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THE BENEFITS AND PROBLEMS OF BASE SEISMIC ISOLATION FOR LMFBR REACTOR PLANTS

by

Ralph W. Seidensticker
Manager, Engineering Mechanics Program
Reactor Analysis and Safety Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439 USA

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Abstract

The use of seismic isolation as an approach to aseismic design has gained increasing interest as a viable and efficient engineering solution to earthquake ground motion both within and outside of the nuclear field. Seismic isolation design is fundamentally different from conventional design practice. In the conventional approach, seismic loads are resisted by making the structures, equipment, piping, and associated supports strong enough to resist seismic loads and to provide high levels of ductility. The use of seismic isolation approaches the problem by decoupling the structure (and its contents) from the seismic input resulting from ground shaking.

Because LMFBR systems operate at virtually atmospheric pressure, vessels, piping, and associated components tend to be quite thin-walled. The problem is that these thin-walled items have little inherent resistance to earthquake effects and are vulnerable to seismic load effects. As a result, earthquake loads have an even greater influence on LMR designs than they already are in LWR plants.

Several design approaches have been studied to cope economically with these difficult seismic problems, including deep embedment of the whole plant, making the reactor block very rigid, use of horizontal seismic isolation of the entire nuclear island, partial horizontal isolation of the primary sodium system, vertical isolation of the primary system, and combined horizontal and vertical isolation.

The potential benefits of seismic isolation for an LMR plant are considerable, including minimization of high-cost commodities such as stainless steel, large reductions in internal equipment loads, increased margins of safety for beyond-design-basis loads, and enhancement of plant standardization design.

There are, of course, a number of issues and concerns in the use of seismic isolation for a nuclear power plant. These issues cover a number of items such as the lack of experience in actual earthquakes, effects of long-period ground motion, effect of vertical loads, traveling waves, and other related concerns. This paper presents an evaluation of the benefits and problems in the use of seismic isolation in LMR plants.

I. Scope and Purpose

The objectives of these papers are: (1) to identify and discuss the benefits expected from the use of seismic isolation for LMR plants, and (2) to explore the potential problems or design issues which must be resolved to achieve a fully licensable design using seismic isolation.

This report deals mostly with horizontal seismic isolation. However, there appears to be incentives for vertical isolation of some parts of some LMR plants, and vertical isolation is included as appropriate. Finally, though focused on LMR plants, the material present in this report should be applicable, generally, to other types of nuclear reactor facilities.

II. Introduction and Background

Appropriate resolution of the seismic design issues associated with LMR plants is of utmost importance if these plants are to become economically competitive. Before addressing the special design problems and technical issues associated with seismic isolation, it may be useful to reflect on the extremely complex sequence of causes and effects which occur in any significant earthquake. In particular, it is important to keep these events and phenomena in perspective in estimating the loads and other effects experienced by the LMR reactor system and its components. The following list presents the major items which have a strong influence on evaluation of seismic response:

(1) The type and magnitude of the earthquake under study and its location relative to the LMR plant;

(2) The effects upon the original energy release in the earthquake as it travels outward from the initiating source;

(3) The reactor plant site-specific earth characteristics;

(4) The soil-structure interactions between the plant and its foundation;

(5) The actual response of the reactor plant structures to the local ground motions;

(6) The actual seismic input to equipment located within the reactor building; and

(7) The response of any particular structure, piece of equipment, or piping system to the seismic input it receives from the reactor building structure.

It is clear from the list above that earthquakes and their ultimate effect on the LMR reactor block and its contents constitute a complex series of interrelated phenomena. Good progress has been made to improve our ability to analytically predict the structural responses of buildings and associated equipment and piping. On the other hand, our ability to accurately predict earthquake sources, related energy releases, types of earthquakes, and transmission through the intervening ground structure is not as highly developed. Much has been done, of course, and much more will be accomplished.

The main point to be made is that most experts agree that there will probably always be greater uncertainties involved in estimating the earthquake source and its associated site-specific effects than those uncertainties involved in the structural analysis of the buildings and components. Add to this the observation that while a building may survive an earthquake, even one which is greater than that to which it was designed, the contents of the structures may still collapse or fail due to lack of proper holddown, excessive loading, etc., caused by amplification effects from the main structure. Viewed from these last two points, the fundamental benefits of seismic isolation can be stated as follows:

- The ability to handle very large earthquakes, even with much uncertainty about the magnitude of the earthquake, and
- The level of protection of the contents of the isolated structure is greatly increased.

It should be noted that the problems involved in earthquake source definition mentioned above are well recognized by seismologists, geologists, and engineers. There are very good signs that the need for improved interdisciplinary efforts in source characterization is receiving considerable attention. One such example is a NRC workshop on soil-structure interaction held in Bethesda, Maryland, on June 16-18 1986 (1). This workshop brought together structural engineers, seismologists, geotechnical engineers, researchers, and regulatory persons to try to better understand the nature of the issues involved and to help to reduce the conservatism added to each step in the seismic design process (i.e., input, site analysis SSI, etc.).

It is also important to take note of other events taking place in the United States nuclear industry which complement the efforts to improve earthquake source definition. For example, at a joint USNRC/EPRI workshop on outstanding seismic issues (LWR plants) held in December 1986 at North Carolina State University, it was clear that both plant designers and regulators are moving toward closer to an accord on the need to simplify the seismic design of nuclear plants. These groups also are moving toward greater use of the worldwide experiences in earthquakes which have demonstrated the inherent resistance of many structures, components, and piping systems to rather strong earthquakes, even though these structures and components were not designed to very stringent seismic standards.

Seismic isolation, properly used, should be able to ensure these inherent characteristics cited above and to provide even greater margins of safety against beyond-design-basis earthquakes. It is, therefore, best to consider a seismic isolation design strategy as a potentially very useful tool in coping with difficult seismic effects such as those encountered in the design of an LMFBR reactor block.

III. Basic Seismic Isolation System Characteristics

The concept of seismic isolation is not new. In fact the earliest recorded ideas date back almost eighty (80) years ago when a medical doctor in England -- Dr. J. A. Calentarients -- suggested the use of a layers of talcum powder between the structures and their foundations to decouple the strong ground shaking effects from the structure [2].* Many concepts have been proposed over the years and recently advances in materials technology, fabrication practices and engineering have produced a number of advanced and promising isolation systems. These systems have been described in detail in several survey papers, see for example References [3], [4], and [5].

It is far beyond the scope of this paper to review all types of seismic isolation systems currently under serious study. It is also beyond this paper's scope to go into much detail on the behavior of these various systems. What is presented next are examples of systems which been recently used or proposed for use in nuclear power plants, along with a discussion on two or three of the most important features and differences among these systems.

*It is interesting that very recently the Chinese have been using layers of sand on top of foundation walls for light residential structures to accomplish virtually the same sliding effect.

The following is partial listing of seismic isolation systems which are in use now, or which have been proposed for use in nuclear plants:

1) Elastomeric bearings -- similar to those used for many years on bridges for thermal movements -- which consist of several layers of fairly thin steel plates embedded (by vulcanizing) in the elastomeric matrix (Fig. 1). The bearings carry the vertical loads and have a relatively low horizontal spring constant which allows them to deform laterally during an earthquake. This type has been used in a French LWR plant in Cruas, France. Recently advances have been made in developing very high damping rubber for this type of isolator; one such use was on a large three-story building, the Foothills Community Justice Center in San Bernadino, California, USA.

2) Elastomeric bearings laminated with steel plates as in 1) above, but with a central core of lead which provides substantial damping as the bearing deforms laterally during an earthquake (see Fig. 2). These bearings have been installed in several buildings and were originally developed in New Zealand.

3) A combination of laminated steel-reinforced elastomeric bearings with sliding plates (see Fig. 3). By employing bearing plates with coefficients of sliding function of about 0.2 these bearings behave just as those shown in Fig. 1 until the horizontal forces exceed the sliding friction coefficient. The contact bearing plates then slide to accommodate the higher seismic loads. Such a system was used by the French (EdF) in a LWR plant in Koeberg, South Africa.

4) Sliding bearing plates with independent horizontal restoring spring devices. The best developed system of this type is the Alexisismon system which uses sliding plates of Teflon with very low coefficient of sliding friction to accommodate the horizontal ground motion during an earthquake relative to the superstructure above the bearings (see Fig. 4). Horizontal restoring forces are supplied by neoprene, rubber or steel springs which take no vertical load from the structure.

5) An assembly of steel helical coil springs used with a viscous damping devices. The best known system of this type is the German GERB system shown in Fig. 5. Use of this system theoretically can accommodate both horizontal and vertical, seismic isolation. It appears, however, that reactor plant designers prefer to limit this type of system to vertical isolation to avoid complex interactions which might occur if displacements occurred both horizontally and vertically.

There are several features of each of the five (5) isolation systems described above which differ from one system to another, or which are quite similar in each system. There are, however, two important distinguishing characteristics which must be given special note. The first of these characteristics, and perhaps the most important, is whether the horizontal restoration force is applied by the same bearing system which carries the (always present) vertical load of reactor block. Virtually all laminated elastomer bearing systems carry both the vertical dead weight (and vertical earthquake forces) while also providing the horizontal restoration spring force due to lateral displacements occurring during the earthquake. Thus, interactions occur within the bearing between vertical and horizontal loads and deflections. Care must be exercised to assure that vertical load does not cause bearing instability due to excessive lateral displacements. The designer can compensate for this by limiting the aspect ratio between the heights and diameter of the bearing.

In most sliding bearing systems, such as the Alexisismon system, the function of providing support for vertical static and dynamic loads and the function of horizontal spring force restoration are kept completely separate. In the Alexisismon system the sliding (teflon) pot bearings support all of the weight of the structure (including the additions and reductions of the load due to the vertical earthquake motions). The horizontal springs do not support vertical loads at any time. Their sole function is to follow the movements of the structure (relative to the ground) providing restoring forces. They exert only horizontal forces and then only when the structure is displaced laterally relative to the ground.

A second important characteristic of any given seismic isolation system is whether its force-lateral deformation loading curve is basically linear (or whether it is bilinear). No system is perfectly linear or perfectly bilinear, but the basic load/deflection curves can be represented by simple models, at least within the deformation limit for which the isolator was designed. For example, the laminated elastomeric bearing and the Alexisismon pot and horizontal spring systems act is a basically linear fashion as shown in Fig. 6. (Note: In Fig. 6, the dashed lines show a slight deviation from the nominal linear curve due to the inherent friction in the pot bearing.) In Fig. 7, we see the basic bilinear behavior exhibited by some systems. such as that used in the Koeberg South Africa LWR plant by the French.

IV. Comparisons of System Responses between Isolated and Nonisolated Structures

There are, of course, fundamental differences in the way in which isolated and nonisolated structures behave in an earthquake. Some of the more important differences, as they affect the design of a LWR power plant area, are as follows:

A. Conventionally designed buildings rely on high levels of ductility and strength to resist seismic loads. A seismically isolated structure, however, lowers the seismic forces on the structure and also reduces loads on the contents within the building.

B. In conventional design, careful attention must be given to every structural element and connection in the structural system resisting the earthquake. An earthquake affects everything in the building structure and all of its contents. If a weak link exists due to design or construction deficiencies, failure may occur well below the global earthquake resistance capability of the structural system. On the other hand, the use of seismic isolation significantly reduces the seismic loads experienced by the building structure and also the equipment within the building. Thus, these structural elements are not as sensitive to the dynamic effects of the earthquake. (Of course, even seismically isolated structures should be designed with adequate ductility and strength and with appropriate attention given to application of good seismic design practices throughout the system.)

C. When seismic isolation is used, it is obvious that emphasis on structural quality assurance and control will shift somewhat away from the building superstructure and move to the isolation system and its component parts. The isolation system components such as the bearing, springs, and damping devices should be designed to facilitate in-service inspection and also to facilitate relatively easy removal and replacement of any parts of the system should that become necessary.

D. When seismic isolation is used, large relative displacements can occur between the isolated portion of the plant and the nonisolated structures adjacent to the isolated structure. These differential motions will impose loadings and other effects on piping and other services connecting these two types of structures. The design must provide flexible connections or sufficient piping flexibility to accommodate these differential displacements. In addition, adequate "rattle-space" must be provided around the isolated structure to allow free operation of the isolation system. For conventional seismic design, the interbuilding service and piping connection generally do not experience much differential displacement, although it can occur in some cases, but to a lesser degree than in the isolated system.

E. The use of dynamic in-situ testing can be expanded considerably for a seismically isolated structure. Such things as dynamic "snap-back" tests and new forms of applying external soil compression wave loadings under development can be used even at interim stages of building construction, both to confirm analytical predictions and to confirm proper installation and working conditions of the seismic isolation system components. Such tests can also be used periodically during the life of the plant to detect any significant changes in global system response to dynamic test loads. System identification techniques which are useful for these tests and for assessing potential damage following a large earthquake are being developed at a number of research organizations. Initial results are promising and the prospects of these techniques becoming reliable diagnostic tools are quite good.

V. Major Benefits of Seismic Isolation

One of the major conclusions of the U.S. NRC Workshop on Soil-structure (June 1986 -- Ref. [1]) concerns the inevitability of accepting large uncertainties in estimates of ground motions expected at any given site. The following important quotation is taken directly from Ref. [1]:

> "....It is important to recognize the large uncertainty associated with ground motion estimation, that it is perhaps irreducible and that we need to express this uncertainty and devise ways of living with it." (p. 399, as part of Session 2, "Definition of Free-Field Motion").

Another significant (though not entirely unexpected) conclusion from that NRC workshop also addresses the difficulty in estimating ground motions. It is quoted directly from Ref. [1] as follows:

> "....While the state-of-the-art of earthquake ground motion estimation has improved greatly over the past years, so has our realization that the earthquake process is more variable than previously thought." (p. 399, as part of Session 2).

What these two items mean, of course, is that structural designers will probably always have to contend with not only large uncertainties in ground motion estimates, but may also have to be able to cope economically with the discovery of new seismological and geological information, even after the plant design has been completed (and, in fact, after construction has started). The designer has at least two strategies to handle these problems. The first is to use very large safety factors in the design to account for possible underestimates of ground motions and the occurrence or discovery of new information. This course of action has been the predominant approach in the seismic design of nuclear power plants. It is costly, time-consuming, and, in some areas, may have even led to reductions in safety margins. There are, of course, large research programs underway to reduce these design overconservatisms.

The second alternative strategy is to try to concentrate the effects of these ground motion estimate uncertainties into a small portion of the NPP plant. The use of seismic isolation is an effective tool to implement this strategy. If the seismic isolation system is designed properly, significant increases in seismic load and displacement input can be accommodated by modifying the seismic isolation system (i.e., more bearings, changing response frequency, etc.), thus leaving the superstructure and its contents unchanged.

This capability of seismic isolation also contributes to the enhancement of standardization of major portions of the nuclear plant, especially the safety-related structures and components.

In most isolated structures, the building generally moves as a rigid body, which means that the acceleration forces which pass through the isolators are relatively constant over the height of the entire structure. Thus, equipment on the top floors also benefit from reduced seismic loadings.

The following important comments are quoted directly from Ref. [6], and add additional insights concerning expected benefits from seismic isolation:

> "The advantages of seismic isolation include the ability to eliminate or very significantly reduce structural and nonstructural damage, enhance the safety of the building contents and architectural facades, and to reduce seismic design forces. The factor of 5 to 10 reduction in elastic force reductions achieved with seismic isolation can be expressed in simplistic terms as a reduction of a Magnitude 8 event to an event in the 5-to-6 range. Clearly, this is a very significant reduction. These potential benefits are greatest for stiff structures fixed rigidly to the ground, such as low- and medium-rise buildings, nuclear power plants, bridges, and many types of equipment. Some tectonic and soil foundation conditions may, however, preclude the use of seismic isolation."
>
> "For new structures, the current code applies in all seismic zones and, therefore, many designers may feel that the 'need' for seismic isolation does not exist because the code requirements can be satisfied by current designs. However, the commentary to the Structural Engineers Association of California (SEAOC) Recommended Lateral Force Requirements states that buildings designed in accordance with its provisions will
>
> - resist minor earthquakes without structural damage but with some nonstructural damage
> - resist moderate earthquakes without structural damage but with some nonstructural damage.
>
> Seismic isolation provides the capability of providing a building with better performance characteristics than our current code approach and, thus, represents a major step forward in the seismic design of civil engineering structures. .... Seismic isolation significantly reduces both floor accelerations and interstory drift and, thus, provides a viable economic solution to the difficult problem of reducing nonstructural damage."

Given the present high-cost of providing seismic design (at least, in the United States), the use of seismic isolation holds considerable promise of lowering initial capital and operating costs and providing even greater margins of safety.

I. Technical Issues Involved in the Use of Seismic Isolation in LWR Plants

There are a number of technical issues related to the use of seismic isolation. While most of these issues are of concern for application of seismic to any facility (e.g., hospitals, computer facilities, emergency centers, public buildings, etc.), it is clear that these issues must receive greater attention when we consider using seismic isolation for a nuclear reactor facility.

The existence of these technical issues in itself is not unexpected in any emerging technology. Even the more conventional seismic design approaches have a fairly lengthy list of unresolved issues. These is one issue, however, that is of greatest concern: The general lack of experience of actual seismically isolated structures subjected to actual (and reasonably strong motion) earthquakes. There simply is no real substitute for the real thing: a real earthquake involving actual full-size structures. As the number of isolated major structures grows worldwide (as it seems certain to do), this lack of field experience will recede. Also, there are research programs involving the measurement of response of full-sized seismically isolated structures to actual earthquakes. In addition, numerous laboratory tests are being conducted or planned on large- to full-size individual isolator bearings. Eventually, sufficient data will be available -- worldwide -- to close the present gap in our experience.

The following list presents most of the issues which are or will be receiving attention to improve understanding of the problems involved and to seek acceptable solutions:

a. Lack of experience of response of actual isolated structures to strong earthquakes;

b. Insufficient test data for some isolation systems;

c. Effects of long-period earthquake ground motions;

d. Need to use earthquake records which do not filter low-frequency content;

e. Isolator bearing material properties (including fire resistance);

f. Effect of vertical component motion of earthquake;

g. Stability of isolator bearings for beyond-design-basis conditions;

h. Sloshing effects -- resonance; nonlinearity of response;

i. When is the use of vertical isolation favorable?

j. Nonlinear behavior of isolators and related response of internal equipment;

k. Effects of non-ideal field conditions, e.g., tolerances, imperfections, differential settlement, etc.;

l. Traveling waves.

Obviously, all of these issues are neither of equal importance nor are they listed in any particular order of significance. There seems to be sufficient reason to believe that satisfactory solutions to all of these problems or issues will be found. As for the economics of the use of seismic isolation, it is probably too early to state with certainty that costs will be significantly lower. But, everything points to the hope that seismic isolation holds considerable promise to cut capital and operating costs of LMR plants.

Work is underway in most of the areas delineated above at universities, national laboratories, engineering firms, and reactor manufacturers. For example, at least one paper on traveling waves was presented at the SMIRT-9 Conference in Lausanne, Switzerland (17-21 August 1987).[7] Another paper at SMIRT-9 dealt with the combined use of horizontal and vertical isolation.[8] Still another paper dealt with the problems of nonlinear behavior of sliding bearings and the resulting effects on equipment response.[9] Another paper dealt with the effects of vertical motion.[10] Sloshing effects are also receiving increased attention.[11]

Since the fundamental frequency of a seismically isolated structural system is much lower than that of the nonisolated system, the effects of distant earthquakes and long-period earthquakes become more important. Relative displacement between isolated and nonisolated portions of the complex can be fairly large, and the design must accommodate these displacements. Reliability of the isolators over the life of the structure must be assured and replacement of individual unites facilitates, if necessary. All of these things need to be demonstrated convincingly to the satisfaction of the regulatory bodies governing licensing of nuclear facilities. Sensitivity and parametric studies are good ways to assess many of these design concerns. Both laboratory testing and field testing of individual isolators, models of structures, and field tests are essential. Good measurements of response history and behavior of isolated structures to actual earthquakes is also needed (and is proceeding). Comparative tests measuring the response of identical structures both with and without isolation subjected to the same natural or experimental field tests are a very powerful way to establish the effectiveness of seismic isolation. Such programs are underway or are in advanced planning stages.

VII. SUMMARY AND CONCLUSIONS

Seismic isolation is rapidly emerging as one of the most significant earthquake engineering developments in recent years and is being used for many important civil engineering structures throughout the world. The technical issues are well known and the research needed to resolve these issues is either underway or being planned in several countries.

Much field observation and testing is needed and encouraged not only to provide validation of analytical techniques, but as a means to help establish construction practices needed to produce reliable structures. More testing needs to be done on individual isolator bearings, especially dynamic tests and static load tests to failure of the bearings.

As pointed out in a recent survey paper by Kelly,[12] there is a need to consider incorporation of "fail-safe" mechanisms. Great care must be exercised, however, so as not to undo all of the advantages of isolation by adding devices, etc. which could have undesirable feedback into the isolated structure. The goal should be simplicity and inherency of desired features within the isolators themselves.

For LMR plants, the use of seismic isolation has great potential for improving safety margins, reducing capital costs, promoting standardization, and enhancing thermal response by avoiding heavy stainless steel sections for structures, vessels, and other components.

The isolation system should be designed with many isolators for redundancy so that an unexpected failure of one or more of the isolators does not influence the functioning of the total system. Regular inspection and maintenance of the isolation system, redundancy of isolators, and the capability of replacing any suspect isolation components give the isolated nuclear power plant additional advantages over the conventional nonisolated plant. The ultimate acceptance of seismic isolation for nuclear power plants will depend on the performance of isolated structures throughout the world, the overall economics of the system, and demonstrated existence of adequate safety margins for beyond-design-basis earthquakes.

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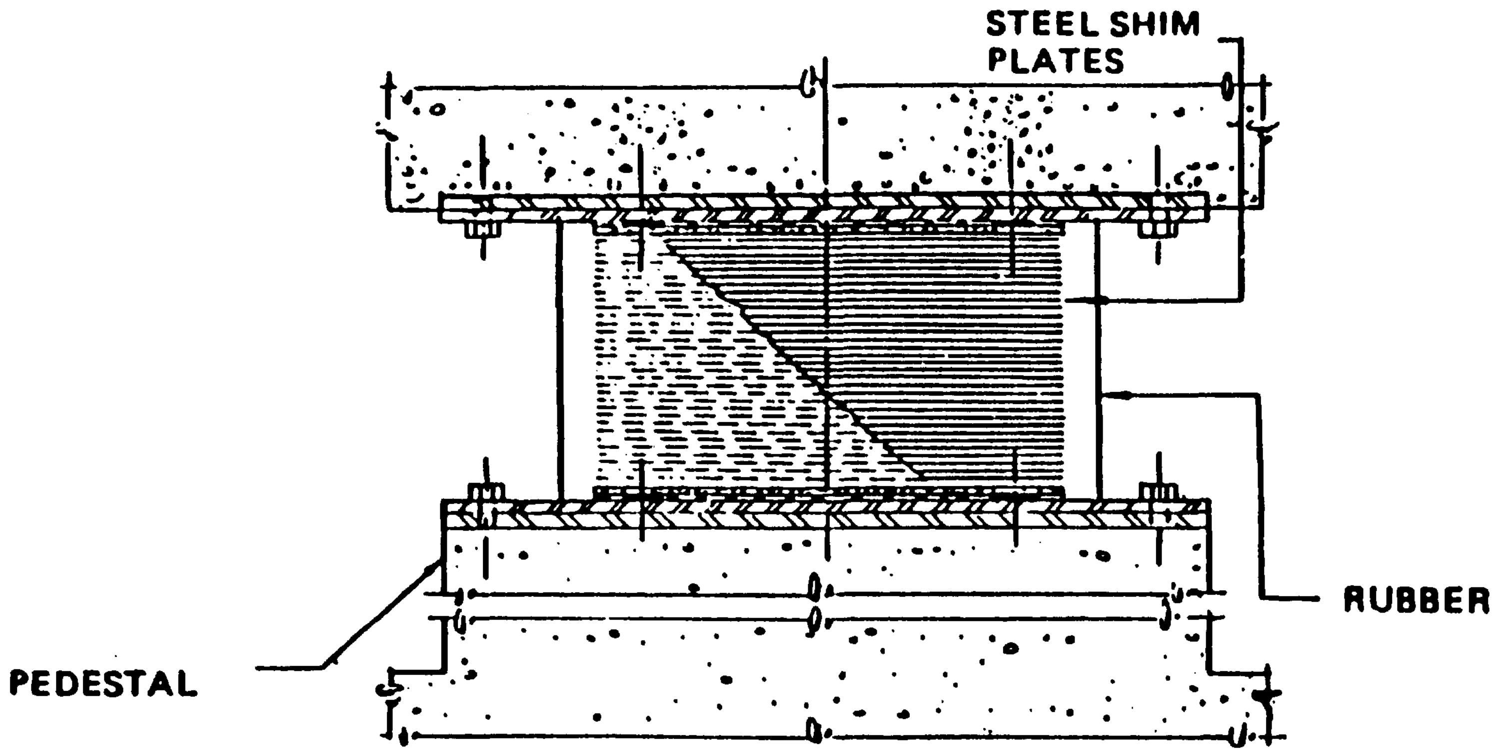

Fig. 1. Laminated Elastomeric Bearings

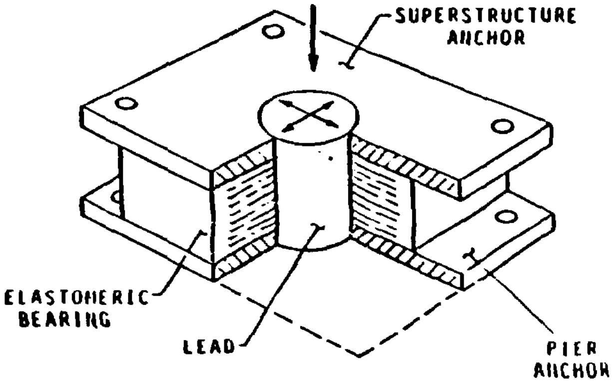

Fig. 2. Laminated Elastomeric Bearings with Lead Plug

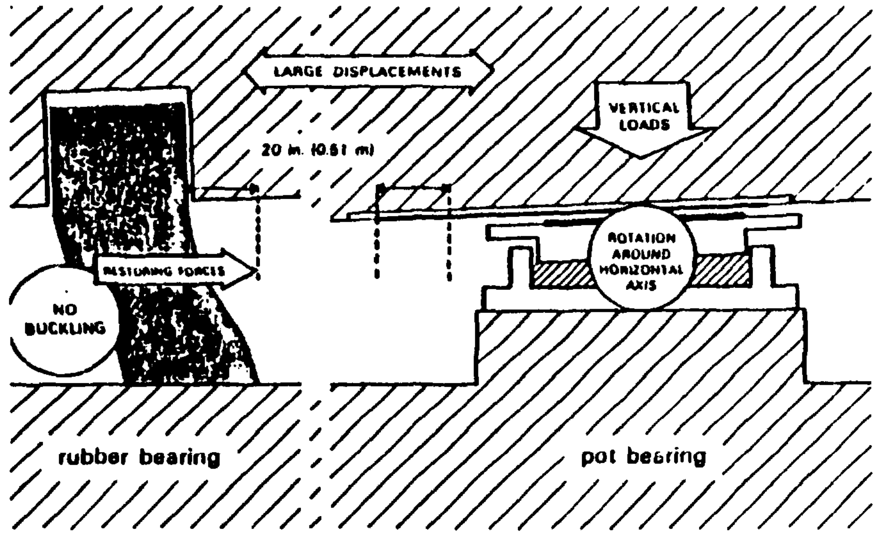

Fig. 4. Alexisismon Sliding Pot Bearings System

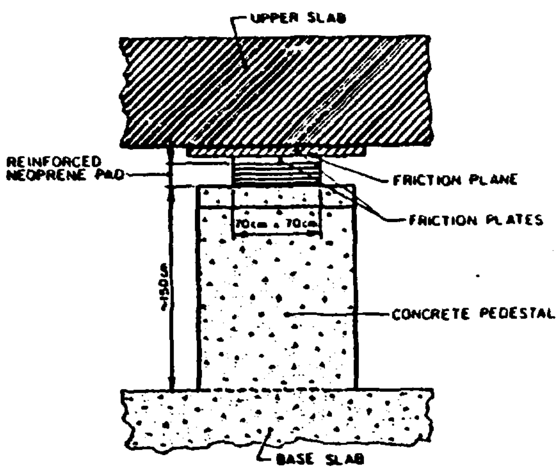

Fig. 3. Combined Laminated elastomeric Bearing and Sliding Plates

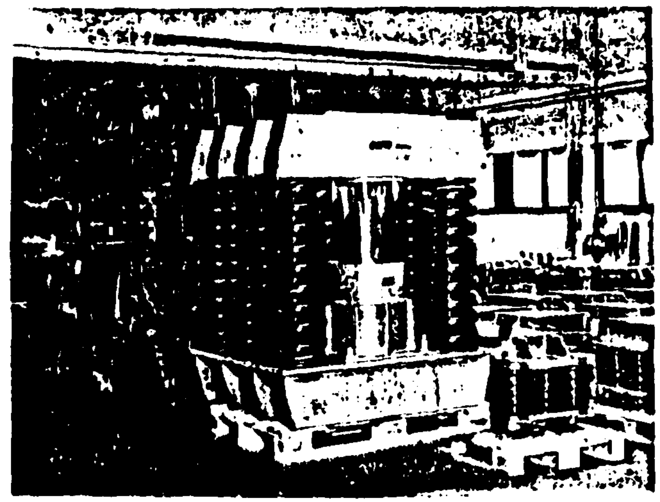

Fig. 5. GERB Helical Coil Isolator

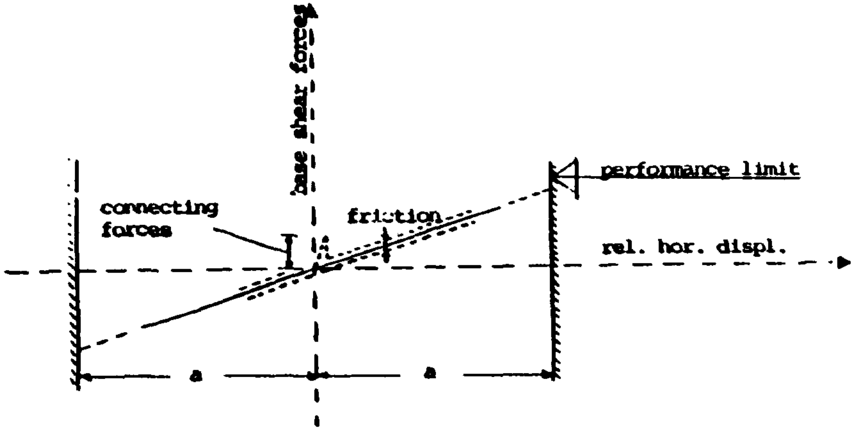

Fig. 6. Linear Isolation System

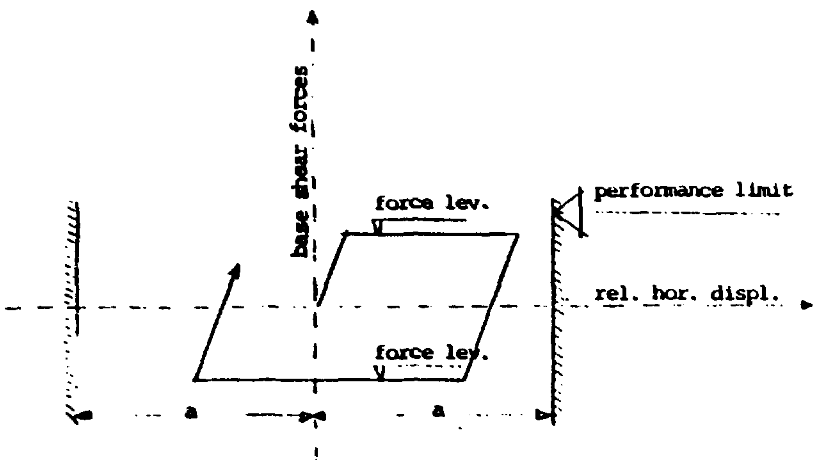

Fig. 7. Bilinear Isolation System

IAEA-IWGFR Specialists' Meeting on LMFBR Reactor-Block Seismic Design and Verifications

Oct. 12-15, 1987 Bologna, Italy

APPROACH TO LMFBR FLOOR RESPONSE REDUCTION

Yoshihiro SAWADA, Akio SAKURAI, and Chizuko KURIHARA

Central Research Institute of Electric Power Industry

PAPER NR. 11

Abstract

To reduce seismic load for the nuclear components of pool-type LMFBR, dynamic characteristics of the partially embedded reactor building, optimum depth of embedment and adequacy of response analysis method were examined.

In addition to this, introduction of several isolation systems, siting on the soft rock and inshore floating plant were also investigated to evaluate possibility of further rationalization of seismic design.

1. Introduction

As the nuclear power plants in Japan are required to withstand against severe earthquake input motion, reduction of seismic load for nuclear components is one of the most important problems to achieve a economical design of LMFBR power plant.

In the past feasibility study done since 1980 to 1983, the floor response acceleration of main vessel supporting level was several times greater than those obtained from other invesigations in foreign countries, and it needed to develop a original aseismic structure in Japan.

Therefore, reduction of floor response spectrum (FRS) at main vessel supporting level due to embedding the reactor building in the bedrock was investigated. The seismic response analysis was carried out and effectiveness of embedding was evaluated. Moreover, the simulation studies about several observed earthquake records of a real building were performed to verify the analytical modeling.