XA0055390

STUDY OF SEISMIC RESPONSES OF CANDU3 REACTOR BUILDING USING ISOLATOR BEARINGS

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FOR PRESENTATION AT THE IAEA SPECIALISTS' MEETING ON ISOLATION TECHNOLOGY AT SAN JOSE, CALIFORNIA, MARCH 1992

ABSTRACT

Seismic isolator bearings are known to increase reliability, reduce cost and increase the potential sitings for nuclear power plants located in regions of high seismicity. High seismic activities in Canada occur mainly in the western coast, the Grand Banks and regions of Quebec along the St. Lawrence river. In Canada, nuclear power plants are located in Ontario, Quebec and New Brunswick where the seismicity levels are low to moderate. Consequently, seismic isolator bearings have not been used in the existing nuclear power plants in Canada. The present paper examines the effect of using seismic isolator bearings in the design for the new CANDU3 which would be suitable for regions having high seismicity.

The CANDU3 Nuclear Power Plant is rated at 450 MW of net output power and is a smaller version of its predecessor CANDU6 successfully operating in Canada and abroad. The design of CANDU3 is being developed by AECL CANDU. Advanced technologies for design, construction and plant operation have been utilized. During the conceptual development of the CANDU3 design, various design options including the use of isolator bearings were considered. The present paper presents an overview of seismic isolation technology and summarizes the analytical work for predicting the seismic behavior of the CANDU3 reactor building.

A lumped–parameter dynamic model for the reactor building is used for the analysis. The characteristics of the bearings are utilized in the analysis work. The time–history modal analysis has been used to compute the seismic responses. Seismic responses of the reactor building with and without isolator bearings are compared. The isolator bearings are found to reduce the accelerations of the reactor building. As a result, a lower level of seismic qualification for components and systems would be required. The use of these bearings however increases rigid body seismic displacements of the structure requiring special considerations in the layout and interfaces for interconnected systems. The relative advantages and disadvantages of the potential use of isolator bearings in CANDU3 are discussed.

INTRODUCTION

Seismic isolation is a remarkable advancement in earthquake engineering which is gaining international acceptance. It can be used to reduce the seismic loads on nuclear power plants and other structures specifically in locations of high seismicity. Today's nuclear power plants and other critical structures are designed to accommodate the effects of high levels of seismicity to meet safety and licensing requirements. Reduction of seismically induced loads results in an economic structural design. When using isolation bearings, the secondary components and systems located in the plant would require a lesser degree of seismic qualification. It results in cost savings in two ways. Firstly, it avoids strengthening and implementations of costly design features which are otherwise necessary. Secondly, due to the decrease in the seismic response levels, a relatively simple analysis procedure can be employed to predict the behaviour of secondary components. For example, supported systems will behave in a linear elastic way and the need for non–linear analysis considering impact, sliding, gaps, etc. can be reduced if not avoided. Isolation devices that are developed today can increase the safety margin of structures. It is claimed that the behaviour of an isolated structure can be predicated with a higher degree of accuracy. The properties of bearing materials are tested and controlled during the manufacturing process whereas the soil properties are subjected to a higher level of uncertainty. Isolation bearings increase the potential of using a standard design in different sites without undertaking costly redesign work.

To date many buildings around the world are designed and built using isolation devices. At present there are more than 18 buildings on isolation bearings constructed in Japan [1] and many more have received construction permits. The Foothill Community Centre in San Bernardino County, California is the first building in the United States built with isolation bearings in 1986. In many buildings and bridges built in the U.S.A. the use of isolation bearings have reduced the seismic loads. Bearings are often used for retrofiting existing installations to higher seismic requirements or rehabilitating structures damaged by earthquakes. In New Zealand a number of industrial buildings and 37 bridges are built using isolation bearings. In a number of other countries, isolation devices have been used for buildings, bridges and heavy equipment. In Japan, U.S.A, United Kingdom, Italy and many other countries, research work including testing of bearings and monitoring of seismic responses of demonstration structures are being undertaken with the object of understanding the behaviour of various isolation systems.

The adaptation of seismic isolation bearings for nuclear facilities has been slow. The Cruas in France is the first nuclear power plant built with isolation devices in 1982 [2]. At present there are a total of six base isolated standard PWR units. Four units are located in Cruas, France and two units in South Africa [3]. There is one fuel processing plant in England that uses isolation devices. Many studies and conceptual designs have included the use of base isolation using bearings. A nuclear waste storage facility has been built in France using seismic isolation bearings [4]. Isolation bearings have been used in the conceptual design of the 1500 MW Liquid Metal Fast Breeder Reactor (LMFB). Countries interested in the development and use of this technology are sponsoring joint research activities. The U.K., EPRI and the Japanese Central Research Institute of Electric Power Industry (CRIEPI) have undertaken a joint international program for advancement of this technology. As part of this program, the technical feasibility of selected isolation systems have been evaluated for application in large Liquid Metal Reactors (LMR) and the European Fast Reactor (EFR) plants. Analytical work and testing of representative sample bearings for two U.S. compact LMR concepts have been reported [5].

Nuclear power plants built in Canada are strengthened to carry loads due to the design basis earthquake. Since the first use of isolation bearings, AECL CANDU has maintained an active interest in this technology. During the conceptual design of the CANDU3 nuclear power plant, the use of isolation bearings are considered. The present paper deals with an analytical study to predict the effects of using isolation bearings for the CANDU3 reactor building.

CANDU NUCLEAR PLANT

Thirty three CANDU nuclear power plants have been built or are under construction in Canada and abroad. These plants use the CANDU (CANadian Deutrium Uranium) power reactor technology. The power rating of these plants ranges from 203 MW to 881 MW. There are twenty nuclear power plant units located in Ontario. The latest of which is a four unit station at Darlington having the highest capacity of 881 MW per unit. The CANDU6 plant is rated for 670 MW of electric power. One CANDU6 plant has been built at Gentilly, Quebec and another at Point Lepreau, New Brunswick both of which are operating. CANDU6 plants have been built and are operating in Argentina and South Korea. At Cernavoda in Romania a five unit CANDU6 nuclear generating station is under construction. Design and construction of the second power plant unit in South Korea is continuing.

CANDU power plants in Canada and abroad built to date are of fixed base design. These plants are strengthened to sustain the effects of the design basis earthquakes (DBE). The requirements of seismic design is followed in Canada according to the guide-lines given in the Canadian National Standards [6] . High seismic activities in Canada mainly occur in the western coast, the Grand Banks and in regions of Quebec along the Saint Lawrence river. In the Charlevoix region of Quebec, high level seismic activity occurs very frequently. In other parts of the country, the seismicity level is low to moderate. Nuclear power plants in Canada are located in regions where the seismicity level is low to moderate. The highest level of seismic acceleration for CANDU plants built to date is 0.2 g ground acceleration. Studies have been undertaken for siting CANDU plants in other countries having high seismicity levels of 0.5 g ground acceleration.

CANADIAN EXPERIENCE

Experience of using isolating devices in Canada is somewhat limited. A low level of seismic activity in most parts of the country did not necessitate the use of these devices. Moreover, there has been an initial reluctance in adopting a new technology until it has performed satisfactorily. The first use of isolation devices in Canada has been for a coal ship loader at Prince Rupert in British Columbia. The benefit of friction dampers for framed structures was analytically investigated [7] . Such a system of friction dampers has been used in the new design of the library building for the Concordia University in Montreal [8]. By installing friction dampers in steel cross bracings, a large amount of seismic energy could be dessipated mechanically. The use of these devices in the braced frame structure resulted in cost savings by eliminating the shear walls that would be required otherwise. A tuned vibration control device has been installed in the CN tower located in Toronto to reduce the effects of wind induced vibrations. Specially designed devices are used in a number of high–rise buildings in Toronto to reduce subway vibrations and noises. In CANDU plants, heavy equipment such as diesel generators are mounted on vibration isolating devices. These devices consist of coil springs of specific characteristics to eliminate amplification of machine vibrations. Due to the low stiffness, these springs are also useful to provide some reduction of seismic loads.

Currently AECL CANDU is developing the design of CANDU3 nuclear power plant rated at 450 MW of net electric output. This is a smaller version of its predecessor CANDU6 which is successfully operating in Canada and abroad. In CANDU3 advanced technologies for design, construction and operations have been utilized. The design uses the concept of modular construction to reduce schedule and cost. During the conceptual development of the CANDU3 design various options including the the use of isolation bearings were considered. A study of the effect of seismic isolation bearings on the responses of the CANDU3 reactor building is presented in this paper.

SEISMIC ISOLATION SYSTEM

The cross section of the CANDU3 reactor building is shown in Figure 1. The CANDU3 reactor building weighs approximately 450,000 KN and has a height to diameter ratio of about 1. For such a short stubby structure, the use of a seismic isolation device is known to be useful. For the CANDU3 plant a design basis earthquake with a ground acceleration of 0.3 g is considered. The ground response spectra for the design earthquake are shown in Figure 2. It is evident from the spectra that to obtain the benefits of base isolation the horizontal frequency has to be lowered below 1.5 Hz. The target design frequency of the isolated structure in the horizontal direction is chosen to be 0.6 Hz. To provide seismic isolation, a number of isomeric bearings having high shape factors are chosen. The seismic excitations in the vertical direction is generally low and therefore is not of concern. The configuration of the proposed bearing is shown in Figure 3. The bearing is circular in shape, 0.5 m in height and has a diameter of 1.27 m. The end plates are bolted to the concrete slab for shear transfer. The chosen bearing has 24 shim plates impregnated in the elastomer. The material of the bearing will have to be selected to meet the requirements of the analysis. The bearings will be located between a lower slab and an upper slab on top of concrete pedestals as shown in Figure 4. This arrangement provides space needed for inspection and replacement of these bearings during the 100 year life of the plant. The horizontal stiffness (k_h) and the vertical stiffness (k_v) of one bearing are estimated using the following commonly used formulae:

$$k_h = G A_t / n t \qquad (1)$$

$$k_v = E_c A_s / n t \qquad (2)$$

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iaea/isolation/
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Where G is the shear modulus of elastomer

E_c is the effective compression modulus

A_t is the total area

A_s is the shim area

n is the number of layers

t is the thickness

The effective modulus E_c used in the computation of the vertical stiffness depends on the shape factor. The shape factor depends on the geometry and is defined by the the ratio of the loaded area to the area free to bulge. The shape factor of the chosen bearing is obtained as 23 using the following expression for a circular bearing:

$$S = d / 4t \qquad (3)$$

Where d is the diameter at the shim

Using equations 1 and 2 the horizontal and the vertical stiffness of one bearing are computed to be 2800 KN/m and 3000000 KN/m respectively. Some degree of uncertainty exist in the stiffness estimation of these elastomeric bearings using these formulae. To obtain better estimates of stiffness properties, finite element analyses of these bearings are necessary. Additionally testing of samples to define the properties of elastomer may have to be undertaken. Such works will be needed before adopting the system.

The present approximate estimates of bearing stiffness are considered appropriate for a conceptual study. From testing of similar bearings it is known that the properties of these bearings are nonlinear [8]. It has been found that initially the horizontal stiffness decreases with shear strain. At very high levels of shear stain the stiffness increases. The vertical stiffness of such bearings increase slightly with loads. For the purpose of this study the characteristics of these bearings are assumed to be linear.

SEISMIC ANALYSIS

As shown in Figure 1 the CANDU3 reactor building consists of an internal concrete structure and equipment modules enclosed by a cylindrical concrete containment structure with a dome at the top. The internal structure houses the reactor and various components and systems necessary for the operation of the plant. For seismic analysis, the reactor building has been represented by a mathematical model consisting of lumped masses and beams as shown in Figure 5. In this model the beams represent the stiffness of different structural parts of the building and the masses are lumped at a number of key locations. The isolation bearings are represented by one set of springs having equivalent stiffness values. The effect of all bearings are combined into one set of springs in the following way:

$$K_h = N\ k_h \quad (4)$$

$$K_v = N\ k_v \quad (5)$$

$$K_r = K_v\ D^2 / 16 \quad (6)$$

$$K_t = K_h\ D^2 / 8 \quad (7)$$

Where K_h is the horizontal stiffness
K_v is the vertical stiffness
K_r is the rocking stiffness
K_t is the torsional stiffness
N is the number of bearings
D is the diameter of the base slab

A total of 200 bearings are assumed for the study. The spring properties of the isolation system are computed using equations 4 to 7. In the present analysis, the effect of soil–structure interaction is ignored. The isolation system produces a low frequency dynamic response much lower than the soil–structure interaction frequency. Consequently, the response of the structure is predominantly influenced by the stiffness of the isolation system. The effect of soil structure interaction for the hard soil condition is small and and can be neglected.

The analysis is done using the modal time–history method. A response compatible time–history generated using methods suggested in Ref. 10 has been utilised. The computer program STARDYNE has been used for the analysis.

The study is done for two cases with different values of damping. The first case uses a damping value of 8 % which is applicable for rubber bearings. The second case uses a damping value of 15 % to represent the damping value of a high damping elastomer. The additional damping value can also be obtained by using specially designed damping devices. High damping elastomeric bearings and a variety of damping devices have been used in actual buildings constructed in Japan [1].

DISCUSSION OF RESULTS

From the analysis the horizontal frequency of the isolated structure is obtained to be 0.61 Hz. The horizontal response acceleration along the height of the building is plotted in Figure 6 and compared with that for the fixed base structure. Substantial reduction of seismic responses are noted for the isolated building for both cases. For the low damping case (Case 1) the acceleration at all points has a constant value of 0.31 g. For the high damping case (Case 2) the building acceleration at all locations is 0.22 g and is lower than the ground acceleration.

The horizontal displacement of the building along the height of the structure is plotted in Figure 7 and compared with that of the fixed base structure. The displacement of the isolated structure is 175 mm to 200 mm which is much higher than the displacement of the fixed base structure (15 mm). Such increased displacement is characteristic of an isolated structure.

The design of the secondary components governed by the floor response spectra. The floor response spectrum in the horizontal direction for the internal structure at elevation 122.5 m in the reactor building is shown in Figure 8 along with the floor response spectrum for the fixed base structure. The horizontal floor response spectrum at the top of containment is given in Figure 9. For the base isolated building the floor response spectra are substantially lower than those for the fixed base structure for both cases. It is also noted the seismic responses do not vary with the height of the structure.

At the DBE level, these bearings are subjected to shear strains of 60 %. Such bearings are known to sustain shear strains in excess of 300 %.

CONCLUSIONS

Based on the study of seismic responses of the CANDU3 reactor building, the following conclusions can be drawn:

- The use of isolation devices for a CANDU power plant structure can be considered as an alternative to strengthening and designing for the seismic loads. Large reductions of seismic loads is possible by using such a system.
- Isolation devices reduce the accelerations and floor response spectra drastically. The seismic requirements of systems and components, in the frequency range between 3Hz to 33 Hz are substantially lower.
- The use of isolation devices increases the displacement of the structure by a large amount. Displacements of the order of 200 mm will require special considerations for interconnected systems such as the steam mains and other pipes connected to the BOP.
- To obtain full advantage of the base isolation, most buildings of the plant should be located on a common mat. This will result in less number of cases to design systems to accommodate large relative displacements of the buildings.
- Considerable advancement of isolation technology has been achieved in recent years. Further R and D work on properties of the elastomeric bearing is needed. Bearing characteristics need to be expressed in simple design formulae which can be utilised for the analysis and design work.

The isolated system has not been adopted for CANDU3. The added complexity in the design to accommodate large displacements, the penalty to the construction schedule and the added cost of these isolation devices are some of the deterrents in adopting the base isolated system. Further studies to evaluate the economic benefit of using such systems would need to be explored. More experience from the behaviour actual isolated structure subjected to real earthquakes is also needed. Application of this technology, perhaps on an installation on a large common mat would not be ruled out for future consideration.

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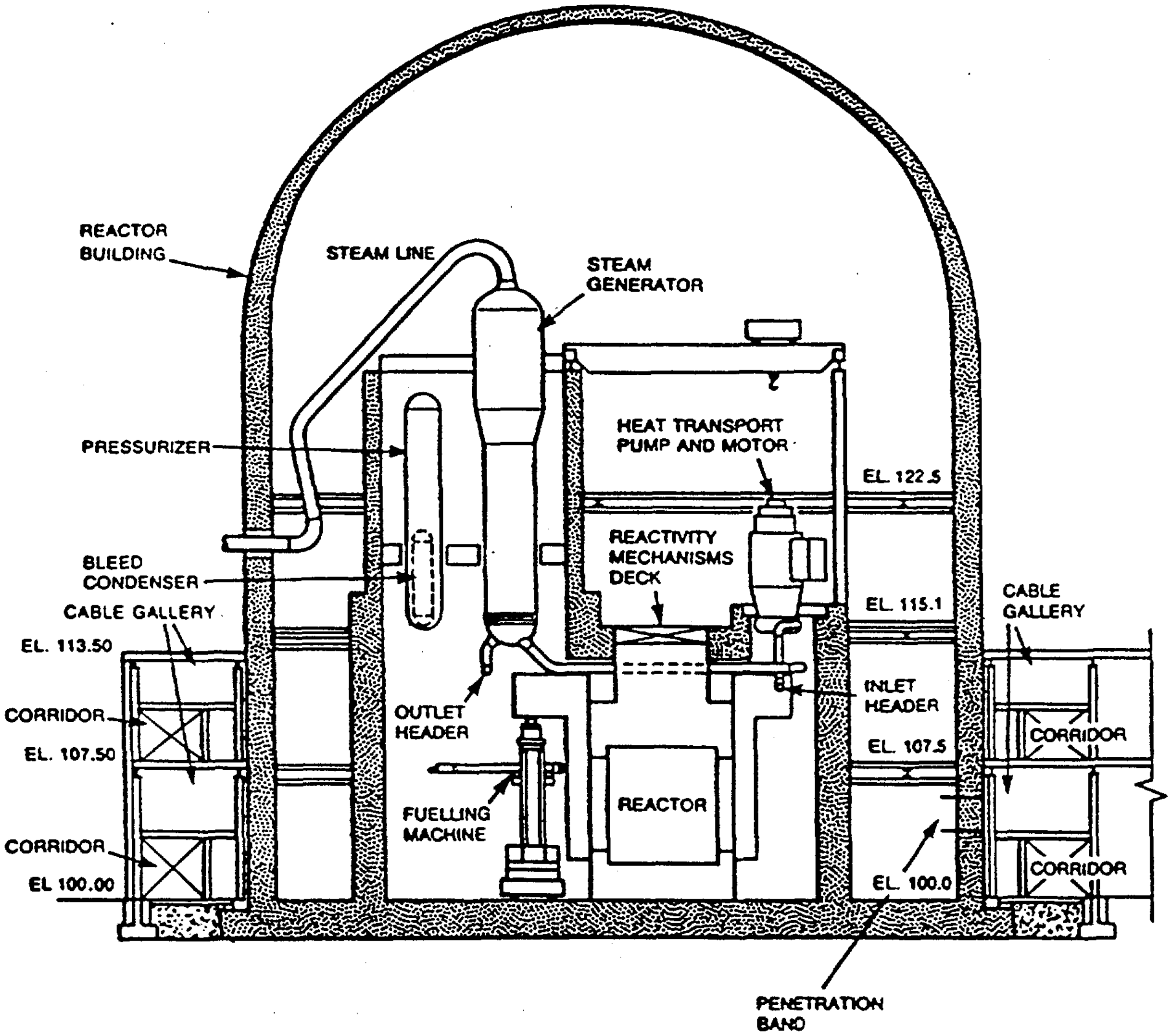


FIGURE 1 CANDU3 REACTOR BUILDING–SECTION

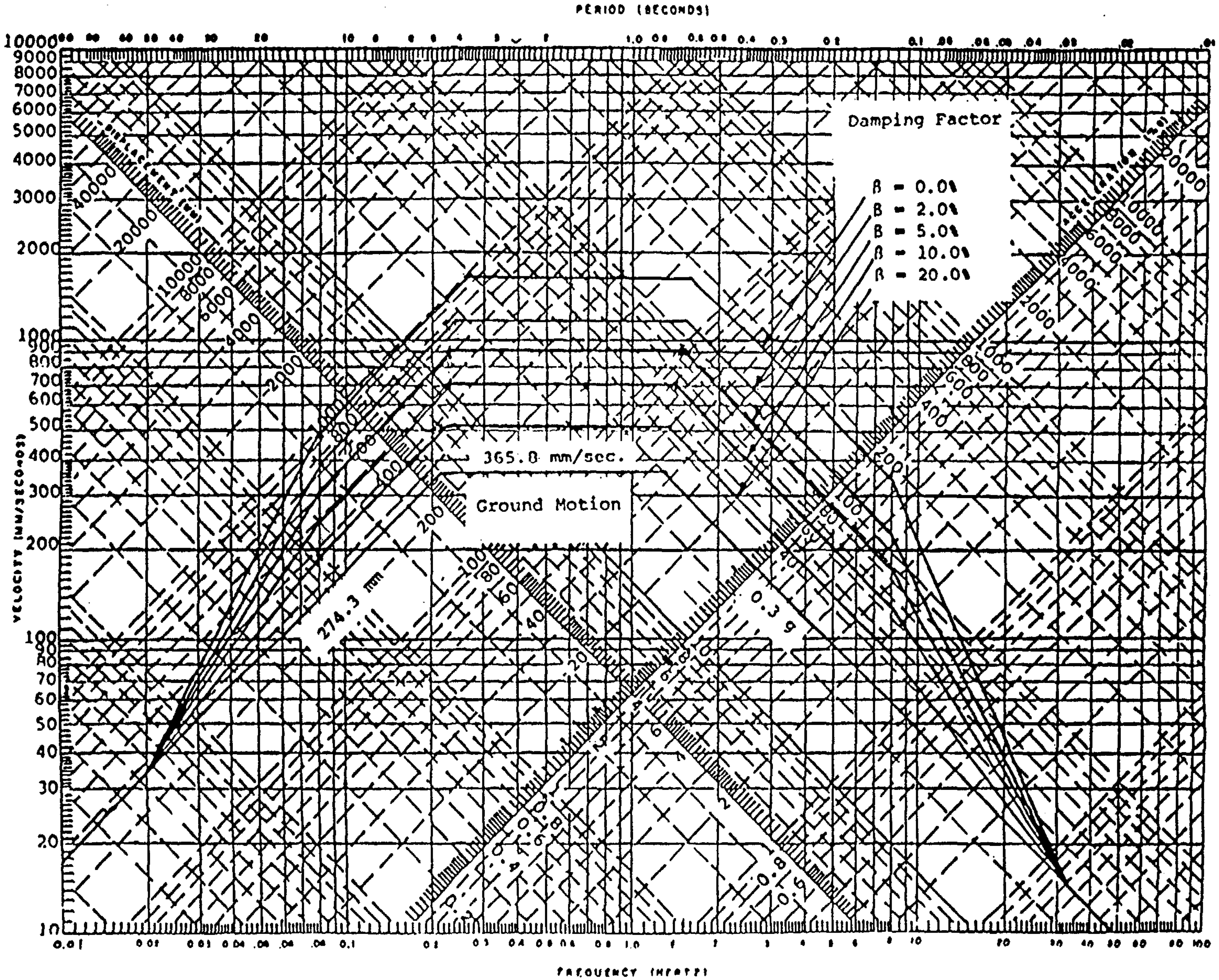


FIGURE 2 GROUND RESPONSE SPECTRA

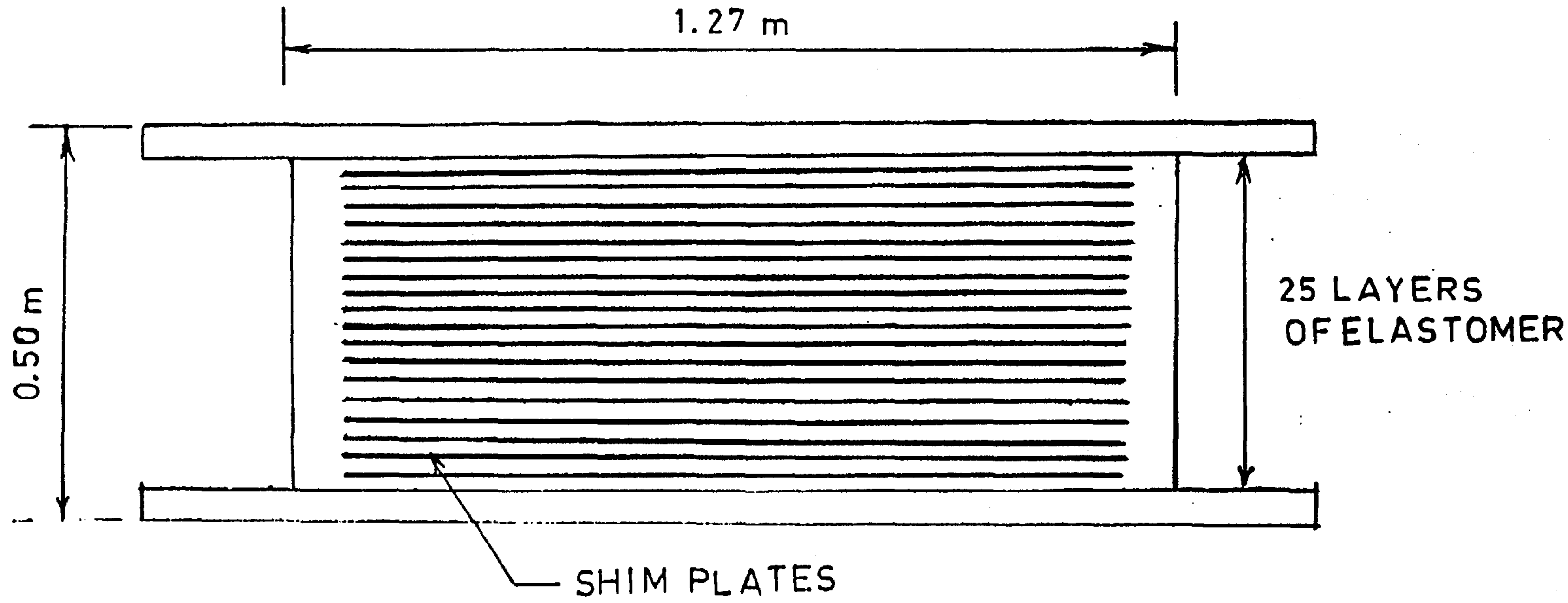


FIGURE 3 PROPOSED ISOLATION BEARING

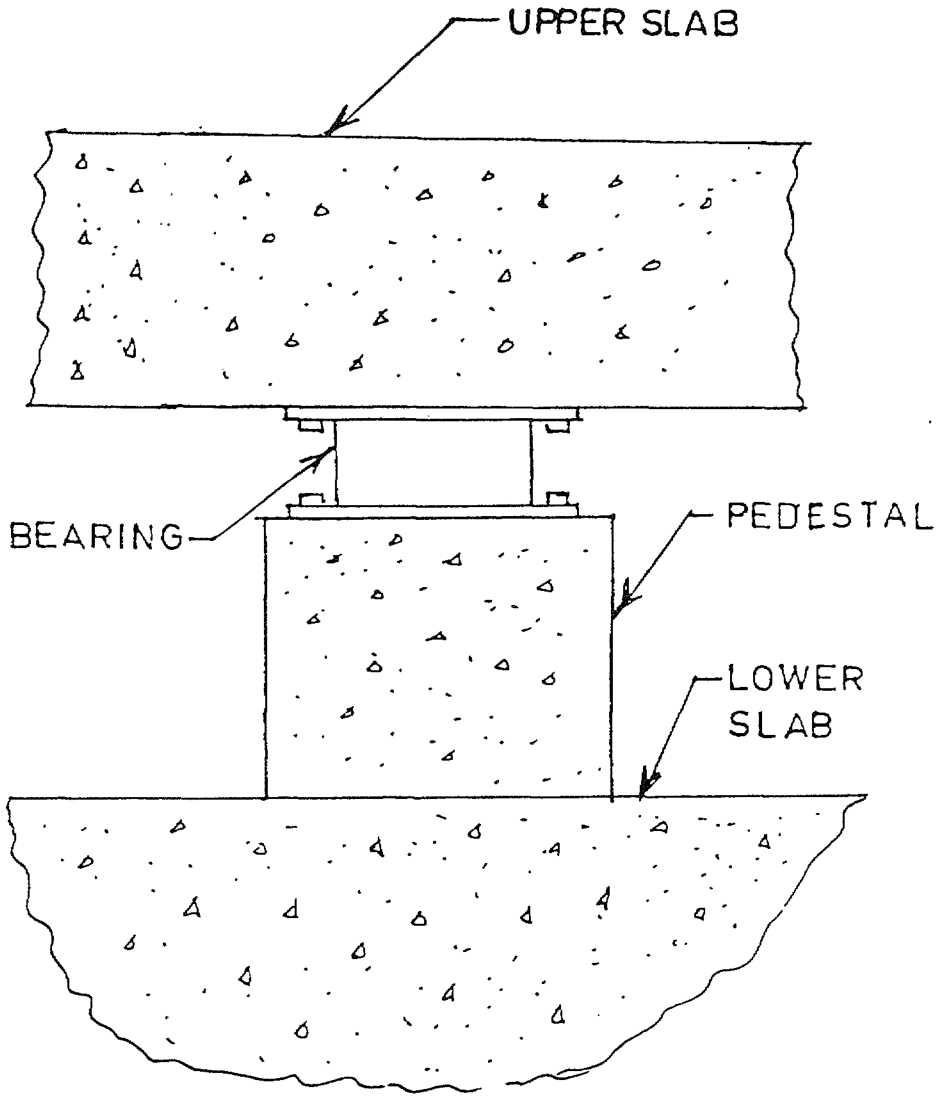


FIGURE 4 BEARING ARRANGEMENT AT THE BASE

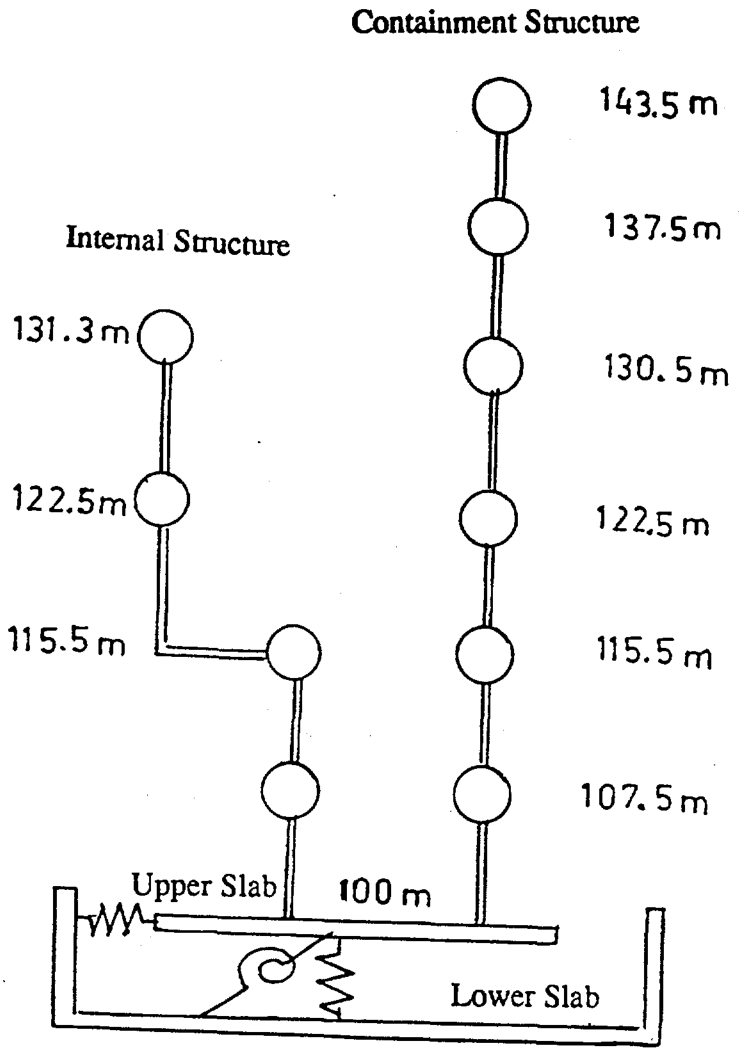


FIGURE 5 REACTOR BUILDING MODEL

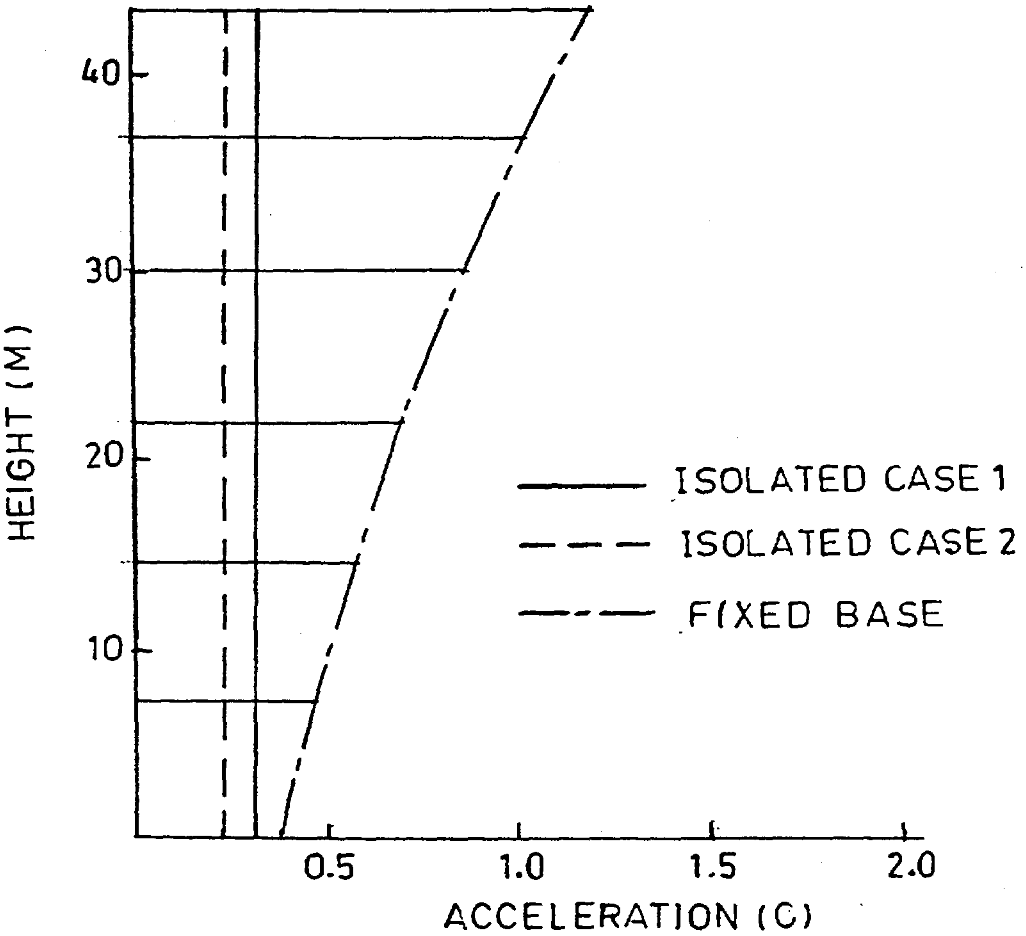


FIGURE 6 RESPONSE ACCELERATION PLOT

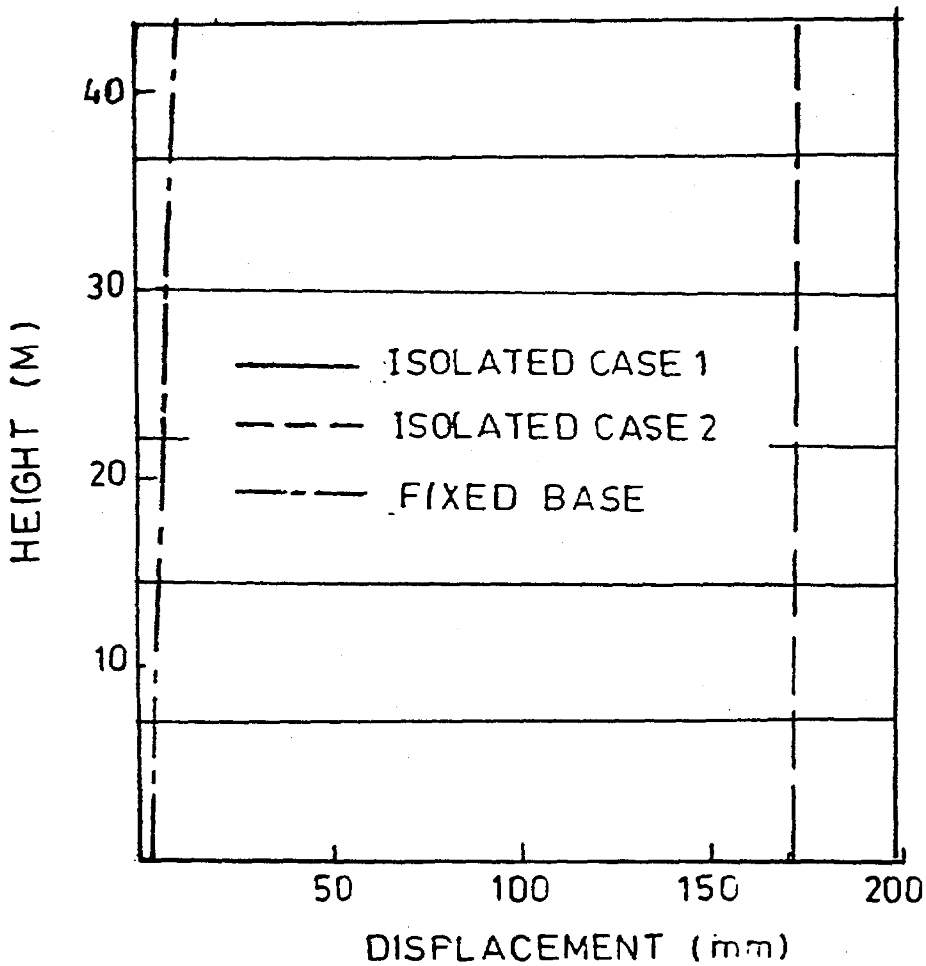
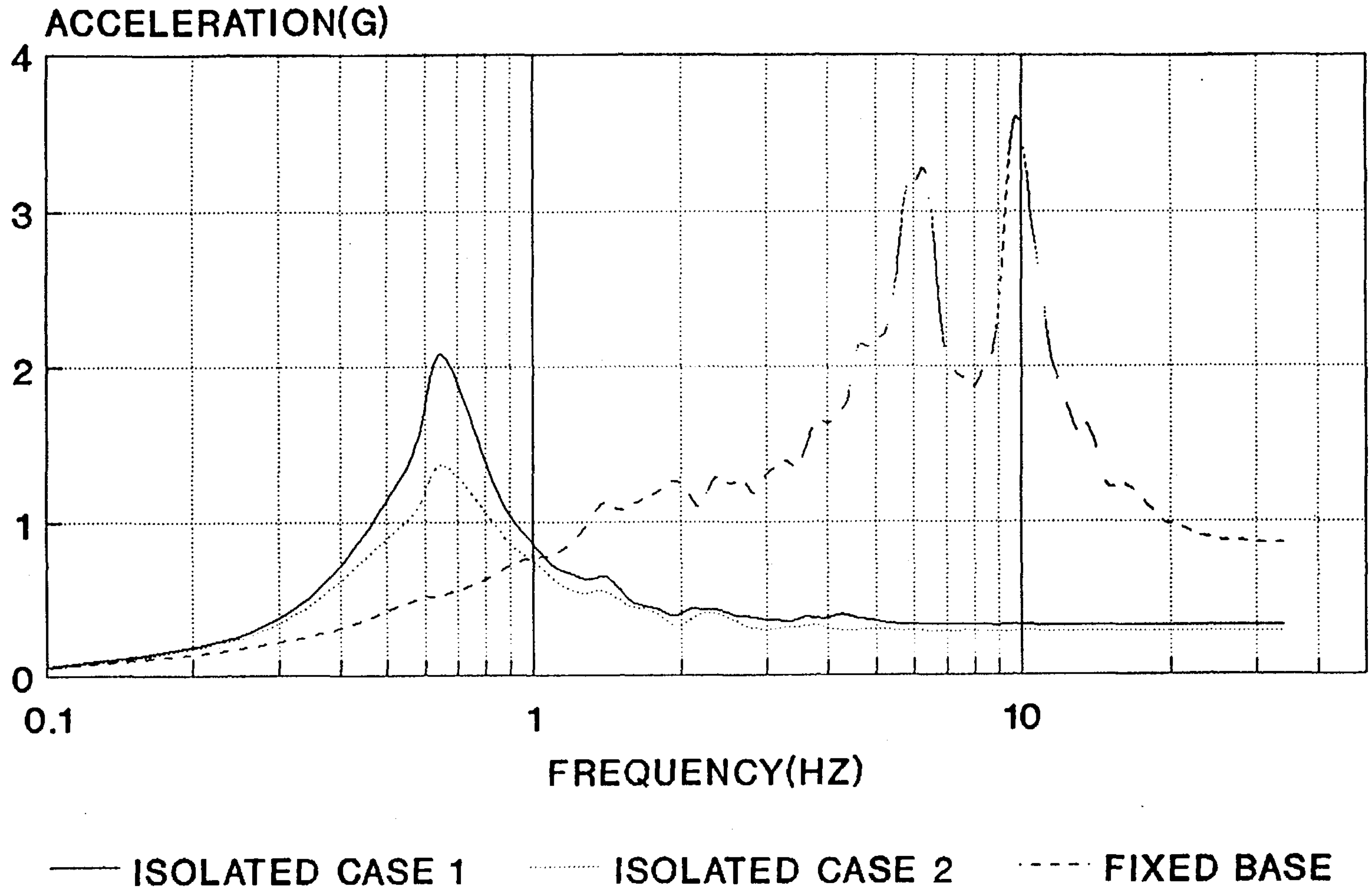


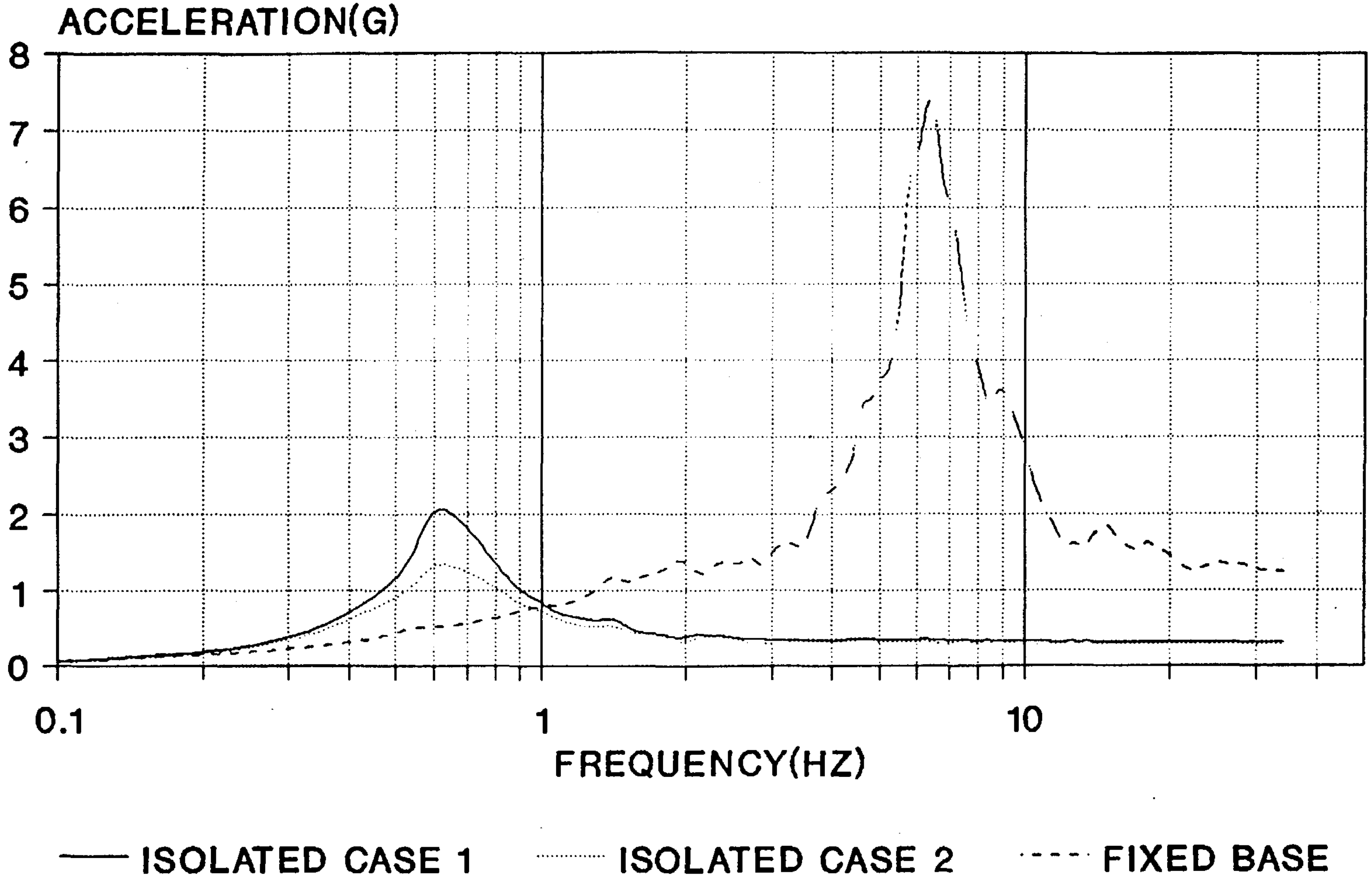
FIGURE 7 RESPONSE DISPLACEMENT PLOT

FIGURE 8 FLOOR RESPONSE SPECTRUM AT THE INTERNAL STRUCTURE



ELEVATION 122.8

FIGURE 9 FLOOR RESPONSE SPECTRUM AT THE CONTAINMENT STRUCTURE



ELEVATION 142.6 M