CRIEPI TEST PROGRAM FOR SEISMIC ISOLATION OF THE FBR

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This paper describes the Central Research Institute of Electric Power Industry's (CRIEPIs) seismic isolation program. The test and research program on seismic isolation was started in 1987 by CRIEPI under contract with the Ministry of International Trade and Industry (MITI) of Japan. It was intended to establish a technical basis for the application of seismic isolation to fast breeder reactors (FBRs). In this paper, some details of the program and results of the preliminary study are described.

Introduction

Seismic isolation is expected to be effective in raising the reliability during earthquakes, reducing the cost, enlarging siting, and promoting design standardization of the fast breeder reactor (FBR).

Although seismic isolation has been applied to several office buildings and residences in Japan, more research and demonstrations are necessary to verify the reliability and effectiveness of seismic isolation for such important structures as the FBR. A test and research program was planned and started in 1987 by the Central Research Institute of Electric Power Industry (CRIEPI) under contract with the Ministry of International Trade and Industry (MITI) so the results could be reflected in the demonstration reactor (Fig. 1 and Table I). It was intended to select appropriate seismic isolation concepts, to determine their effectiveness and feasibility, and to develop a rough draft of design technical guideline within three years. It was further intended to establish seismic isolation concepts, to verify their reliability, and to prepare a design technical guideline (draft) within seven years. In this paper, some details of the program and results of a preliminary study are described.

Test Program

On the basis of a survey of past research, designs, and seismic safety reviews of nuclear power stations, a research program was developed, consisting of the following items[1] (Table II):

1. To prepare an FBR seismic isolation design technical guideline (draft) on the basis of a survey of domestic and overseas standards and codes and the results of the present research.
2. To evaluate slightly long period components of earthquake motion by collecting and analyzing seismic observation records and by applying analytical methods, and to propose a method for setting an appropriate design earthquake motion.
3. To select appropriate seismic isolation systems and elements on the basis of a survey of past cases and seismic response analyses, to develop structural concepts, and to investigate technical issues through analyses, model experiments, etc., and to demonstrate the reliability of FBR seismic isolation systems during a strong earthquake by use of a large-scale shaking table.
4. To demonstrate the reliability of the seismic isolation elements by conducting breaking tests with large-scale seismic isolation element models.
5. To develop seismic PSA techniques for seismic isolation system. In this paper, details of the program are described.

1. Proposal of Design Guideline for Seismic Isolation System

The program intends to propose a technical guideline which will be required in designing seismic isolation for an FBR.

First, a comprehensive survey of aseismic design standards, guidelines, and actual designs of nuclear power stations and seismically isolated buildings in and out of Japan was conducted.

On the basis of the survey findings, terms to be covered by the guideline were selected, the basic philosophy and framework of the guideline were formulated, and the remaining technical tasks were clarified.

Remaining tasks are to be investigated in this program, and by reflecting the results of the program, the design guideline will be proposed.

The principal contents of the technical guideline (draft) are as follows:
Section I Safety design policy for seismic isolation systems
(a) Safety design policy for seismic isolation systems

Section II Seismic isolation design policy for seismic isolation systems

- (a) Basic policy
- (b) Classification of importance
- (c) Methods for evaluating seismic isolation design
  Methods for calculating seismic forces
  Methods for evaluating design earthquake motion
  Methods for evaluating seismic isolation system
- (d) Combination of loads and tolerances

Section III Engineering data

- (a) Evaluation of earthquake motion
- (b) Seismic isolation design methods
- (c) Seismic isolation elements design methods
- (d) Building design methods
- (e) Component design methods
- (f) Construction methods.

2. Study on Earthquake Load and Response

To design seismic isolation systems for an FBR, it is necessary to make rational design earthquake ground motion which includes relatively long-period components. It is also important to confirm the performance of isolation systems and to verify the response analysis method by observing the response of actual seismically isolated structures.

We intend to propose a method to determine design earthquake ground motion for a seismically isolated FBR, and to construct and observe the response of the about 1/3-scale seismically isolated nuclear-island building model.

For investigation of design earthquake ground motion, seismic observation records of large earthquakes (magnitude >6) are analyzed, and comparisons are made with the results of evaluation methods such as the semiempirical formula for Love wave, semi-empirical formula for body wave, and a method for synthesizing strong ground motion using observed seismograms of small events.

3. Development of Seismically Isolated Structure

We intend to select appropriate seismic isolation concepts for an FBR, to develop an isolation structure, and to verify reliability of the structure. This development is conducted according to the following procedure:

(a) Several promising seismic isolation concepts and corresponding isolation devices are picked up based on existing knowledge.

(b) Each plant concept is subjected to seismic response analysis using a tentative design spectrum for a seismically isolated FBR, and the applicability, cost reduction effects, and future research and development items are evaluated on the basis of the results of their findings, and an isolation concept is selected.

(c) The design of an isolation system for an FBR is developed in some detail, and tasks for further investigation are identified.

(d) Analytical studies and model tests are conducted for the identified tasks, and the design of the isolation system is revised.

(e) Reliability of the isolation system is verified by large-scale model tests using the shaking table of the Nuclear Power Engineering Test Center at Tadotsu, Japan.

4. Seismic Isolation Element Demonstration Test

It is intended to conduct tests on large-scale seismic isolation elements for an FBR to demonstrate safety against seismic load and durability of these elements in service life of the plant.

Tests on the elements are conducted according to the following procedure:

(a) A survey of past tests on seismic isolation elements is made to select necessary test items and to develop a test program.

(b) A specification of a laminated elastomer for base isolation of an FBR building is examined. A full-scale (500-ton class) and reduced-scale (200- and 50-ton class) models are fabricated.

(c) A static biaxial load tester, which is capable of breaking large-scale (200-ton class) isolation elements, is fabricated.

(d) Scale law is confirmed by conducting tests on full- and reduced-scale models using the load tester and by testing cut-out samples from the elastomers of different scales.

(e) The breaking loads and displacements are determined from the test results of reduced-scale models using the biaxial load tester, while load-displacement relationships for design loads are determined using full-scale models.

5. PSA Methodology Development and Application on the Isolation System

It is intended to investigate the reliability of seismically isolated FBR structures during earthquakes from the viewpoint of probabilistic safety assessment.

The following methods are employed in the study:

(a) Estimation of the probabilistic factor of safety which consists of capacity factor, response factor, and deterministic safety factor.

(b) Simulation and evaluation of safety margin measures based on second-moment reliability for estimating the reliability index of both isolated and nonisolated FBR structures.

(c) Development of a Monte Carlo simulation technique for more accurate assessment and for investigation of the effect of randomness of isolation devices on the response of seismically isolated FBRs.

Tentative Velocity Response Spectrum

The tentative velocity response spectra are formulated as input seismic motion for development of a seismically isolated structure and for seismic isolation demonstration tests.[2]

1. Basic Conditions for Formulating the Tentative Velocity Response Spectrum (h=5%)

The velocity response spectrum is not aimed at a specific point but is based on a general design condition that a seismically isolated FBR is constructed on the bedrock in any area of Japan. The following four conditions are established to formulate the tentative velocity response spectrum.

(a) Regarding a slightly long-period seismic motion (T=2-10 s), the one which gives an impact of the largest class possible in Japan shall be subjected to evaluation. Limit values are not to be evaluated.

(b) The subject point shall satisfy the siting conditions for light-water reactors (LWRs) in Japan as a general rule, provided that points which have an accumulation layer of several thousand meters and cause a slightly long-period seismic motion to be amplified extremely, shall be excluded.

(c) For short-period domain, the existing spectrum used in LWR-type power reactors shall be respected.

(d) The vertical motion established with respect to the horizontal motion shall be defined by the ratio of amplitude-to-the-horizontal motion.

2. Method for Formulating the Tentative Velocity Response Spectrum

(a) Seismic Scale Subject to Evaluation

From the distribution of seismic damages in Japan, it is observed that earthquakes of M8 class occur off the coast of Sanriku and along the Nankai trough, and many of them occur in the sea areas more than 50 km off the coast of the Pacific Ocean. Also, from the seismotectonics map (Omote's map) for extreme earthquakes (Fig. 2), all M8 class earthquakes occur off the coast of the Pacific Ocean, except for some parts in Central Japan. The velocity response spectrum for tentative study, therefore, is aimed at an M8 earthquake with an epicentral distance of 50 km.

(b) Estimation Using the Accelerogram on Bedrock

With respect to the accelerogram (88 components) of M6 or more, about 50 km in epicentral distance and 60 km or less in hypocenter depth obtained on the bedrock (Vs=700 to 1800 m/s), the spectrum amplitude of each observation record was compensated into the equivalence of M8 using the coefficient γ expressed by Eq. (1).

$$\gamma = 10^{\Delta M} . \qquad (1)$$

Equation (1) considers only the term relating to amplitude and magnitude from the equation for determining the magnitude adopted by the Japan Meteorological Agency (JMA), and an appropriate result can be obtained for the spectrum amplitude in the neighborhood of five seconds in period. Regression analysis was also made at M and $+\sigma$ on 88 pseudo-velocity response spectra (h=5%) obtained from the above-mentioned observation record. Equation (2) was used as the regression equation.

$$\log Sv(T) = a(T)M - [b(T)+m\log R] + c(T) + \Sigma d_i(T) , \qquad (2)$$

Here, if the body wave is assumed, then m=1/2, and R refers to hypocentral distance X; if the surface wave is assumed, then m=1/2 and R refers to hypocentral distance Δ. Also, for differential factor versus observation point, $\Sigma d_i(T)$, the difference in conditions at observation points was taken into consideration. Sv is a velocity response spectrum.

(c) Estimation by the Semiempirical Equation Based on Fault Model

Ishida proposed a method for calculating the seismic motion in bedrock by using a low-pass filter which compensates the short-period spectrum because the theoretical seismic motion spectrum based on a simple fault model (Haskell model) underestimates the amplitude of the short-period seismic motion spectrum. The acceleration Fourier spectrum in seismic bedrock can be expressed by the following equation:[2]

$$\ddot{U}(\omega) \sim \left[(18 \times 10^{0.5M-2}/X)/A(T) \right] \cdot \exp\left[-\omega X/2VsQ\right] , \quad (3)$$

where Vs is shearing wave velocity, Q represents a decay drop in the propagation path, and A(T) is low-pass filter shown by the following equation:

$$A(T) = aT/(1 + aT) \text{ , where} \quad (4)$$

$$a = 0.023\Delta\sigma + 0.22$$

The acceleration Fourier spectrum thus obtained is determined by a seismic moment in the long-period domain and by a stress drop in the short-period domain, as its characteristic.

Kudo assumed as d=10 km the midpoint depth of the underground structural model and fault width obtained by a blasting test at Yumenoshima in Tokyo and determined the semiempirical equation of acceleration spectrum intensity $\ddot{U}(\omega)$ (cm/s) on the ground surface against surface wave as shown below, with M and epicentral distance Δ as parameters.[2]

$$\ddot{U}(\omega) \sim 7.2 \times 10^{0.5M-2} / \sqrt{\Delta} \text{ .} \quad (5)$$

However, considering the fact that this empirical equation relates to Tokyo, which has a thick accumulation layer, and that the evaluation corresponds to the response spectrum of h=0%, there is a strong possibility that this evaluation is considerably large.

3. Tentative Velocity Response Spectrum

The results of these studies are summarized in Fig. 3. Based on these results, the tentative value is set at 100 kine within the range of two to ten seconds in period, with engineering judgment considered. As for short-period domain, the spectrum including a short-period domain and slightly long-period domain is shown in Fig. 4, which adopts existing light-water-type power reactor standards. Since there is a large difference in the spectrum level at a period of two seconds, both spectra will be tentatively used as shown by the dotted line. Meanwhile, for reference, eternal observation records of the Japan Sea Central Earthquake (Mj=7.7), which occurred in 1983, and spectrums of La Union records on the Mexican Earthquake (Ms=8.1), which occurred in 1985, are shown in the figure.

4. Estimation of Vertical Motion Velocity Response Spectrum

The vertical-motion velocity response spectrum (h=5%) is defined by its ratio to the horizontal-motion velocity response spectrum (h=5%). In Fig. 5, the ratio (vertical-motion spectrum/horizontal-motion spectrum) and the value $\pm\sigma$ are shown.

Here, considering the fact that attention is paid to the spectrum amplitude in a slightly long-period spectrum, the ratio of the vertical-motion spectrum to the horizontal-motion spectrum was tentatively set at 0.6.

Evaluation of Isolation Concepts of an FBR

Various isolation concepts for an FBR were evaluated and a candidate concept was selected.[3]

1. Preliminary Selection of Isolation Concepts

Possible seismic isolation concepts are classified by the scope of isolation as shown in Table III. Of these concepts, concepts (1) through (6) correspond to component isolation, (7) and (10) to building isolation, and (8) and (9) to combined isolation. Since horizontal ground motion has a dominant effect on the design of buildings and components, concepts in which buildings or some components are isolated only in vertical direction were excluded.

(a) Building Isolation

At present, there are no effective isolation systems which are capable of supporting a load of about 150,000 tons, and at the same time achieving three-dimensional seismic isolation. Development of such a system will require many tasks such as devising an effective anti-rocking measure.

As for the horizontal seismic isolation of buildings, LWR plants exist (Cruas and Koeberg), which adopt such a system in addition to some experiences with conventional buildings in and out of Japan. It is expected to allow material reduction of building structure and many components. Hence, the horizontal seismic isolation of buildings [(7) of Table I] was selected for the present investigation.

(b) Component Isolation

It was considered inadequate to use three-dimensional isolation devices, since it will be difficult to adjust them in such a way to avoid rocking, because the isolation devices may have material or geometric nonlinearity. It is also difficult to obtain the optimal horizontal and vertical isolation properties since the horizontal and vertical vibrations are coupled together.

In the present investigation, concepts for seismically isolating the primary system alone [(1) and (3) of Table III] were examined. Evaluation of concepts in which seismic isolation covers both primary and secondary systems was made by reflecting the findings of the combined isolation described in the next subsection.

(c) Combined Isolation

The building is given a horizontal isolation for the reason stated above. Hence, components are given a vertical isolation.

As the seismic isolation of the primary system is examined mainly in component isolation, a system for vertical isolation of the primary and secondary systems [(9) of Table III] is examined in combined isolation.

This system prevents any relative displacement of the sodium-system piping [(9) of Table III].

2. Evaluation of Isolation Concepts

Response reduction, relative displacement, material reduction, and necessary technical development items were selected as the items for evaluating applicability of a seismic-isolation system to FBR plants.

To make a comparative evaluation of various systems under the same conditions, the seismically-isolated FBR with respective isolation systems was set according to the following rules, on the basis of a 100-MW(e) semiunderground nonisolated FBR system: (a) each seismically-isolated FBR plant is to be installed on the ground; and (b) the structure of the proposed FBR is to be modified to allow introduction of the isolation system and to enhance its effects. However, no modification of the structure of any systems or components irrelevant to the introduction of the isolation system will be made.

The resulting seismically isolated plants of the respective systems were subjected to response analysis to evaluate their response characteristics. The results are shown in Table IV.

On the basis of these findings, each isolation system was examined in terms of its material reduction effects, it applicability, and technical tasks to be examined in the future. A comparative evaluation is shown in Table V.

The findings may be summarized as follows:

(1) As for horizontal isolation, building, component, and combined isolation are virtually identical in terms of material reduction of isolated portions and improving the reliability of such portions. The wider the scope of the isolation, the greater the material reduction and reliability improving effects.

(2) The material reduction due to vertical isolation is relatively small. Expected relative displacement of the core and control rods, prevention of lifting of the core elements, and reduction of axial compression of vessels is also small.

(3) Relative displacement is expected to be accommodated by elastic deformation of the piping in each isolation system. However, when only the primary system components are isolated, it will be necessary to make a detailed investigation of methods for accommodating relative displacements of the secondary cooling system piping, which contains sodium and the fuel handling systems.

(4) Required R&D items are relatively few for building isolation. Component isolation requires some measures for shielding and air-conditioning of the seismic isolation elements. The addition of vertical isolation will add more R&D items, such as the reliability of vertical isolation elements, and confirmation of performance of vertical isolation mechanisms.

Test on Large-Scale Seismic Isolation Elements

Static biaxial testing facilities for testing isolation elements were built and several large-scale element tests were conducted.[4]

1. Facilities for Testing Elements

A facility for testing seismic isolation elements was built in the Abiko Research Laboratory of CRIEPI. Two actuators can apply both horizontal and vertical loads on the element. The actuators are controlled in the load-control and displacement-control modes.

Maximum available load of each actuator is ±600 tonf. Maximum achievable horizontal displacement is ±600 or 1200 mm, and maximum achievable vertical displacement is ±350 or 700 mm. Maximum velocity of loading of each actuator is 0.5 cm/s. Figure 6 shows the facilities.

2. Seismic Isolation Element

In this program, the concept of base isolation of an FBR building was selected as the most feasible system. In this concept, natural rubber, lead rubber, and high-damping rubber bearings are regarded as the promising seismic isolation elements of the FBR building. The natural rubber bearing was tested first (Fig. 7). One full-scale model and two kinds of reduced-scale models were submitted for the test.

The full-scale model is designed to behave linearly up to a displacement of 500 mm and is designed to provide the 500-ton rated mass with a horizontal natural frequency of 0.5 Hz and a vertical natural frequency of 20 Hz. Parameters of the bearings are summarized in Table V.

3. Horizontal Stiffness Tests

The objectives of these tests are to estimate the horizontal stiffness and to confirm the similarity between a full-scale and reduced-scale model. The tests were performed under low-frequency cyclic loading conditions (under 0.01 Hz).

Four cycles of sinusoidal horizontal displacement were applied under constant vertical load. The amplitude of horizontal displacements are varied from shear strain of rubber ±25% to ±400%. And the amplitude of vertical loads is varied from -20% to +200% of design vertical load and the third-cycle record was adopted as data.

Figure 8 shows the relationship between horizontal load and horizontal displacement of each model and Fig. 9 shows the relationship between normalized horizontal spring constant and shear strain of rubber. From these results, horizontal stiffness of all of bearings turned out to behave almost linearly within shear strains of 200%. But, in the case of shear strains of 300%, restoring force (horizontal load) increases sharply as shear strain increases.

Equivalent horizontal spring constant obtained by the tests of the bearings agree approximately with the design value within shear strain of 200%, but at shear strain of 400% the equivalent horizontal spring constant increases about 30% of the design value owing to the hardening of rubber.

4. Vertical Stiffness Tests

The tests were performed under low-frequency cyclic loading conditions in the same way as horizontal stiffness tests. In the first test, four cycles of sinusoidal vertical load were applied under initial static vertical load and constant shear strain.

Amplitude of sinusoidal vertical load was ±50% of design vertical load. The initial vertical loads were varied from 50 to 150% of the design vertical load, and the constant shear strain of the bearing was valid from 0 to 200%. In the second test, the vertical load was increased gradually from 0 to 200% of the design vertical load.

Figure 10 shows the relationship between a normalized vertical spring constant and shear strain of rubber. The vertical stiffnesses of all bearings around design vertical load without shear strain turned out to be almost linear. It was also provided that the equivalent vertical spring constant agreed approximately with the design value. However, the equivalent vertical spring constants decreased as shear strain increased, and are 50% of the design value at shear strain of 200%.

5. *Breaking Tests*

The objectives of these tests are to evaluate the strength of the bearings and the deformation characteristics around the breaking point and to confirm the similarity rule of two reduced-scale models around the breaking point.

Figure 11 shows the relationship between horizontal displacement and horizontal load of each reduced-scale model up to the breaking point. From these results, breaking points of each model were between a shear strain of ~450 and 500%, and between shear stress of 50 and 75 kgf/cm^2.

Selection of Input Parameter in Fragility Analysis

In the seismic PSA of a nonisolated structure, usually the probability of failure is expressed as a function of peak ground acceleration, Ap, which is considered as the "best" parameter in describing ground motion intensity-response relationship. However, for the isolated structure of which the natural period is 1.0 to 2.0 s, and behaves inelastically under design earthquake motion, Ap may no longer be the best parameter, and peak ground velocity Vp might be the best parameter. To verify this, response analyses of an isolated FBR building (Fig. 12) using 12 observed earthquake records and 3 artificial earthquakes were conducted,[5] where restoring characteristics of the isolator is modeled with a bilinear model (Fig. 13). Natural periods of the isolated building corresponding to the first and the second stiffness K1, K2 of the bilinear spring are 1.0 and 2.0 s, and the yield displacement of the bilinear spring is 1.24 cm.

Observed earthquake records are scaled 10 and 20 times as large as the original records so that the isolator will deform beyond its elastic limit and the ductility factor (defined as the ratio of maximum displacement to the yield displacement) will be considerably large. Maximum acceleration of the artificial earthquake waves is scaled to several levels, and 35 earthquake waves with different peak acceleration are used in all. The ratio of Ap to Vp of the input motion range from 4.1 to 25.6. For the artificial earthquakes which are rich in long period components, the ratio Ap/Vp is smaller than that of observed earthquakes (Fig. 14).

Results of nonlinear response analyses show the maximum displacement of the isolator has a stronger correlation with Vp than with Ap (Figs. 15 and 16). Linear relationship between the maximum acceleration at the support level of the reactor vessel (Fig. 12) and the maximum displacement of the isolator (Fig. 17) indicates that another response quantity, such as interstory shear force, also has a strong correlation with the peak ground velocity Vp.

Conclusions

The CRIEPI test and research program, sponsored by MITI, began in 1987. The purpose of this program is to verify the reliability and effectiveness of seismic isolation for an FBR.

The main results obtained thus far are as follows:

1. The velocity response spectrum of a slightly long-period earthquake was tentatively set at 100 kine in the range of about 2 to 20 s.
2. Isolation concepts of an FBR were evaluated, and horizontal building isolation was considered to be the most feasible concept for an FBR in the near future.
3. A large biaxial loading facility was built. Using the facility, the horizontal and vertical stiffness and breaking strength of large-scale natural rubber bearings were evaluated.
4. Response of the isolated reactor building has strong correlation with peak ground velocity Vp, and it is proper to estimate the fragility of the isolated building in terms of Vp rather than peak ground acceleration Ap.

References

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3. H. Shiojiri et al., "Comparison of Seismic Isolation Concepts for FBR," Trans. 10th SMiRT Conf. (1989).

4. T. Mazda et al., "Test on Large-Scale Seismic Isolation Elements," Trans. 10th SMiRT Conf. (1989).

5. K. Hirata et al., "Reliability Analysis of Seismically Isolated FBR System," Trans. 10th SMiRT Conf. (1989).

Table I
Main Participants (as of March 1989)

	Advisary Committee	CRIEPI Seismic Isolation Group
H. SHIBATA	University of Tokyo	Y. SAWADA
T. FUJITA	University of Tokyo	H. SHIOJIRI
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T. KUBO	Nagoya Institute of Technology	T. MAZDA
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Y. SHIRASAKA	Tokyo Electric Power Company	Y. MASUKO
T. IIDA	Chubu Electric Power Company	Y. MAENO
K. KANAMORI	Kansai Electric Power Company	S. AOYAGI
M. KATO	Japan Atomic Power Company	T. GOTO
T. HIRAI	Electric Power Development Company	

Table II
Seismic Isolation Study Program

	1987~1989		1990~1993	
Seismic Isolation Element Demonstration Test	Fabrication of Test Rig for Large Scale Isolation Element; Isolation Element Test		Isolation Element Test	
Development of Seismic Isolat Structure	Study on Various Systems; Evaluation of Concept and Determination of Development Target; Preliminary Model Test; Preliminary Draft of Design Method	o Draft Proposal of Design Guideline for Seismic Isolation System	Design and Fabrication of Large Scale Seismically Isolated Structure Model; Large Scale Seismically Isolated Model Test at Tadostu; Proposal of Design Method	o Proposal of Design Guideline for Seismic Isolation System
Study on Earthquake Load and Response	Construction of Seismically Isolated Nuclear Island Building Model; Examination of Design-Base Earthquake		Observation of Characteristics Seismically Isolated Nuclear Island Building Model; Proposal of Desing-Base Earthquake	
PSA Methodology Development and Application on the Isolation System	Establishment of Evaluation Method		Evaluation using Reliability Method	

Table III
Candidate Isolation Concepts

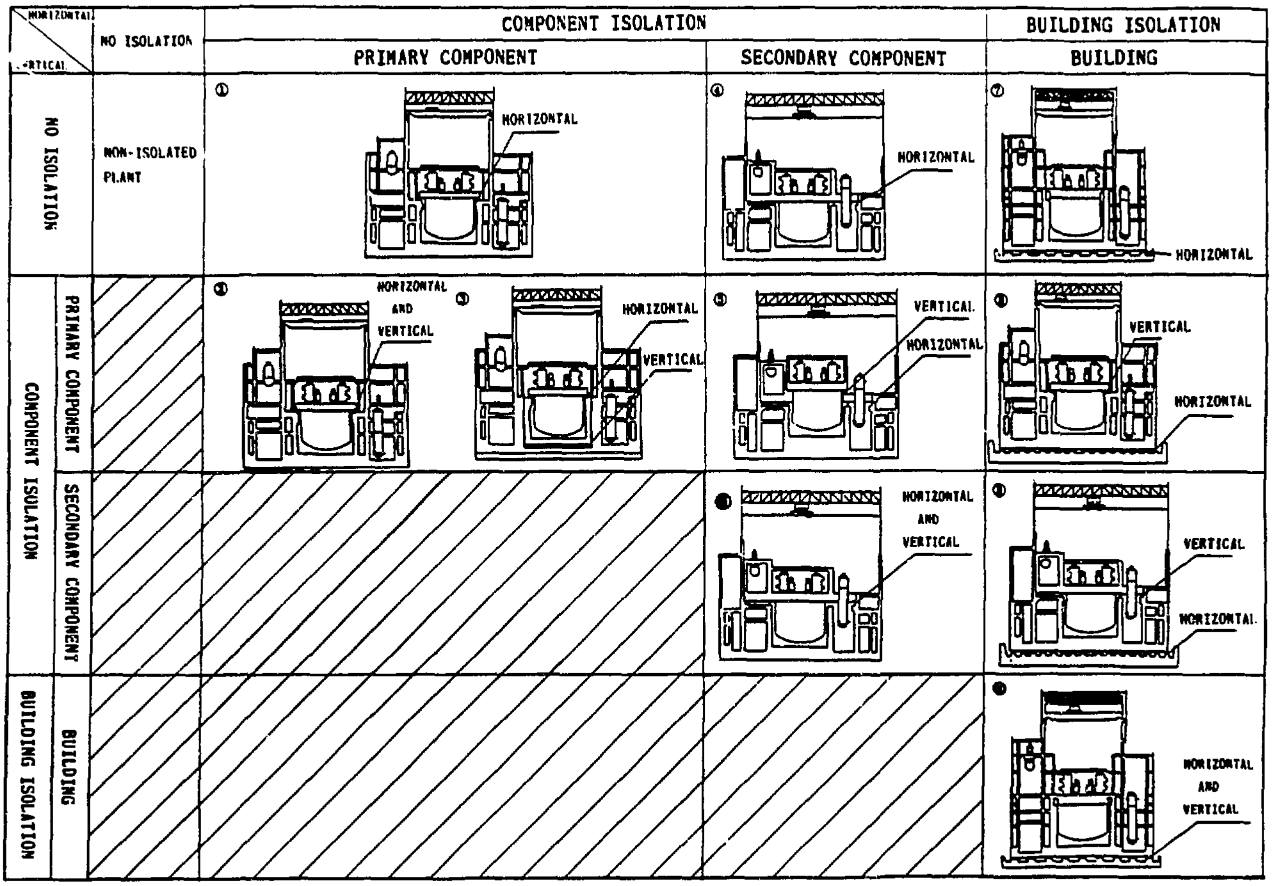


Table IV
Response of Isolated Plants to S1 Earthquake

ITEM		BUILDING ISOLATION	COMPONENT ISOLATION		COMBINED ISOLATION
			HORIZONTAL	HORIZONTAL AND VERTICAL	
DEVICE CHARACTERISTICS	NATURAL FREQUENCY	0.5 Hz	1.0 Hz	HORIZONTAL 1.0 Hz VERTICAL 1.5 Hz	HORIZONTAL 0.5 Hz VERTICAL 1.5 Hz
	DAMPING			VERTICAL 30 %	VERTICAL 30 %
	YIELDING ACCEL.	50 GAL	100 GAL	HORIZONTAL 100 GAL	HORIZONTAL 100 GAL
MAX. RESPONSE ACCEL. AT REACTOR SUPPORT		216 GAL	330 GAL	HORIZONTAL 330 GAL VERTICAL 175 GAL	HORIZONTAL 217 GAL VERTICAL 179 GAL
MAX. RELATIVE DISP.		18 cm	6.1 cm	HORIZONTAL 6.1 cm VERTICAL 1.7 cm	HORIZONTAL 18 cm VERTICAL 1.7 cm

Table V
Material Reduction

SYSTEM	BUILDING ISOLATION	COMBINED ISOLATION		COMPONENT ISOLATION				REMARKS
SCOPE OF ISOLATION: HORIZONTAL / VERTICAL	BUILDING / —	BUILDING / PRIMARY SYSTEM	BUILDING / PRIMARY + SECONDARY SYSTEM	PRIMARY SYSTEM / —	PRIMARY SYSTEM / PRIMARY SYSTEM	PRIMARY + SECONDARY SYSTEMS / —	PRIMARY + SECONDARY SYSTEMS / PRIMARY SYSTEM	
REACTOR VESSEL (SIDE WALL)	30 mm	23 mm	23 mm	30 mm	23 mm	30 mm	23 mm	TO ABOUT 1/2 ~1/4 OF NON-ISOLATED PLANT. VERTICAL ISOLATION EFFECT IS SMALL.
REACTOR VESSEL (BOTTOM)	50 mm	20 mm	20 mm	50 mm	20 mm	50 mm	20 mm	TO 60 % BY HORIZONTAL ISOLATION. TO ABOUT 1/4 WHEN VERTICAL ISOLATION IS COMBINED.
ROOF SLAB	125 mm	25 mm	25 mm	100 mm	25 mm	100 mm	25 mm	EFFECTS OF VERTICAL ISOLATION ARE GREAT.
VESSEL SUPPORT SKIRT	40 mm	40 mm	40 mm	40 mm	40 mm	40 mm	40 mm	TO ABOUT 1/3 OF NON-ISOLATED PLANT. VERTICAL ISOLATION EFFECT IS SMALL.
QUANTITY OF BUILDING MATERIALS	UPPER BUILDING / LOWER FOUNDATION	UPPER BUILDING / LOWER FOUNDATION	UPPER BUILDING / LOWER FOUNDATION	UPPER BUILDING	LOWER FOUNDATION	UPPER BUILDING	LOWER FOUNDATION	BUILDING ISOLATION REDUCES CONCRETE REQUIREMENT TO ABOUT 60 % ,AND REBAR TO ABOUT 50 %, BUT IT INCREASES STEEL FRAME QUANTITY.
o CONCRETE (m^3)	48,000 / 8,500	49,800 / 9,600	49,800 / 9,600	71,400		71,400		
o REBAR (t)	7,200 / 1,300	7,500 / 1,450	7,500 / 1,450	14,200		14,200		
o STEEL FRAME (t)	2,400	2,300	2,300	2,300		2,300		
o OTHERS			NSSS FLOOR (STEEL FRAME) 1,000t			NSSS FLOOR (STEEL FRAME) 1,000t		
ISOLATION DEVICE — HORIZONTAL	500 t 264 UNITS	500 t 280 UNITS	500 t 280 UNITS	200 t 38 UNITS	200 t 38 UNITS	200 t 73 UNITS	200 t 73 UNITS	RUBBER BEARING WITH LEAD PLUG
ISOLATION DEVICE — VERTICAL		20 t 800 UNITS	50 t 68 UNITS 100 t 10 UNITS 150 t 67 UNITS		20 t 800 UNITS		20 t 400 UNITS	COIL SPRING.

Table VI
Design Parameters of Bearings

Parameter \ Type	full-scale model	1/1.58 reduced scale model	1/3.16 reduced scale model
Diameter (mm)	1600	1000	500
Height (mm)	560	340	160
Thickness of Rubber Sheet(mm)	9.0	5.7	2.8
No of Rubber Sheet	25	25	25
Thickness of Steel Plate(mm)	5.8	3.1	1.6
No of Steel Plate	24	24	24
Rated Vertical Load (tonf)	500	200	50
Horizontal Spring Constant(tonf/cm)	5.036	3.19*	1.59*
Horizontal natural frequency(Hz)	0.5	——	——
Vertical Spring Constant(tonf/cm)	8057	5099*	2550*
Vertical natural frequency(Hz)	20	——	——

* : Value is fixed from similality

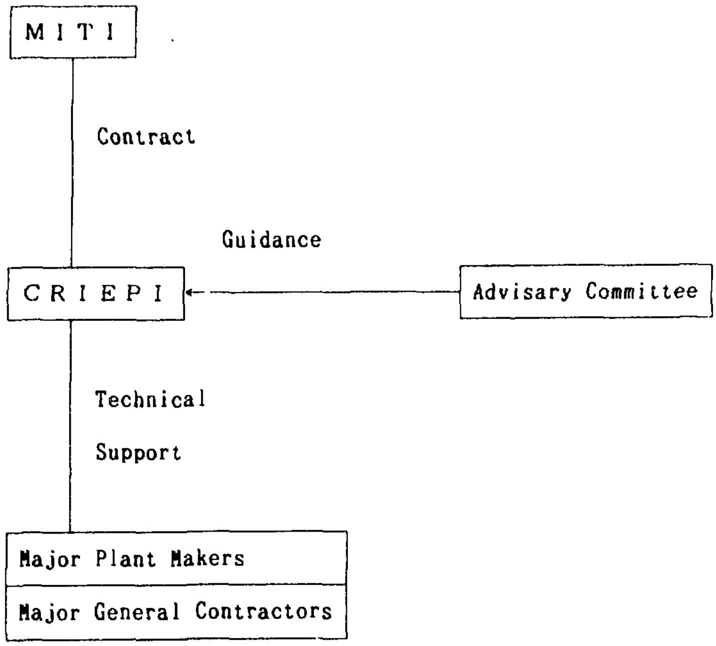


Fig. 1. Organization for Project

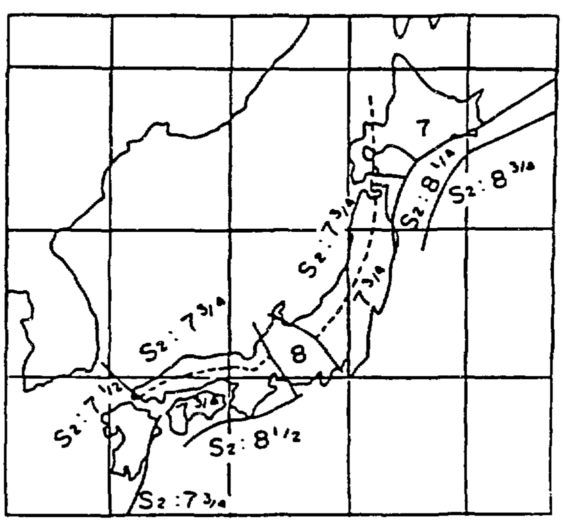


Fig. 2. Map on Seismotechtonics (Omote's Map)
Numerals of the figure indicate extreme magnitude which is expected to occur.

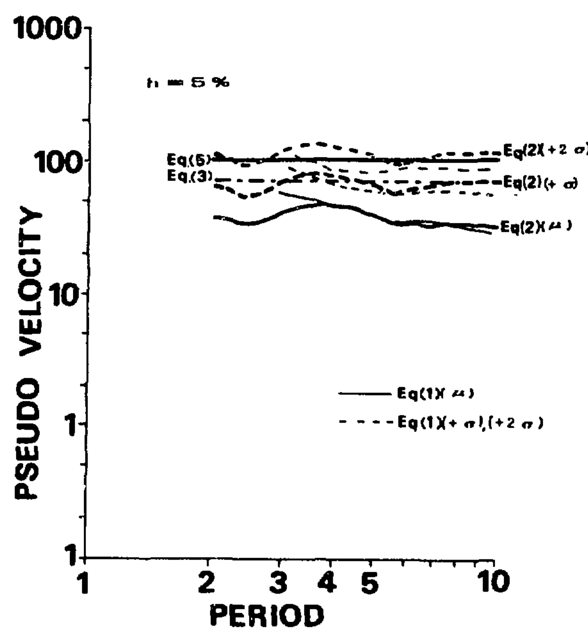


Fig. 3. Comparison of the Results Obtained by Various Methods [Eqs. (1)-(5)]

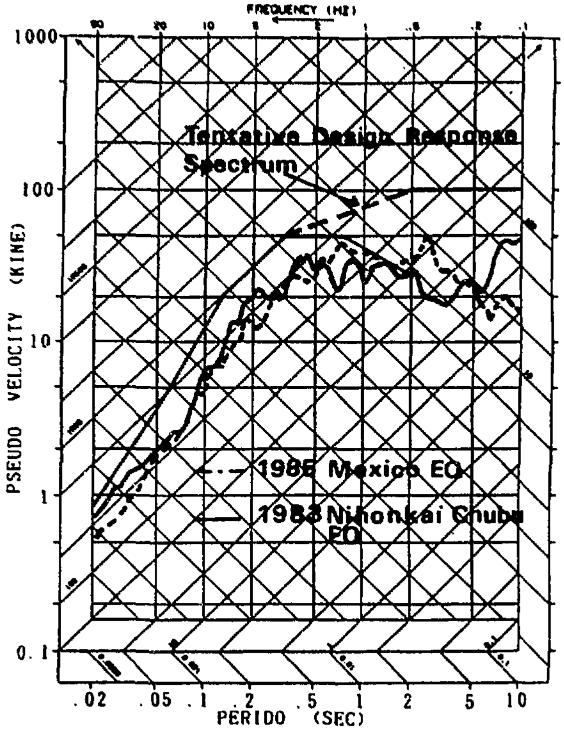


Fig. 4. Tentative Design Base Velocity Response Spectrum (h=5%) and the Comparison with Observed Response Spectra of 1983 Nihonkai-Chubu and 1985 Mexico Earthquakes

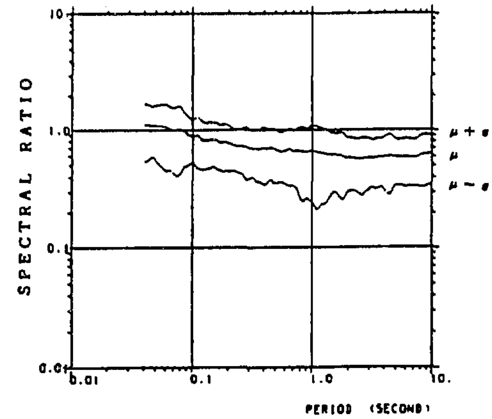


Fig. 5. Spectral Ratio (Vertical/ Horizontal)

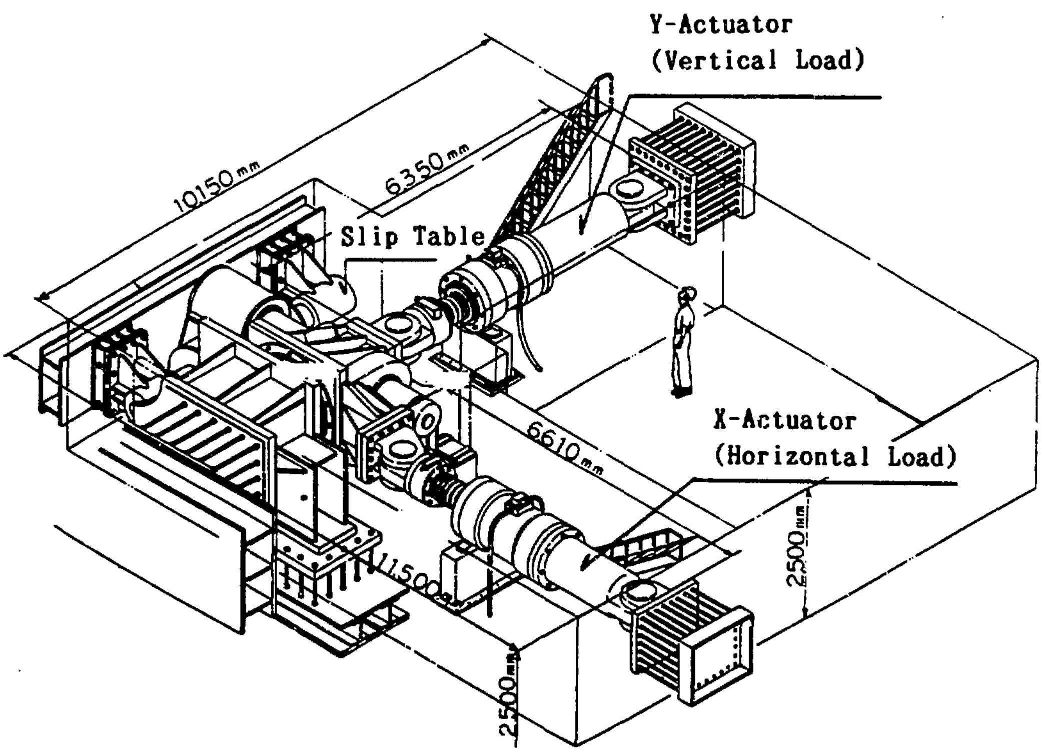


Fig. 6. Facilities for Testing Isolation Element

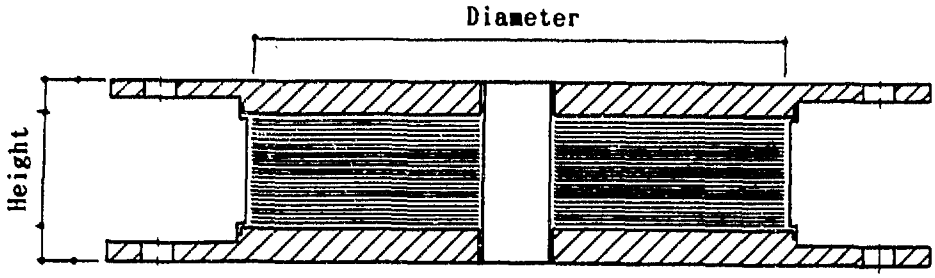
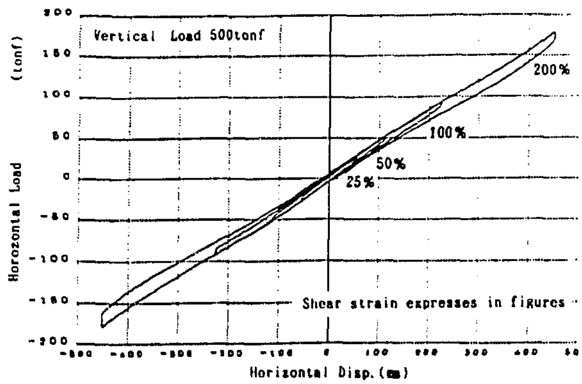
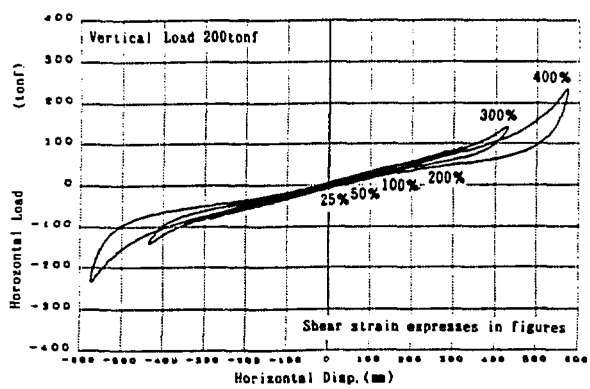


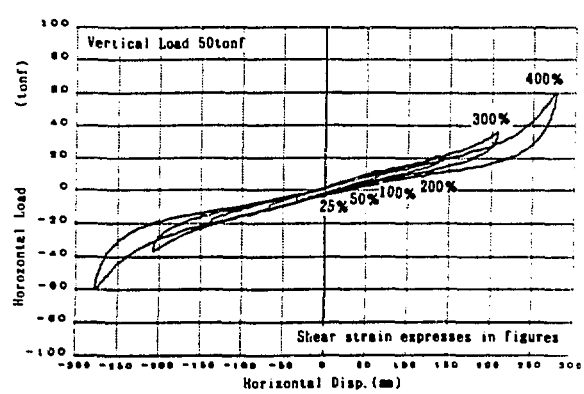
Fig. 7. Natural Rubber Bearing



(i) Full-Scale Model(500tonf)



(ii) Reduced Scale Model(200tonf)



(iii) Reduced Scale Model(50tonf)

Fig. 8. Relationship Between Horizontal Load and Horizontal Displacement

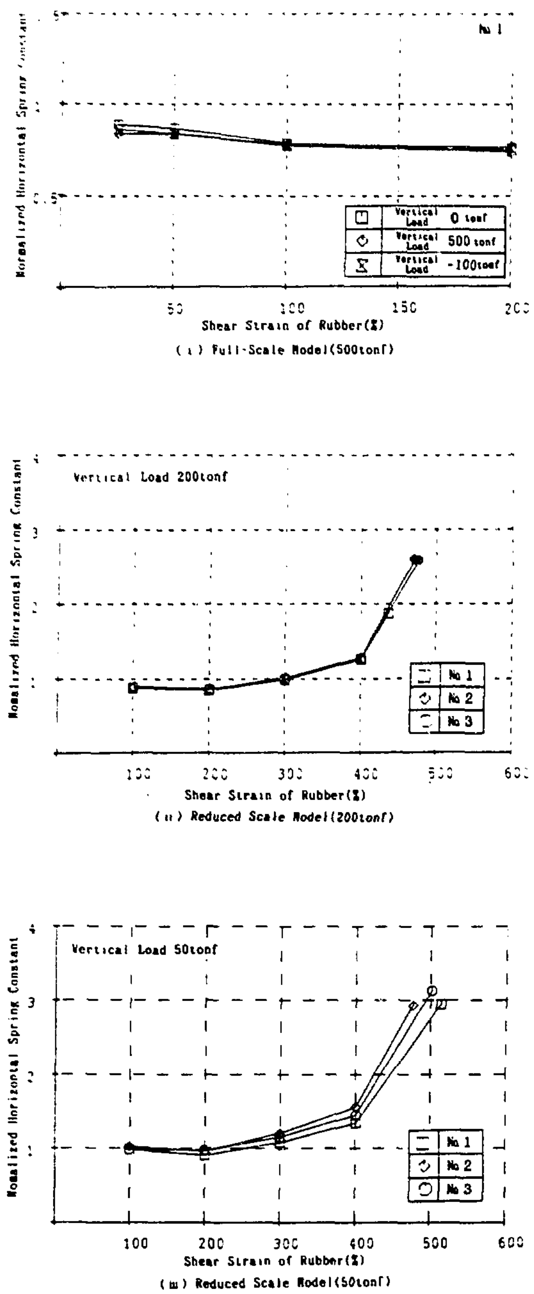


Fig. 9. Relationship Between Normalized Spring Constant and Shear Strain of Rubber

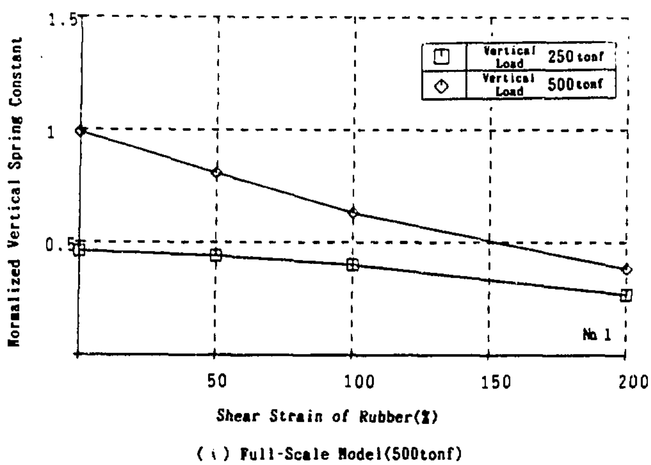


Fig. 10. Relationship Between Normalized Vertical Spring Constant and Shear Strain of Rubber

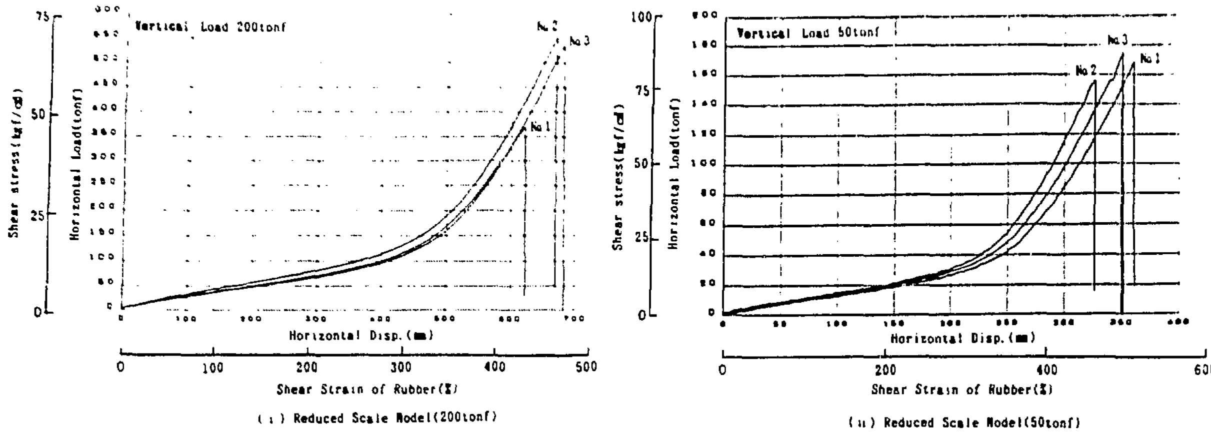


Fig. 11. Relation Between Horizontal Load and Horizontal Displacement

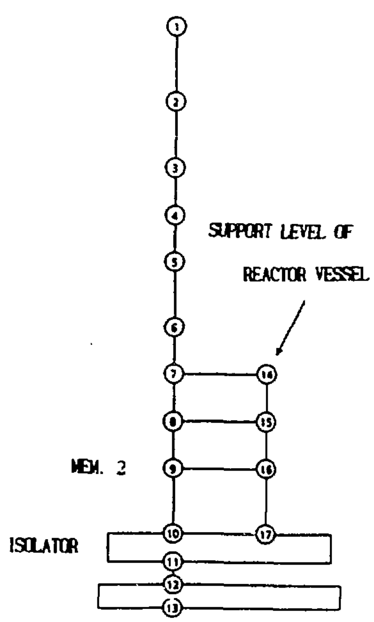


Fig. 12. Lumped Mass Model for FBR Building

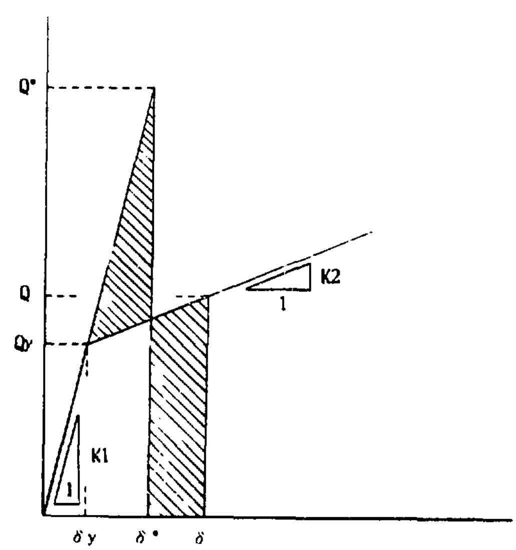


Fig. 13. Bilinear Model for Isolator and Concept of Equivalent Linear Response

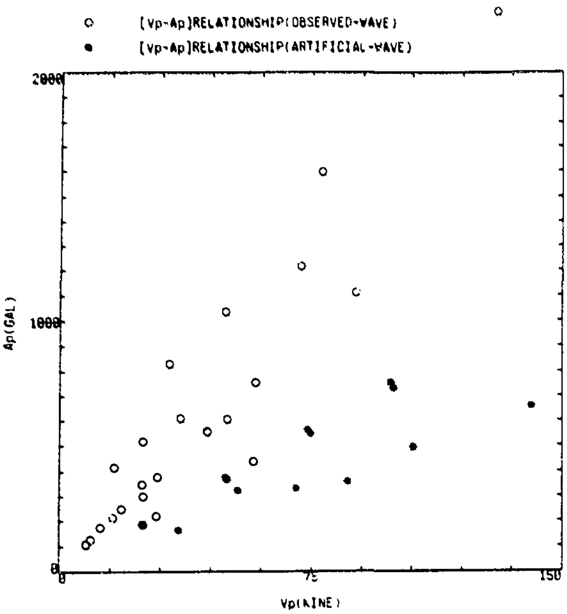


Fig. 14. Vp versus Ap of Earthquake Waves

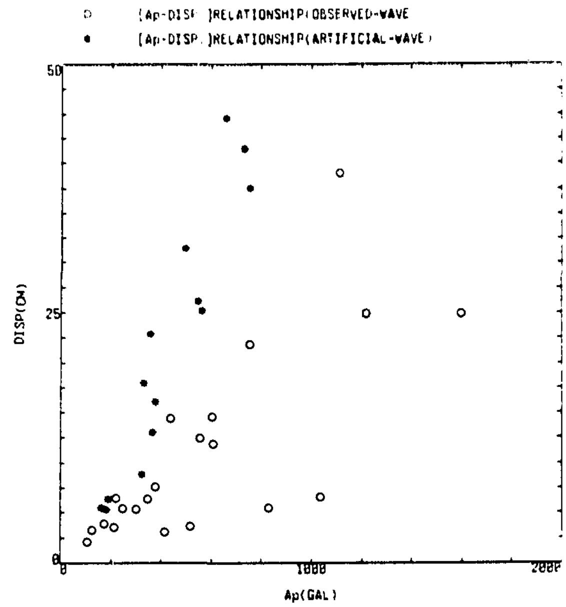


Fig. 15. Ap versus Maximum Displacement of Isolator

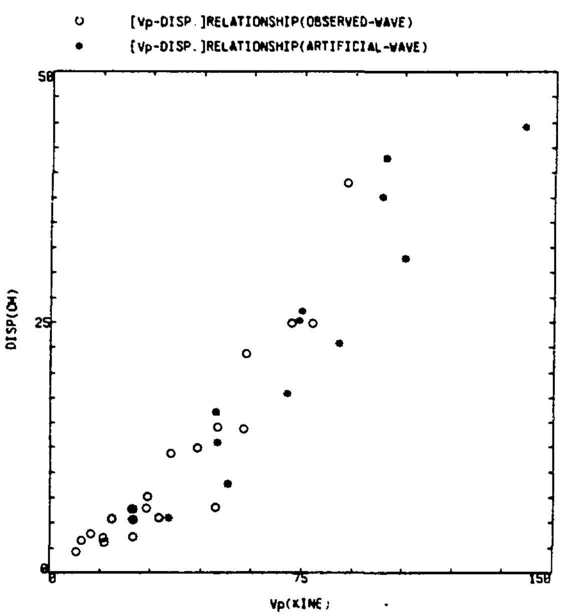


Fig. 16. Vp versus Maximum Displacement of Isolator

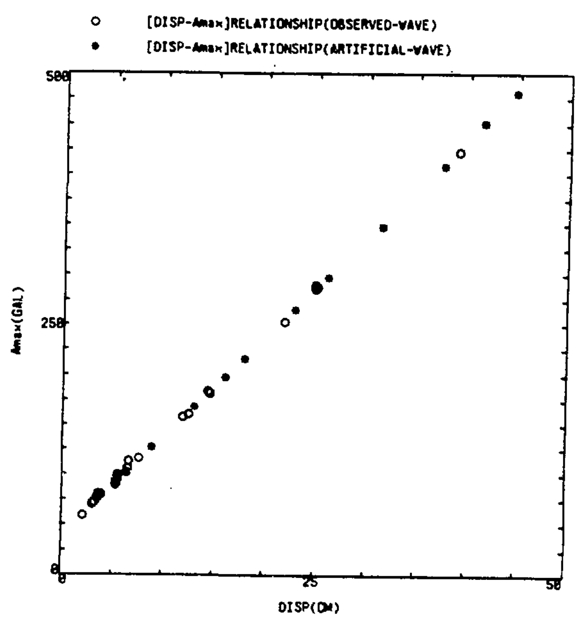


Fig. 17. Maximum Displacement of Isolator versus Amax at Support Level of Reactor