum displacement d max, We : Elastic potential energy at time of maximum displacement d max, n : Number representing response repetitions



Restoring force characteristics of rubber bearing

Restoring force characteristics of damper

Fig.1 Hysteresis absorption energy and elastic potential energy

Here, n depends on the seismic motion characteristics. Thus, a small n indicates that a sudden input energy acts on the structures and the energy absorption occurs within a short period of time (few repetitions). If n is determined based on seismic motions in general, and if the hysteresis absorption energy per cycle is obtained from the restoring force characteristics and the elastic potential energy are established, then it becomes possible to predict the response from the total input energy.

Fig.13 shows the response prediction flow. Fig.14 shows the curvilinear relationship between maximum displacement and the total input energy obtained from Eq.(3) when n=2,4,6. The figures correspond to natural vibration periods of 2.0, 2.2, and 2.5 seconds. The figure also shows the response analysis results obtained by the hysteresis model. The maximum base shear coefficient is indicated in the same way. From the figures, if the El Centro wave is considered as approximately n=2, and Hachinohe and DBE(Design basis earthquake) are considered as about n=4, then it is found that the maximum response in general can be predicted.

The energy spectrum is useful in predicting the response. It was found in chapter 4 that if the input is large, the total energy spectrum by the hysteresis model with the damper could approximately equal the spectrum of the elastic viscous damping model (h=20%). That approximation using elastic viscous damping can make it possible to predict the maximum response of the isolation layer. The total input energy of DBE analyzed by the elastic viscous damping model(h=20%) is shown in Fig.14 by a vertical broken line, and the response prediction, which is obtained from the intersection of the vertical line(h=20%) and the curve obtained by Eq.(3), is in good agreement with the analysis results by the hysteresis model.

7. CONCLUDING REMARKS

The response of a base isolated structure with hardening stiffness restoring force characteristics was studied from the stand point of input energy.

First, a total input energy spectrum and momental input energy spectrum that considers the hardening stiffness of the rubber bearing were derived, and their characteristics were reviewed. The obtained energy spectrum indicated a stable configuration identical to the energy spectrum that is applicable to the non-linear response of non-isolated structures. It was thus verified that the spectrum obtained here can be utilized for base isolated structural design.

Second, it was made clear that the input energy, the response displacement and the response base shear coefficient correlate closely. It was also confirmed that the response could be predicted rather simply from the total input energy and the restoring force characteristics of the base isolation layer.

8. ACKNOWLEDGMENT

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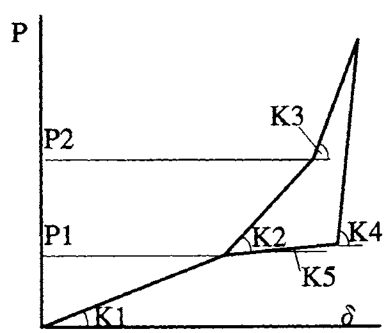
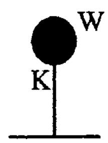
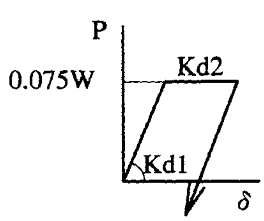




W=182,310tonf
K1=183,600tonf/m(when T=2sec)
K2=3.5K1
K3=12.0K1
K4=29.5K1
K5=0.2K1
P1=103,275tonf
P2=262,319tonf

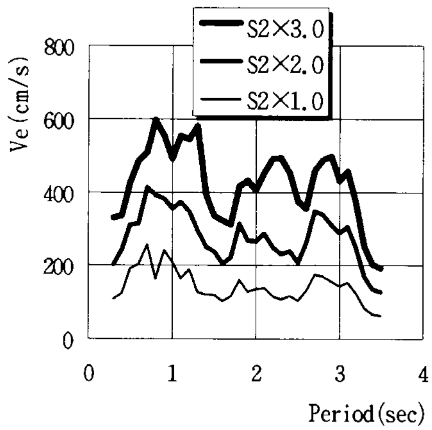
K1=
When the natural bearing period is defined as T, the rubber bearing stiffness(K1) is calculated by T.

Fig.2 Vibration model and restoring force characteristics of rubber bearing

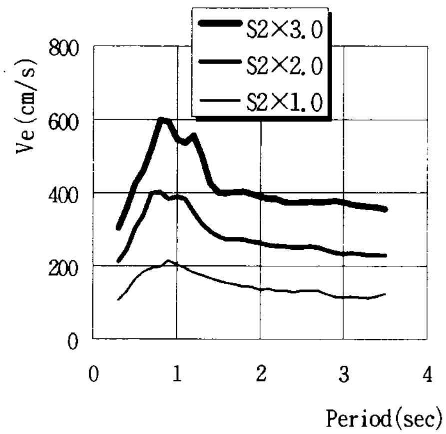


Kd1=
Kd1 is given so that the natural vibration period becomes 0.5T, due to the combined stiffness(K1+Kd1) of the rubber bearing and damper.

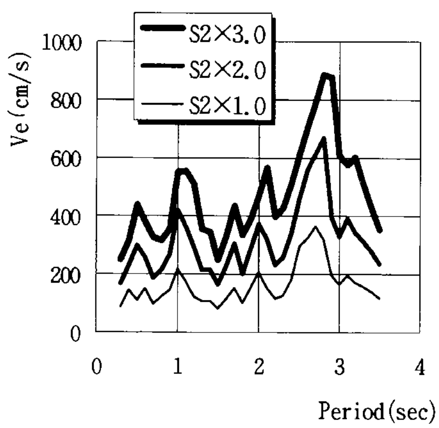
Fig.3 Restoring force characteristics of damper



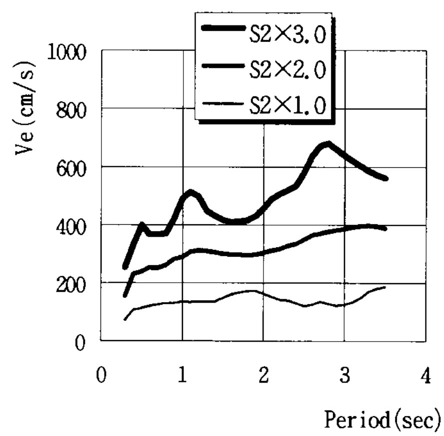
a) El Centro ns (No damper)



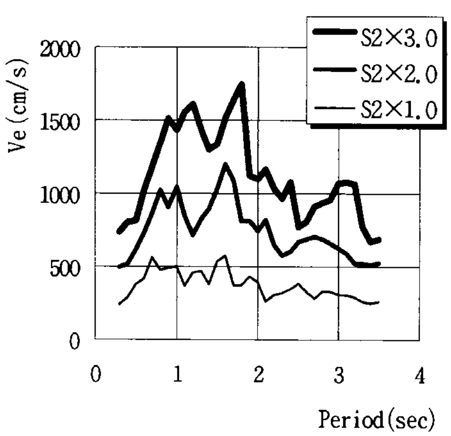
b) El Centro ns (Damper)



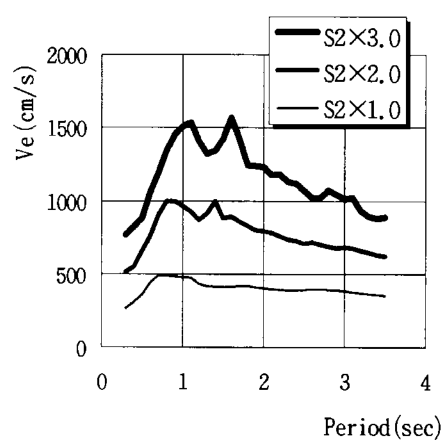
c) Hachinohe ns(No damper)



d) Hachinohe ns(Damper)

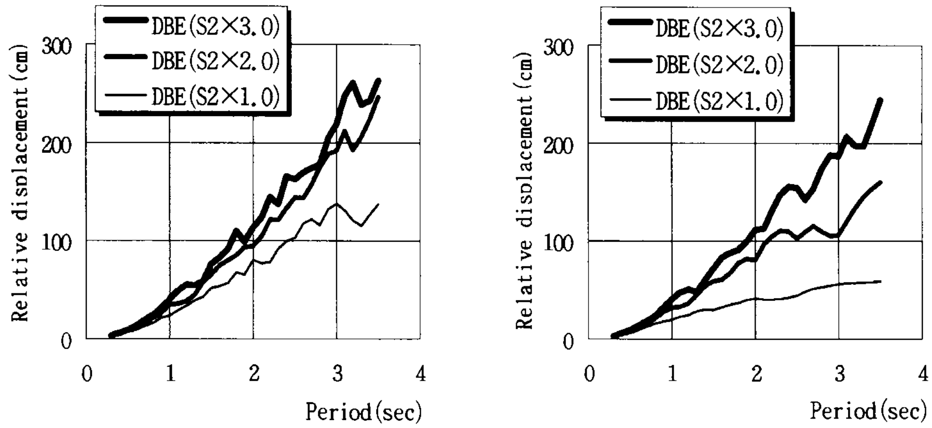


e) DBE (No damper)



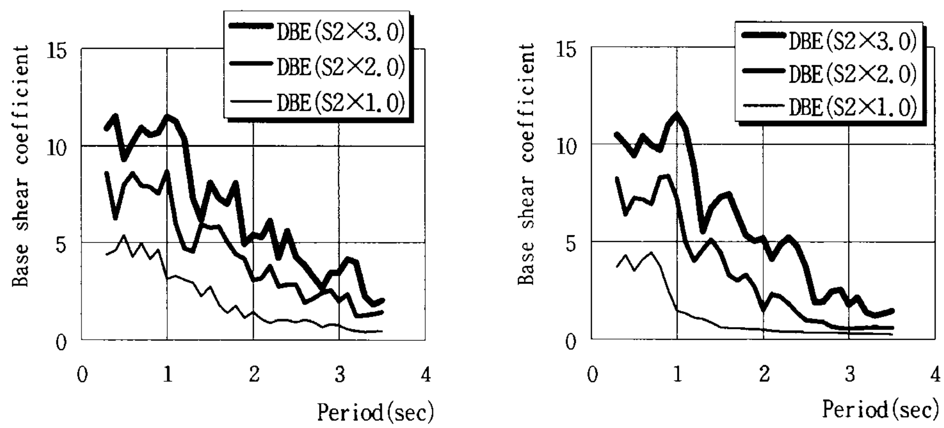
f) DBE (Damper)

Fig 4 Total input energy spectrum



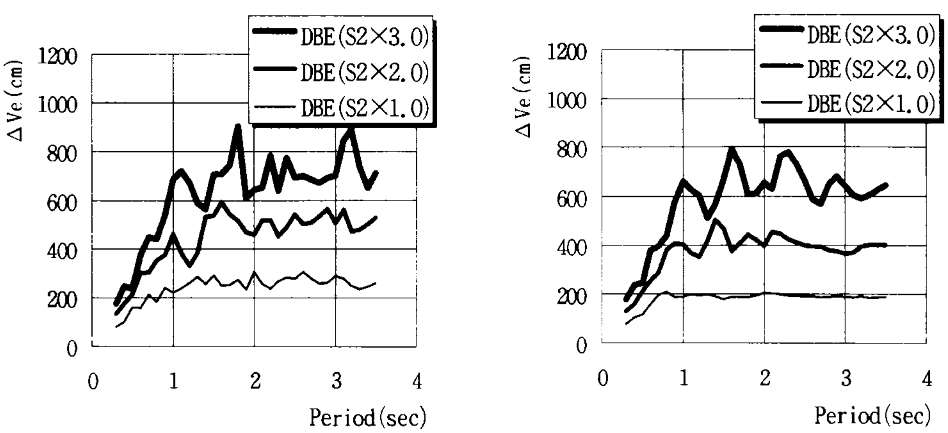
a) No damper b) Damper

Fig.5 Relative displacement spectrum(DBE)



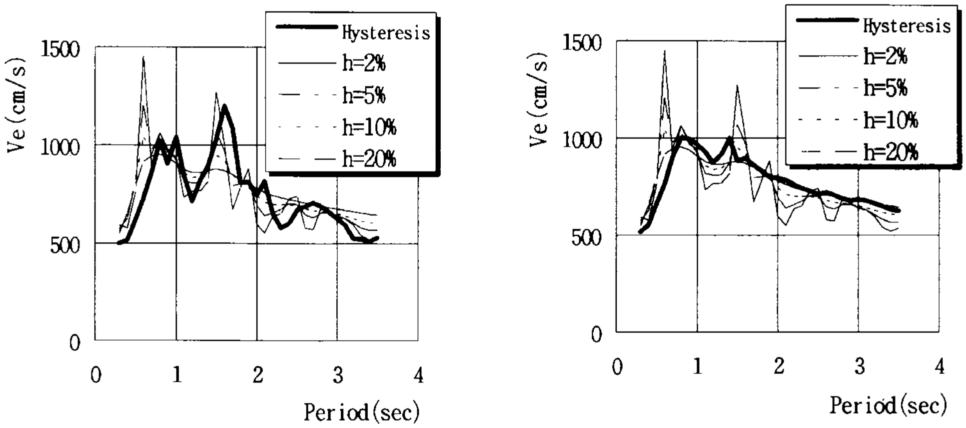
a) No damper b) Damper

Fig.6 Base shear coefficient spectrum(DBE)



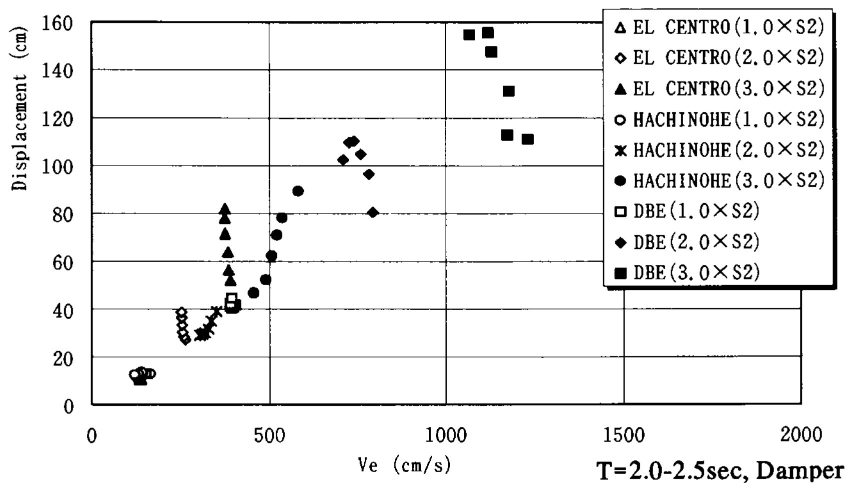
a) No damper b) Damper

Fig.7 Momental energy spectrum(DBE)



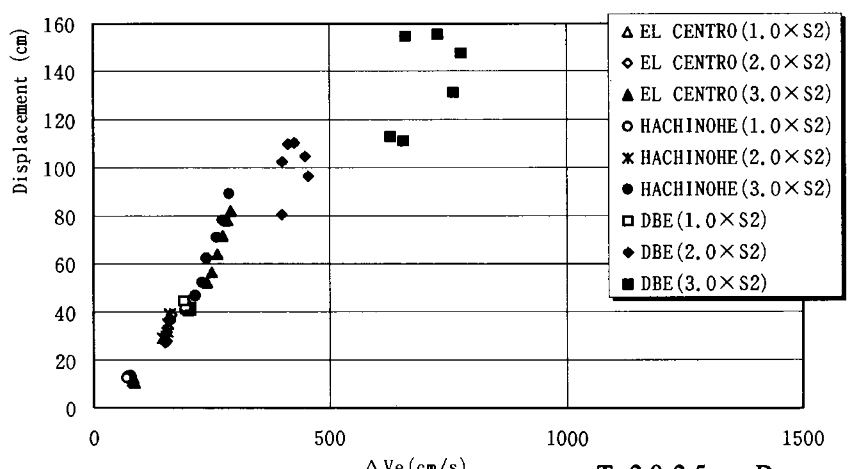
a) No damper DBE S2×2.0 b) Damper DBE S2×2.0

Fig.8 Comparison between the total input energy spectra of the elastic viscous damping model and the hysteresis model



T=2.0-2.5sec, Damper

Fig.9 Relationship between total input energy Ve and displacement



T=2.0-2.5sec, Damper

Fig.10 Relationship between momental input energy Δ Ve and displacement

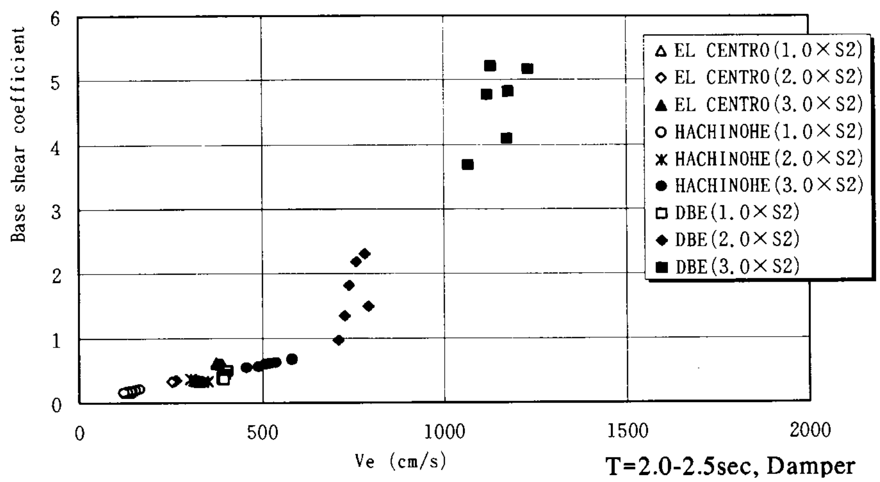


Fig.11 Relationship between total input energy Ve and base shear coefficient

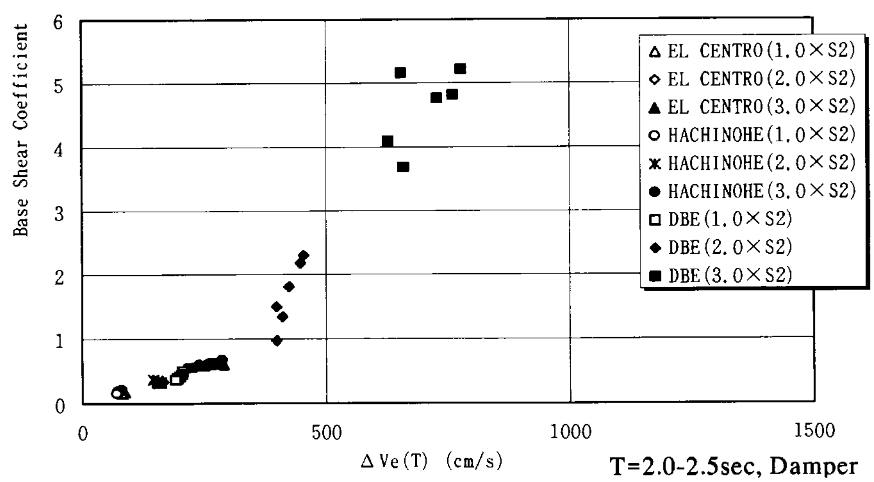


Fig.12 Relationship between momental input energy Δ Ve and base shear coefficien

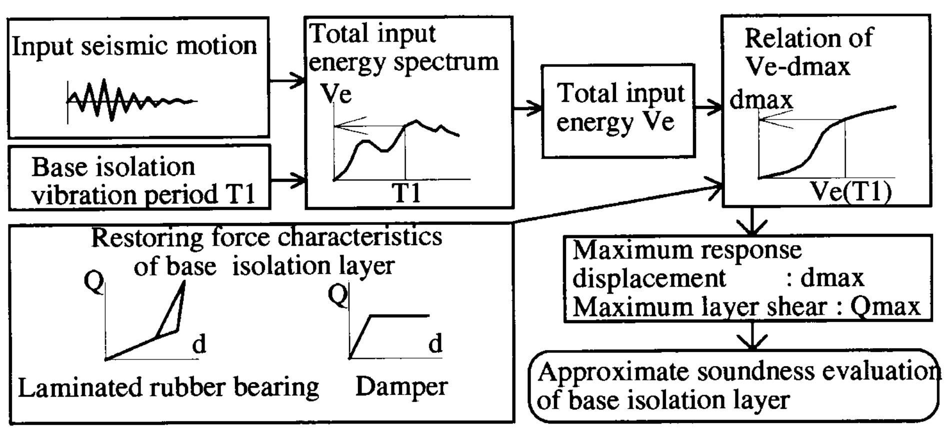
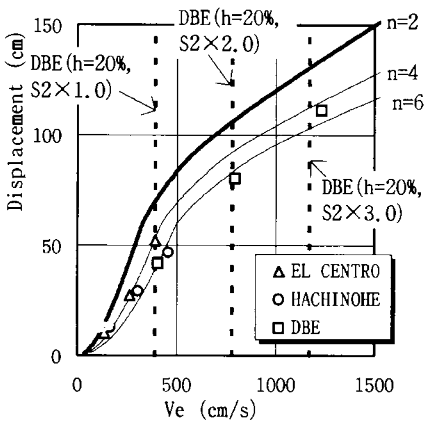
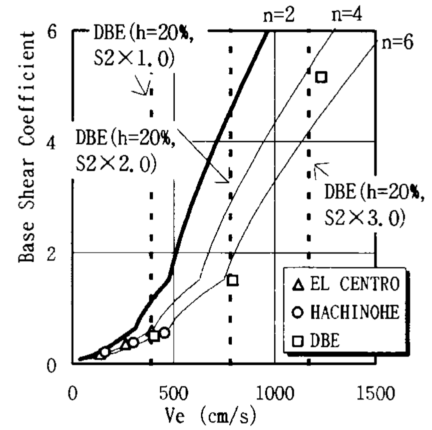


Fig.13 Response prediction flow

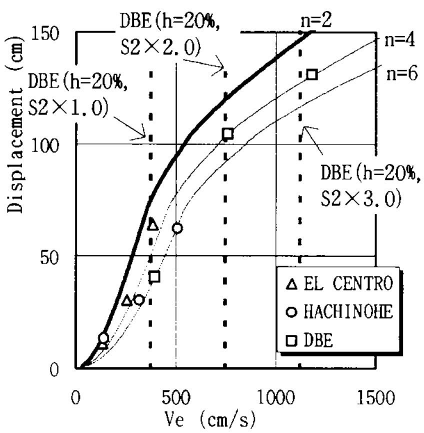


1) Displacement

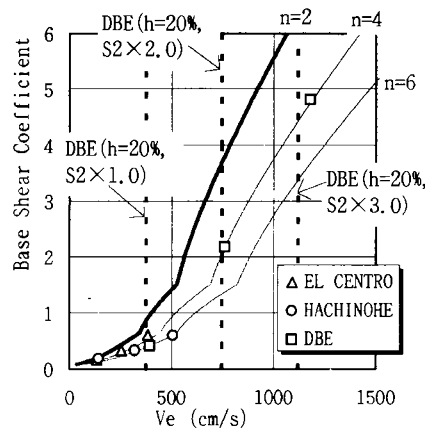


2) Base shear coefficient

a) T=2.0sec(n=2,4,6), Damper

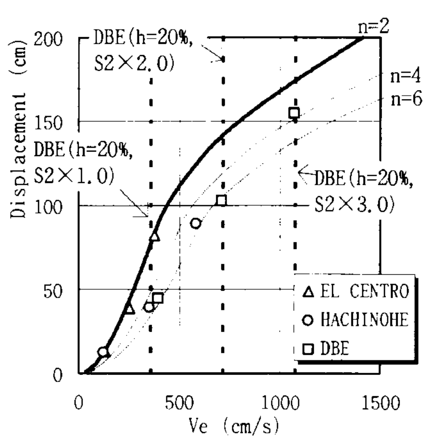


1) Displacement

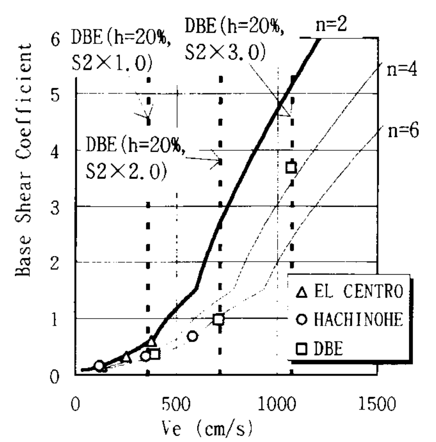


2) Base shear coefficient

b)T=2.2sec(n=2,4,6), Damper



1) Displacement



2) Base shear coefficient

c)T=2.5sec(n=2,4,6), Damper

Fig.14 Comparioson of anlysis results and response predictions