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3-D SEISMIC RESPONSE OF A BASE-ISOLATED FAST REACTOR

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ABSTRACT

This paper describes a 3-D response analysis methodology development and its application to a base-isolated fast breeder reactor (FBR) plant. At first, studies on application of a base-isolation system to an FBR plant were performed to identify a range of appropriate characteristics of the system. A response analysis method was developed based on mathematical models for the restoring force characteristics of several types of the systems. A series of shaking table tests using a small scale model was carried out to verify the analysis method. A good agreement was seen between the test and analysis results in terms of the horizontal and vertical responses. Parametric studies were then made to assess the effects of various factors which might be influential to the seismic response of the system. Moreover, the method was applied to evaluate three-dimensional response of the base-isolated FBR.

1. Introduction

It is getting recognized that the application of a seismic isolation system to a nuclear plant seems promising to enhance its seismic safety. Especially for an FBR plant, where the components are designed of thin walled structures and hence relatively vulnerable to a seismic event, a reduction of seismic loads with use of a base-isolation system is effective.

With these considerations as background, Power Reactor and Nuclear Fuel Development Corporation started its research and development program for seismic isolation technology in 1983. The purposes of the program are;

- to examine feasibility of the isolation system to an actual design taking the severe seismic design requirements in Japan into account, and
- to develop reliable evaluation methods for the seismic response of a base-isolated structure which can be used in design and safety assessment.

The program is made up of three phases as follows;

Phase-1	Parametric study to identify appropriate restoring force characteristics of isolation systems and to assess the effects of various factors,
Phase-2	Analysis method development and its verification tests,
Phase-3	Application of the method to a base-isolated FBR plant.

2. Application of base-isolation to an FBR plant

Fig.1 illustrates generic restoring force characteristics of an isolation system. The reduction of seismic response of the upper structure is achieved through lengthening the system period by rubber bearings and absorbing vibrational energy by various types of dampers. A trigger function against a strong wind or a small earthquake and a stopper function preventing an excessive displacement of the system may be added. There are three factors which determine the characteristics of the system as follows;

f : basic isolation frequency which is related to the secondary stiffness by the equation $f = (1/2\pi)\sqrt{K_2\ g/W}$, where K_2 is the secondary stiffness, W is the total weight of the upper structure, and g represents the acceleration due to gravity,

α: ratio of the secondary stiffness to the first stiffness,

β: ratio of the yielding force of the hysteretic damper to the total weight of the upper structure.

In order to identify a range of appropriate restoring force characteristics of the system, a parametric survey was made under several conditions of soil properties and ground motions. The isolation system was modeled as a bi-linear type spring which will be described in the next section. Table 1 lists the response acceleration, the response displacement, and the shear force coefficient which is the ratio of the shear force acting on the top of the isolation system to the total weight of the upper structure. Through these analyses, following knowledge was obtained. The response acceleration and the shear force coefficient reduced well when the basic isolation frequency f is 0.5 to 1.0 Hz. As for a hysteretic damper, it is effective for reduction of the response displacement to select the ratio of second stiffness α of 0.1 to 0.5 and the ratio of yielding force β of 0.1.

3. Analysis method

3.1 Modeling of the isolation system

Four types of mathematical models for the restoring force characteristics of the isolation system were used to develop the seismic analysis method. These include the bi-linear and tri-linear expressions, the Ramberg-Osgood type functional expression, and the equivalent linearization model, as illustrated in Fig.3.

The bi-linear model is made up of a linear spring simulating the horizontal stiffness of the rubber bearings and an elastic-plastic spring for the restoring force characteristics of the hysteretic dampers.

In the tri-linear model, to approach the characteristics of the model to that of the real system, tri-linear expression was used.

For the Ramberg-Osgood model, the restoring force characteristics of the hysteretic damper is modeled more realistically by the following equation;

$$\delta = a + b F^{c-1}$$

where F, δ denotes the restoring force and the displacement respectively and a, b, and c are constants. The constants are determined so that the initial stiffness at $\delta = 0$ and the tangent stiffness at $\delta = 4\delta_y$, where δ_y is the yielding displacement, are coincident with desired ones.

And, for the equivalent linear model, the restoring force characteristics of the hysteretic damper is approximated by one equivalent linear spring with an equivalent viscous damping. The equivalent stiffness of the spring is determined from the secant stiffness of the bi-linear model of which energy is equal to that of the maximum response displacement obtained from linear response analysis of the upper structure using the first stiffness. The equivalent damping ratio is calculated from the ratio of the dissipated energy of the bilinear model to the elastic energy of the equivalent stiffness as illustrated in Fig.3.

3.2 Verification tests

A series of shaking table tests using a small scale model consisted of an upper structure and various base-isolation devices was performed with the purpose of verifying the above mentioned analysis method. As for the isolation system, a rubber bearing with a steel hysteretic damper, a lead rubber bearing, and a high damping rubber bearing were used. The upper structure was designed with a steel frame structure as shown in Fig.4. Its weight was about 1,600 kg. A primary natural frequency of the model was approximately 12 Hz in the case of no base-isolation.

Before the verification tests, experimental studies on vibration characteristics of the the isolation system were done. The purposes of the tests were to investigate the basic response characteristics, such as natural frequencies, damping factors, and transfer functions, using the harmonic excitation and to understand the seismic response characteristics using the observed waves and artificial waves. In the seismic response tests, the effect of the intensity and duration of the input wave, and the influence of multi-axial input were assessed. For example, Fig.5 compares the maximum response acceleration and floor response spectrum between one-directional and three-directional excitation. The influence of orthogonal input on one direction is small and the vertical motion input hardly affects the horizontal response.

3.3 Simulation analysis

One-directional simulation analyses were performed with a three-lumped-mass model illustrated in Fig.6 inputting the E-W component of the Hachinohe Harbor record in Tokachi-oki Earthquake 1968 shown in Fig.7. Values of the stiffness and damping of the upper structure were obtained from resonance tests. For the base-isolation system, four types of models which were described in the previous section were used. The constants which determined the restoring force characteristics of each model were obtained by a curve fitting method through static loading tests of the isolation devices.

In order to judge the validity of simulation analyses, comparisons of the time histories of acceleration and displacement and the floor response spectra are shown in Fig.8. From the figure, in the case of the steel damper, it can be noted that the analysis results using the bi-linear model tend to estimate the response a little larger. On the contrary, the results using the equivalent linear model tend to estimate a little smaller. The results using the trilinear model and the Ramberg-Osgood model are in good accordance with the test results. These tendencies can be seen in the cases of the lead rubber bearing and the high-damping rubber bearing. In either case, the validity of the analysis method is verified through these studies.

Three-directional simulation analyses were also executed. Here, an equivalent linear model was used for modeling the restoring force characteristics of horizontal component of the isolation system. The vertical and rotational stiffness of the device were also considered.

Fig.9 shows a comparison of the time history of acceleration, the orbit curve, which is a trace of two-directional motion of the upper plate of the bearing, the maximum acceleration distribution, and the floor response spectrum between the test and the corresponding simulation analysis. A good agreement was seen in terms of both the horizontal and vertical responses. It was found possible to simulate the horizontal and vertical responses by using an equivalent linear model.

4 Analysis of the actual FBR plant

4.1 Parametric studies on effects of various factors

Parametric studies were made to assess the effects of various factors which might be influential to the seismic response of a base-isolated structure. A base-isolation system which had the restoring force characteristics based on the analysis mentioned in the second section was designed for a 1,000 MWe class loop-type FBR. Earthquake response analyses were performed with a multiple-lumped-mass model as shown in Fig.10. An artificial ground motion, based on a modified Osaki spectrum in which the long period components were enhanced, was chiefly used here. The response acceleration spectrum of the generated ground motion is shown in Fig.11. The leading results through these analyses were as follows.

Fig.12 shows the relation of the maximum input acceleration and the maximum response displacement to compare the effect of the soil properties. The fact that the difference of the response between the soft rock site (Vs = 700 cm/sec) and the hard one (Vs = 1500 cm/sec) is small suggests us a possibility of adopting a site independent standard seismic design of the base-isolated FBR plant.

In order to grasp the effect of soil-structure interaction, three types of models were considered. That is the sway-rocking model, the lattice model, and the FEM model illustrated in Fig.13. Fig.14 compares the results of maximum response accelerations. In the case of the base-isolated structures, the effect of the interaction was insignificant, as opposed to an ordinary one.

The effect of variability of the characteristics of the isolation system was investigated. Here, the variability of the stiffness of the bearings and the steel dampers was assumed ± 20 % and that of the yielding displacement was assumed ± 10 % as illustrated in Fig.15. Fig.16 shows the upper and lower bounds of the responses owing to the variability of the characteristics. The variability of the response is almost the same degree as that of the stiffness. Then a possibility of the torsional vibration due to the eccentricity of the center of the stiffness was examined. Fig.17 compares the response displacement as a function of the eccentricity between the center of gravity and the edge of the isolation device. From these analyses, the effect of the variability of the characteristics of the system is so small that we can disregard it in the design analysis.

4.2 Evaluation of the vertical response of an FBR plant

There are some structural parts in an FBR plant which are relatively sensitive to the vertical component of a seismic load. Conceptually, a horizontal base-isolated structure is designed so that there is no, or at least a small, amplification of the vertical earthquake component at the bearing. But in reality, a certain amount of amplification is unavoidable due to a finite axial stiffness of the bearing. Therefore it is valuable to estimate the vertical response of the isolated structure for component design purpose. From this point of view, the method was applied to evaluate a vertical response of a base-isolated plant, in addition to a horizontal response.

The restoring force characteristics of the isolation system was supposed to be a bi-linear type and fixed at isolation frequency f = 1.0 Hz, yielding coefficient β = 0.1, and secondary stiffness ratio α = 0.1. A two-directional artificial wave (N-S : 500 gal, U-D : 350 gal) was used for a seismic input and shown in Fig.18. Earthquake response analyses were performed with two kinds of soil properties and three kinds of vertical stiffness of the bearings as parameters.

An analytical model consisted of a multiple-lumped-mass model, an isolation system model, and soil springs as shown in Fig.10. The isolation system was modeled as an equivalent linear model. Values of the soil springs were estimated by Tajimi's method.

The time history responses of acceleration and displacement at the support position of the reactor vessel and the floor response spectra in the horizontal and vertical direction were obtained through these analyses, among which an example is shown in Fig.19. Table 3 lists the maximum response acceleration and displacement at the support position. From the table, it can be observed that the vertical response can be controled at a low level, when the vertical stiffness of the device is designed sufficiently high. Note here, however, a care should be taken for the relation between the peak of the response spectrum and the component frequency, so that excessive vertical response of the component do not occur. Moreover, from a point of view of component design, the soft rock site has the advantage of response reduction as far as the vertical response is concerned. Since the seismic isolation has its advantage on a hard rock site, we must assess the effect of soil properties more synthetically.

5. Conclusion

From studies on application of a base-isolation system to an FBR plant, a range of appropriate restoring force characteristics of the isolation devices was obtained. An analysis method was developed based on mathematical models for the restoring force characteristics of several types of isolation bearings. The method was verified by a series of shaking table tests. Parametric studies to assess the effects of various factors were done. The base-isolated plant was not so much influenced by soil properties and soil-structure interaction as the non isolated plant. The method was applied to evaluate the vertical response of a base-isolated FBR plant.

ACKNOWLEDGEMENT

The shaking table tests and the simulation analysis described in the section 3 of this paper were carried out at Shimizu Corporation under a contract with PNC. The authors would like to thank Mr. Kobatake who was in charge of the tests and analyses.

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[1] M.Morishita, M.Kobatake, K.Ohta, Y.Okada; Investigation on Base Isolation for Fast Breeder Reactor Building, 10th-SMiRT, Anaheim, U.S.A., (1989)

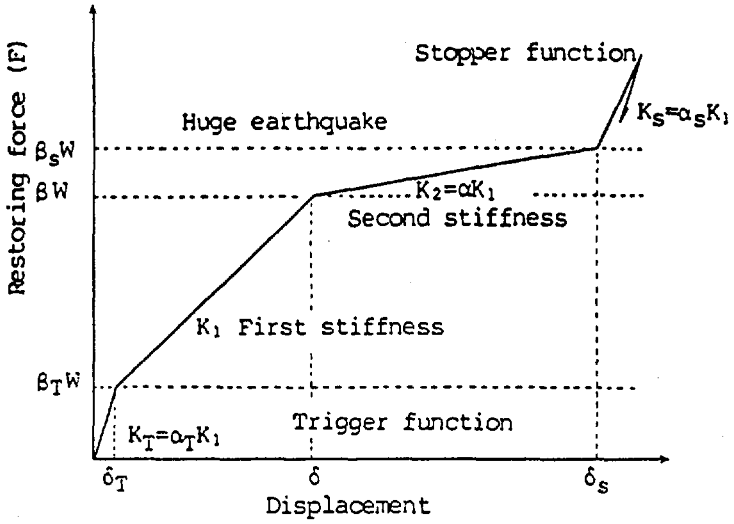


Fig. 1 Generic restoring characteristics of an isolation system

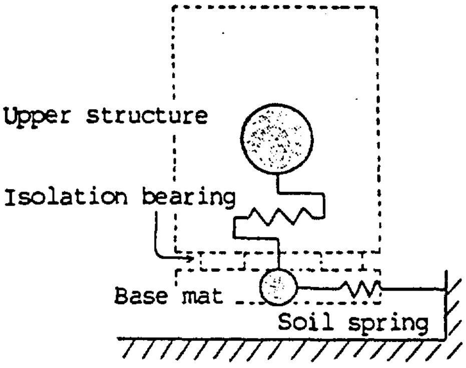
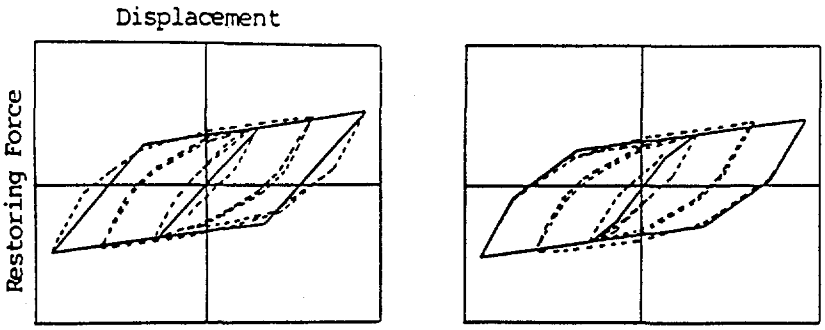


Fig. 2 A two-lumped-mass model

Table 1 Results of Parametric Study

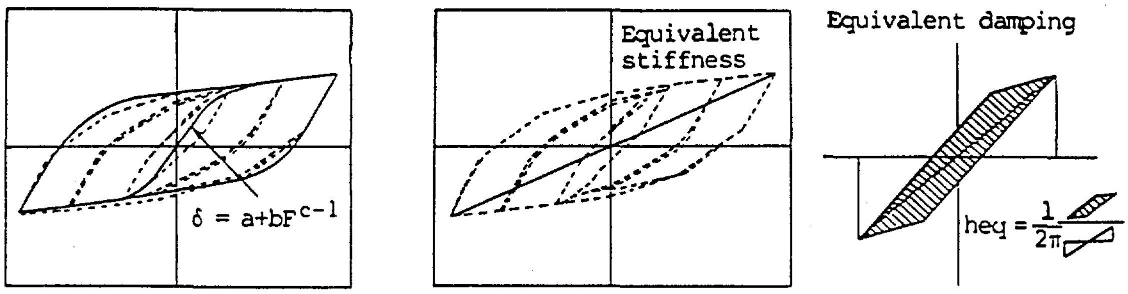
f (Hz)	α	β	Max.Accel. (gal)	Max. Disp. (cm)	Shear force coefficient
0.5	0.5	0.05	65	8.3	0.067
0.5	0.5	0.1	109	12.1	0.111
1.0	0.1	0.05	66	5.2	0.066
1.0	0.1	0.1	116	6.6	0.117
1.0	0.1	0.2	206	6.9	0.208
1.0	0.2	0.05	85	5.7	0.086
1.0	0.2	0.1	130	6.5	0.132
1.0	0.2	0.2	212	6.8	0.214
2.0	0.05	0.05	77	3.7	0.077
2.0	0.05	0.1	127	3.8	0.125
2.0	0.1	0.05	104	3.7	0.104
2.0	0.1	0.1	148	3.7	0.149

Artificial wave input, Input acceleration = 300 gal
Hard rock site (V_S=1500 cm/sec)



(a) Bi-linear model

(b) Tri-linear model



(c) Ramberg-Osgood model

(d) Equivalent linear model

Fig. 3 Models of the restoring force characteristics

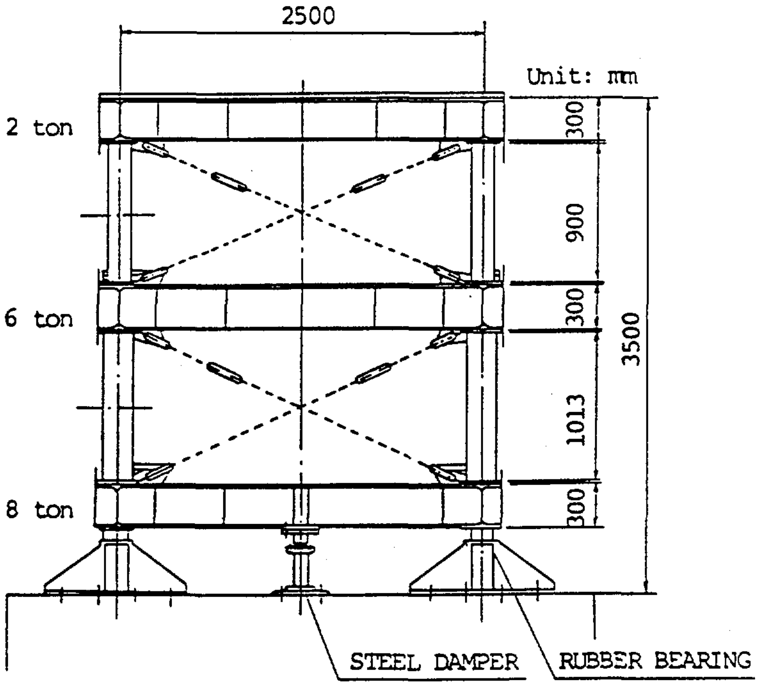
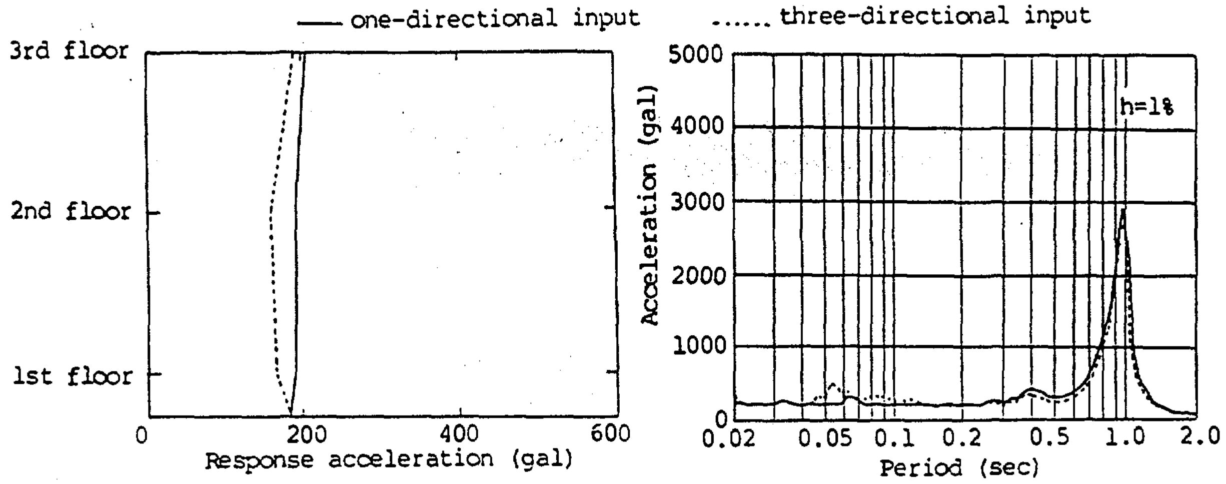


Fig. 4 A steel frame structure



(a) Maximum response acceleration

(b) Floor response spectrum

Fig. 5 Comparison of the responses between one-directional and three-directional input

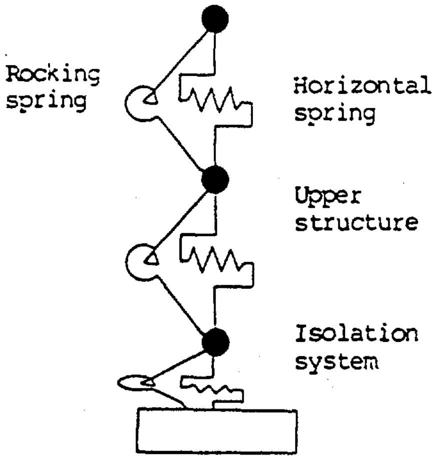


Fig. 6 A three-lumped-mass model

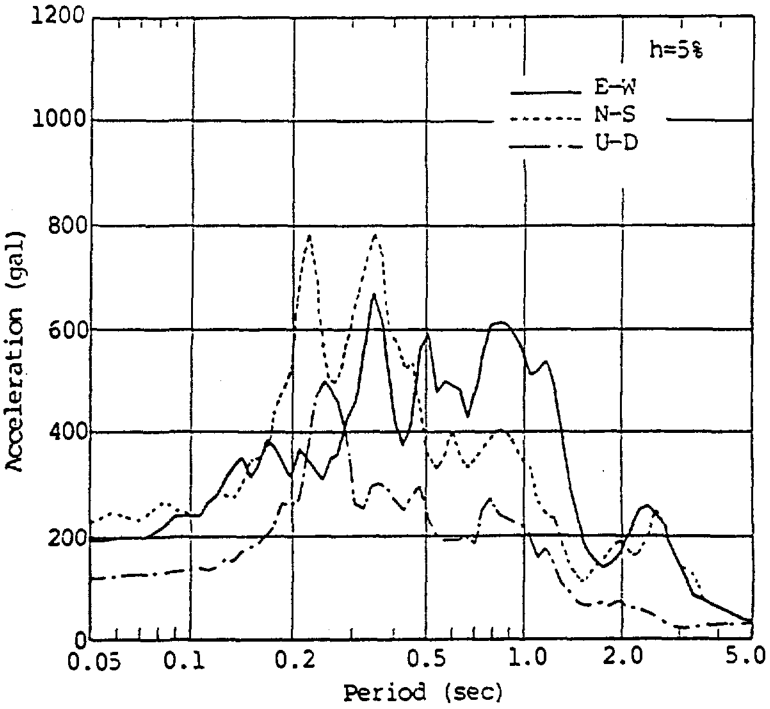
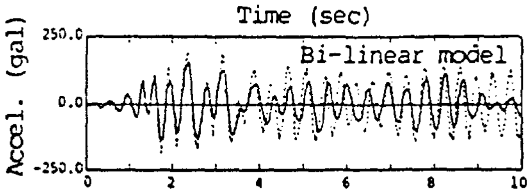
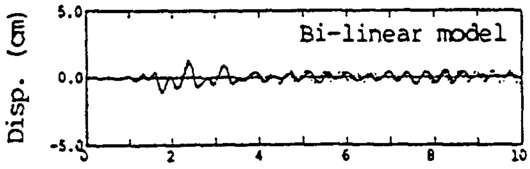


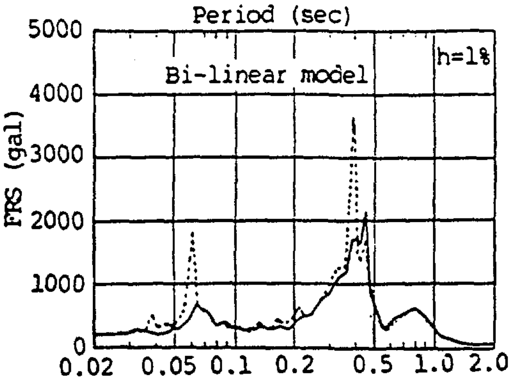
Fig. 7 The Hachinohe Harbor record in Tokachi-oki Earthquake



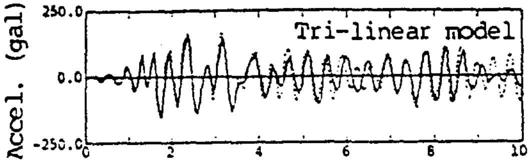
(a) Acceleration



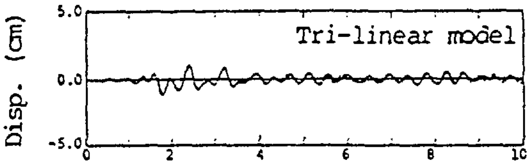
(b) Displacement



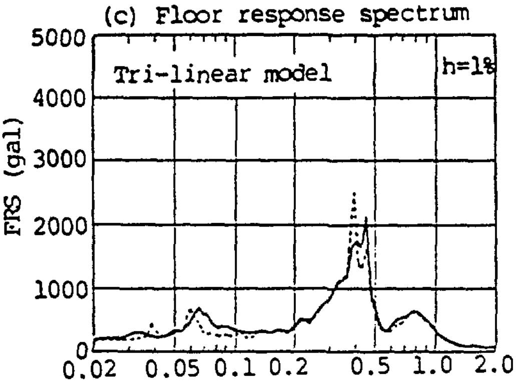
(c) Floor response spectrum



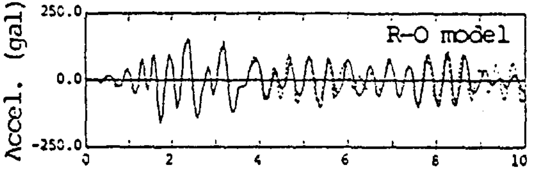
(d) Acceleration



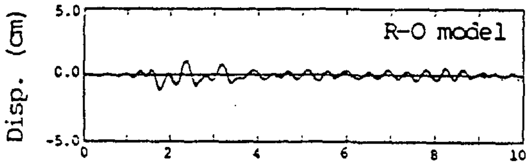
(e) Displacement



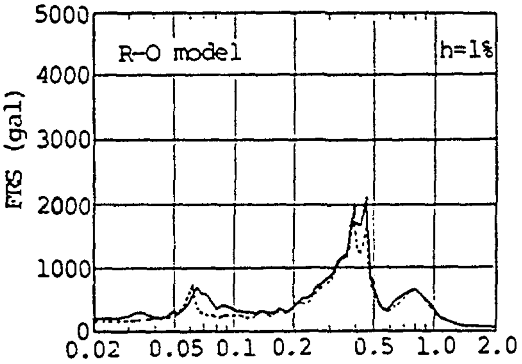
(f) Floor response spectrum



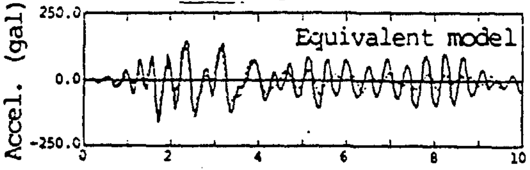
(g) Acceleration



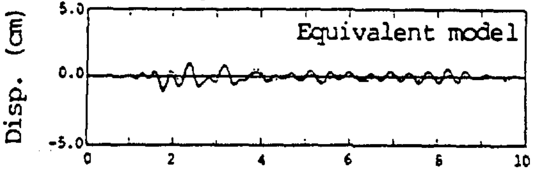
(h) Displacement



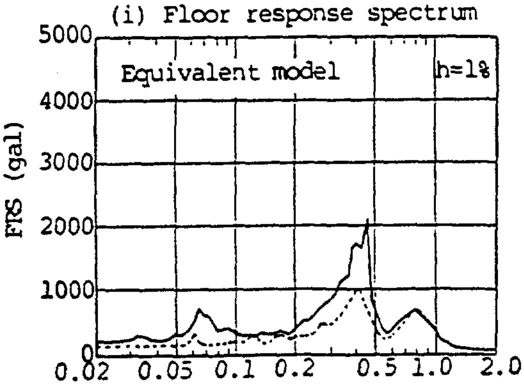
(i) Floor response spectrum



(j) Acceleration



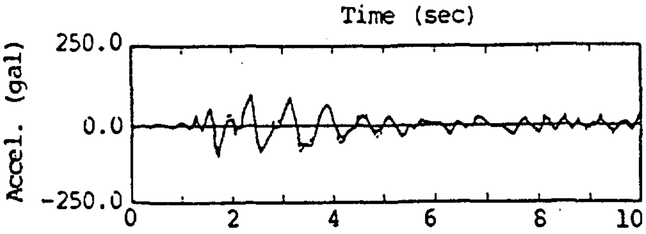
(k) Displacement



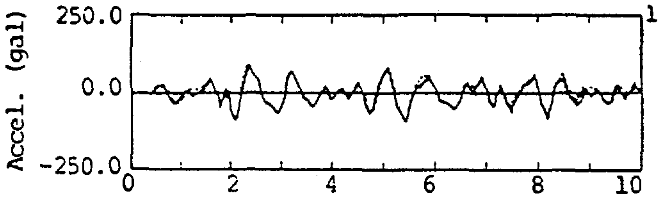
(l) Floor response spectrum

Fig. 8 Comparisons between the test and analysis results

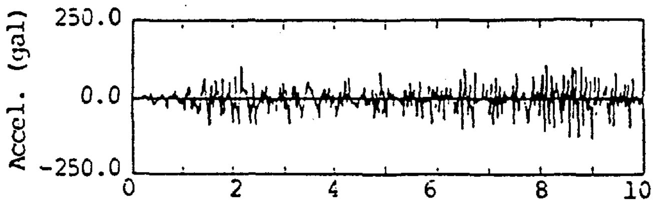
——— test ·········· analysis



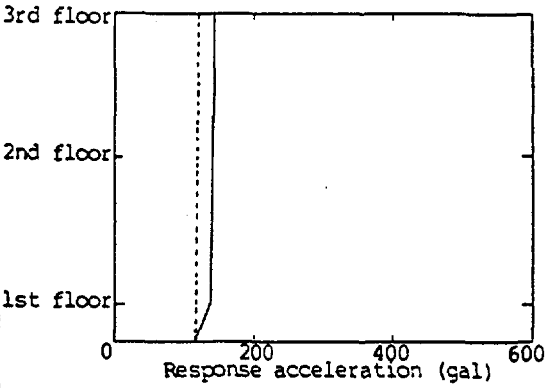
(a) Acceleration in the E-W direction



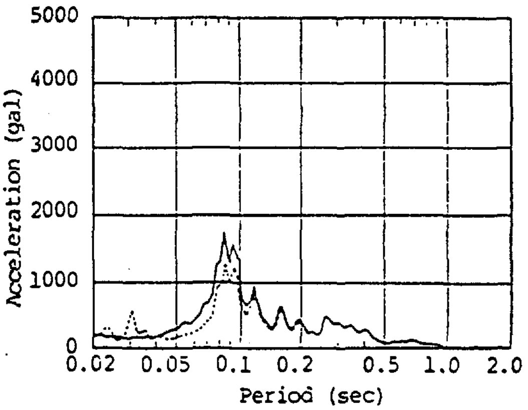
(b) Acceleration in the N-S direction



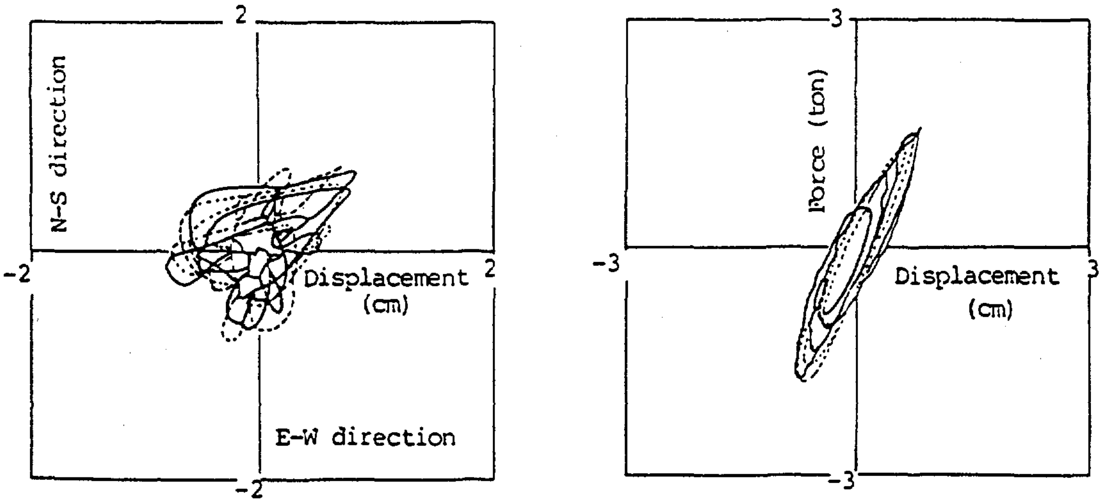
(c) Acceleration in the U-D direction



(d) Maximum response acceleration



(e) Floor response spectrum



(f) Orbit curve

(g) Restoring force characteristics

Fig. 9 Comparisons between the test and analysis results

—— test ······· analysis

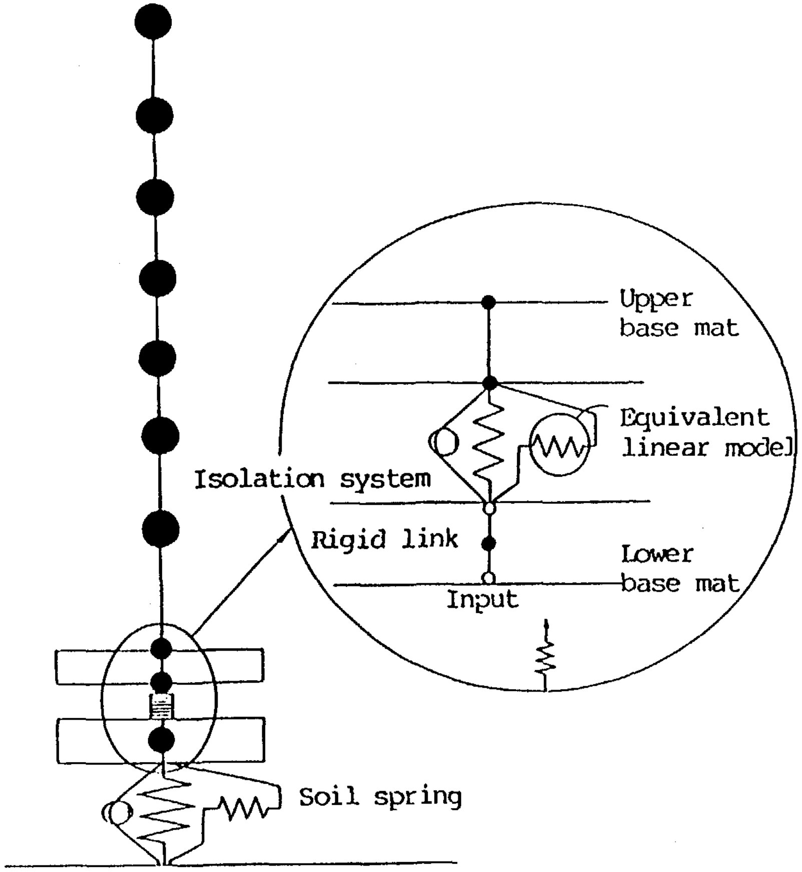


Fig. 10 A multiple-lumped-mass model with an isolation system model

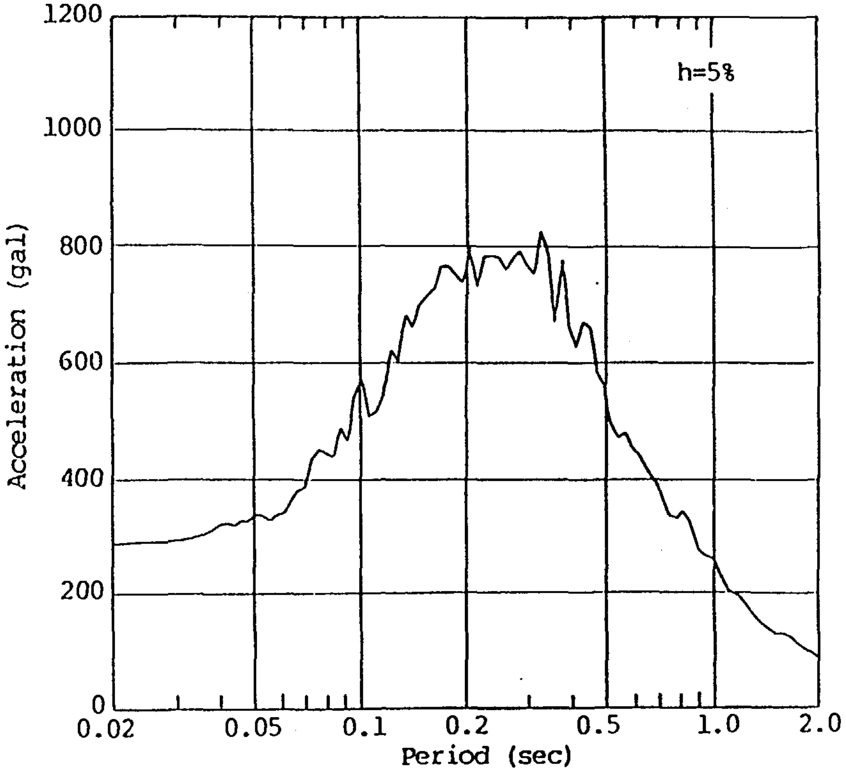


Fig. 11 An artificial ground motion

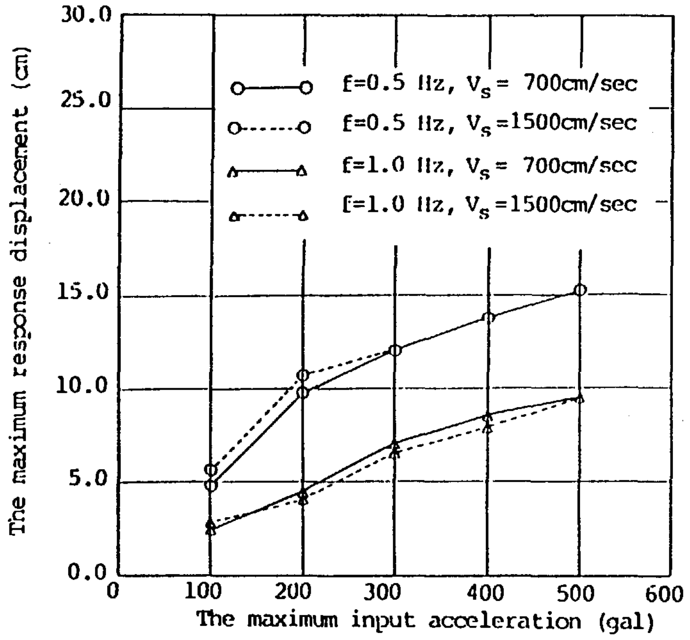


Fig.12 Effect of soil properties

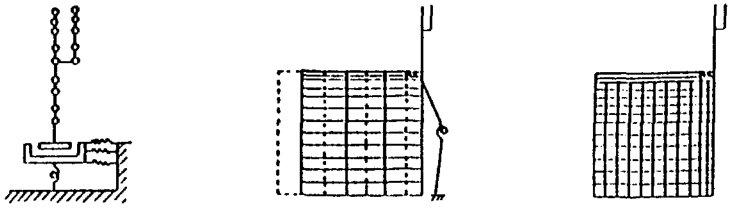

(a) A Sway-Rocking model (b) A Lattice model (c) An FEM model

Fig.13 Analysis models

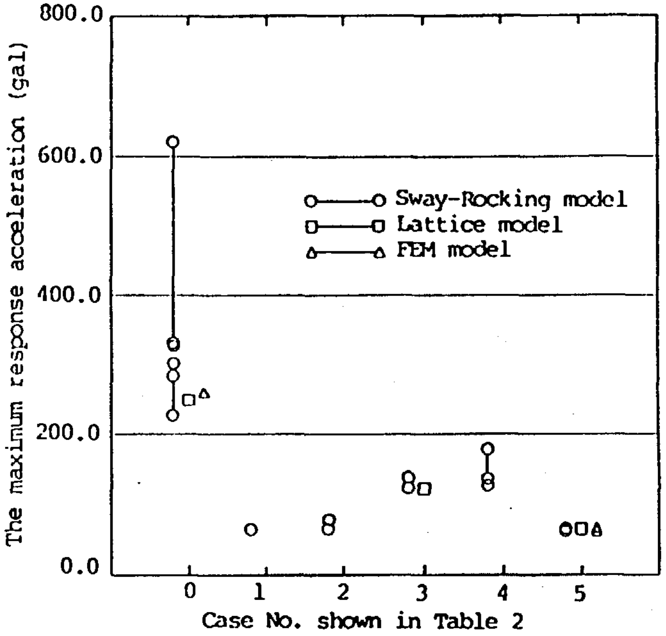
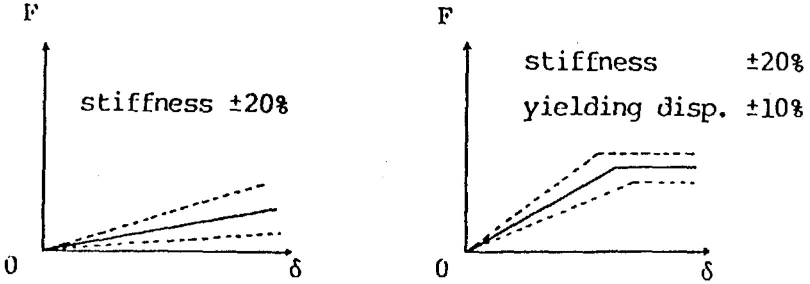


Fig.14 Effect of soil-structure interaction

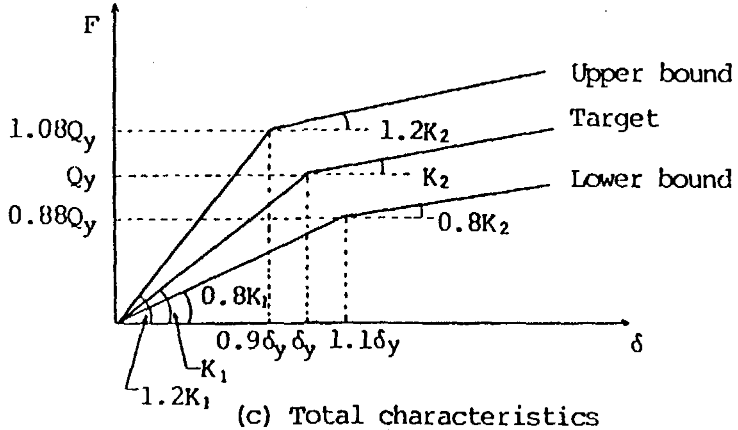
Table 2 Restoring Force Characteristics

No.	f Hz	α	β	β_t	Damping Factor %	Isolation Devices
0						Non Isolation
1	0.5	0.5	0.05		2	LB + HD
2	0.5	0.5	0.1	0.025	2	LB + HD + TR
3	1.0	0.1	0.1		2	LB + HD
4	1.0	0.1	0.1	0.025	2	LB + HD + TR
5	0.5				10	LB + VD

β_t: Trigger yielding coefficient, LB: Laminated Bearing, HD: Hysteretic Damper, VD: Viscous Damper, TR: Trigger

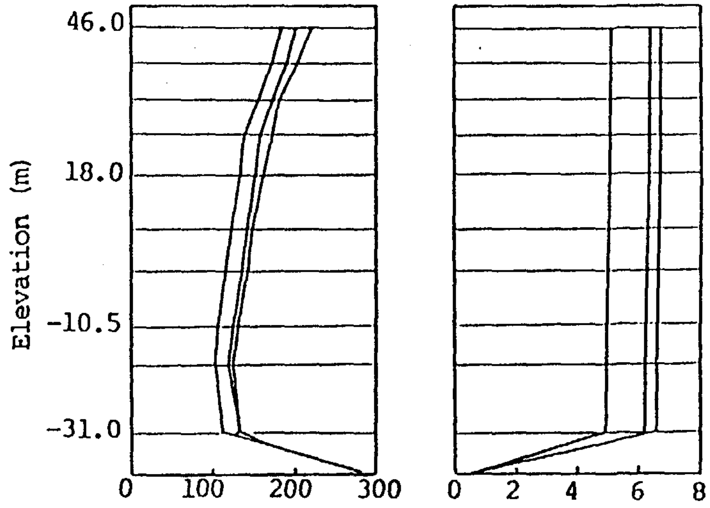


(a) Laminated rubber bearing (b) Steel dampler



(c) Total characteristics

Fig. 15 Upper bound and lower bound of hysteretic characteristics



(a) Acceleration(gal) (b) Displacement(cm)

Fig. 16 The variability of the response

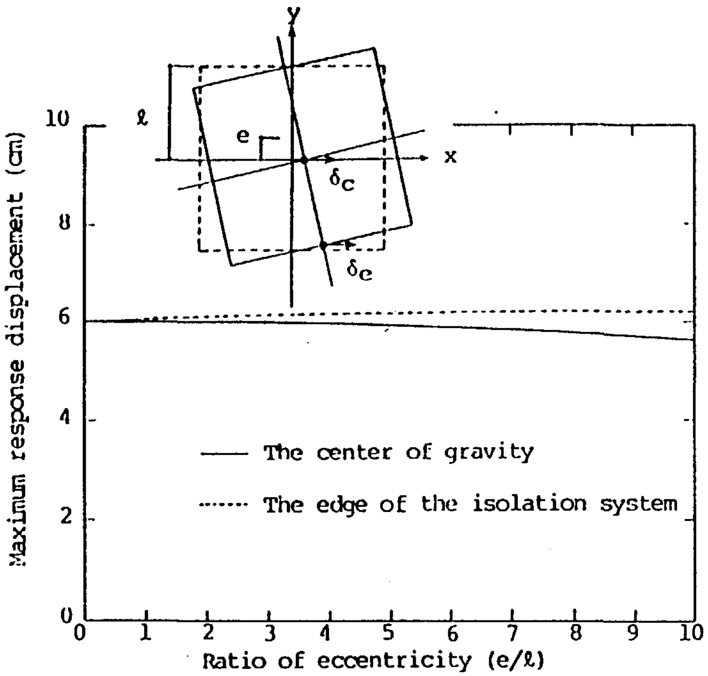
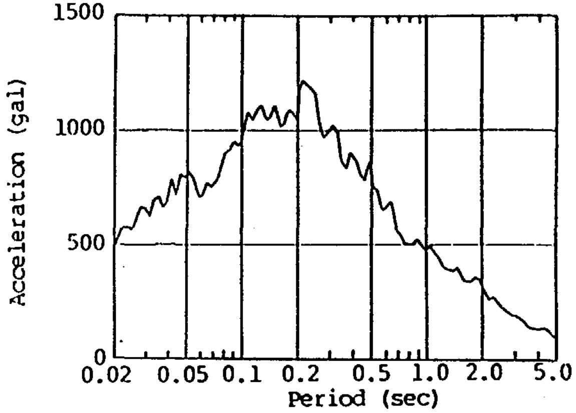


Fig.17 Response acceleration as a function of the eccentricity

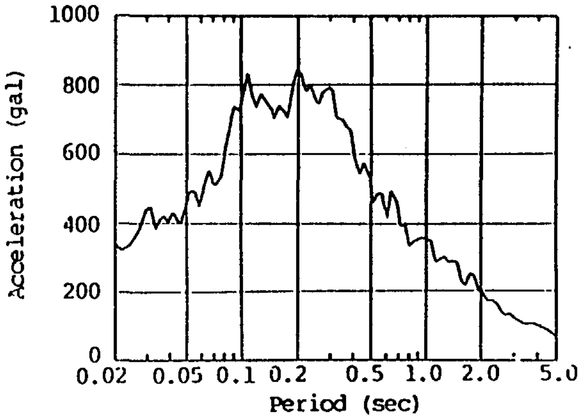
Table 3 Responses of an FBR plant

No.	V_s (m/s)	f_v (Hz)	Horizontal Max.Accel. (gal)	Horizontal Max.Disp (cm)	Vertical Max.Accel. (gal)	Vertical Max.Disp (cm)
1	1500	18	148	10.39	656	0.26
2	1500	12	149	9.65	681	0.33
3	1500	6	148	10.50	979	0.97
4	700	18	148	10.58	354	0.35
5	700	12	148	10.59	379	0.42
6	700	6	147	10.69	455	0.70

V_s: Shear wave velocity
f_v: Vertical isolation frequency

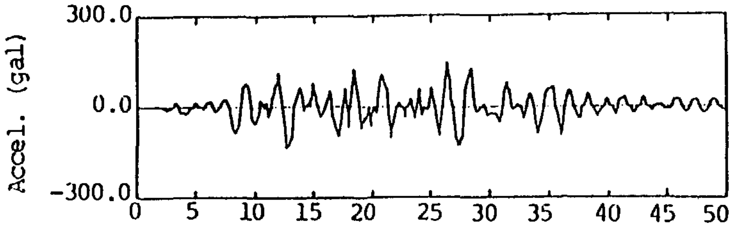


(a) N-S direction

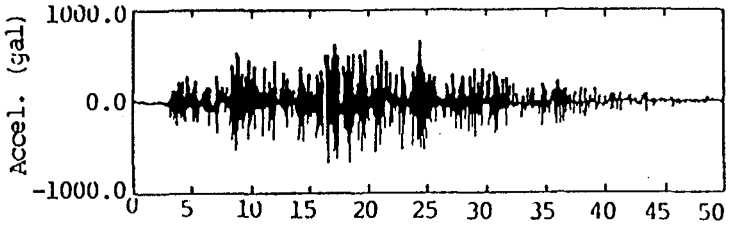


(b) U-D direction

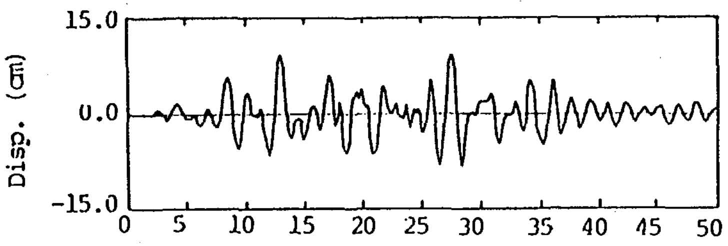
Fig.18 A two-directional artificial wave



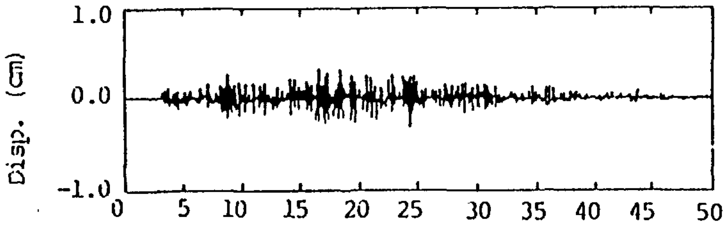
(a) Acceleration (N-S)



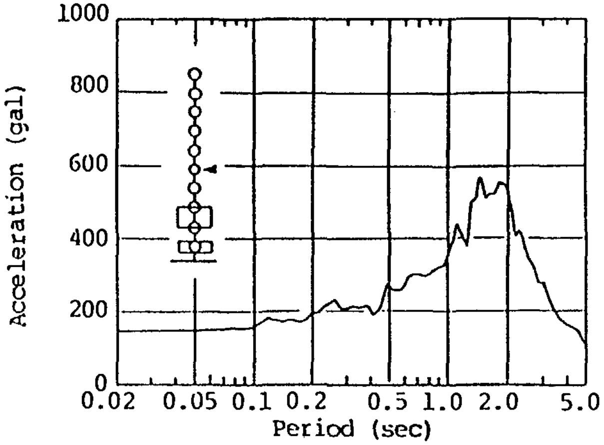
(b) Acceleration (U-D)



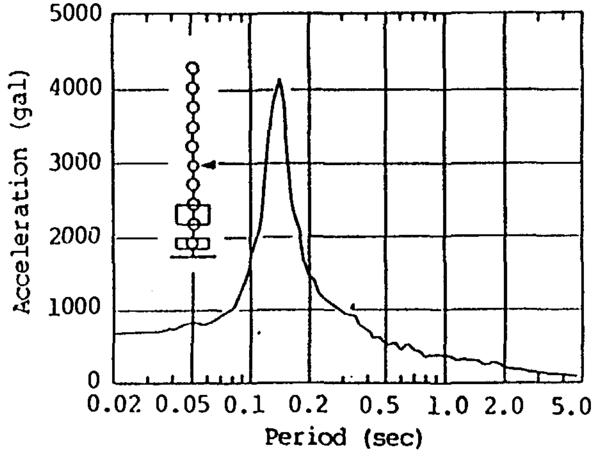
(c) Displacement (N-S)



(d) Displacement (U-D)



(d) Floor response spectrum (N-S)



(e) Floor response spectrum (U-D)

Fig. 19 Response of an FBR plant