Alexisismon Isolation Engineering for Nuclear Power Plants

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Summary

The constant evolution of the seismic maps has brought to a sharp focus the reliability of seismic input as well as the lack of large seismic margins in nuclear power plants. This lack is due to economical reasons since designing strength into a classical structure becomes very costly as the intensity of the earthquake increases.

Today, new structural designs using seismic isolation systems can provide strongly increased seismic safety economically and they are regarded as serious alternatives to classical designs for structures to be built in seismic areas.

The feasibility of using a seismic isolation design in a nuclear power plant from the viewpoints of licensibility and efficiency is studied in this paper.

In order to facilitate the licensing process, it must be possible to predict the behavior of the isolated plant by means of the established analysis procedures: no deviation from the classical soil/structure interaction, use of classical extreme loading distribution patterns, accommodation of potential loss of contact between structure and foundation, etc.., Severe requirements related to the isolation system itself are proposed: performance, verification of performance, etc.., In view of the need for high seismic safety margins, it is suggested that an isolation system should not allow the seismic base shear to exceed 10 % of the weight of the structure for all recorded accelerograms scaled to 1.50 g peak acceleration minimum. This makes possible the future standardization of the plants design.

1. Introduction

The recording of always more intensive accelerograms, the discovery of new faults, etc.., have led to the revision of the seismic criteria of several sites in the U.S. and in other seismic countries and have brought to a sharp focus the reliability of seismic input as well as the absence of large seismic margins in major structures such as nuclear power plants. In addition to the problem of uncertainty in determining seismic input there is another parameter which has become important and that is excessive costs. It is a well known fact that to provide adequate seismic resistance in the classical sense -- i.e., by designing strength into the structure -- becomes very costly as the intensity of the earthquake increases; in fact, a point is eventually reached where it becomes also technically impossible to provide the strength levels required.

Today, new structural designs using seismic isolation systems can provide strongly increased seismic safety economically and in fact with lower cost and they are regarded as serious alternatives to classical design for structures to be built in seismic areas.

Various isolation designs have been proposed all around the world (ref. 1 to 8) and some of them have already been implemented. Among the latter is the Alexisismon system (ref. 8 to 15) which was developed by the author from 1968 to 1972 and was implemented for the first time in 1972 in a multi-story building. Its concept and different schemes have been patented in the U.S. and in other seismic countries and its efficiency when applied to a nuclear power plant was demonstrated in a paper presented at SMIRT-6 in Paris (12).

The purpose of this paper is to address general problems of providing seismic isolation to nuclear power plants.

It must be first noted that, although nuclear power plants have specific architectural, structural and mechanical characteristics, as major structures usually have, none of them deviates so much from common design that it can prevent seismic isolation from being incorporated or operating, as it does in other structures, provided their secondary effects are reliably accommodated by the seismic isolation system.

The major concerns about seismic isolation applied to a nuclear power plant which are likely to be shared, to different extents, by owners, designers, constructors and authorities are (a) the licensibility of an isolated power plant, (b) the efficiency of its seismic isolation, and (c) the cost of the plant.

We shall address the first two areas in the following, attempting to define basic requirements to be met by horizontal seismic isolation when applied to a nuclear plant.

A third point will be addressed supplementarily, namely the feasibility of requiring from the seismic isolation design that it be adaptable to new seismic conditions.

2. Licensibility of an Isolated Nuclear Power Plant

A nuclear power plant design is checked according to very detailed licensibility procedures which most severely control design and analysis methods, design details, material specifications and other related items.

We consider as an imperative requirement for obtaining approval by the authorities that the whole new structural system of the isolated plant fits in the existing codes and that it be possible to predict its behavior by means of the established procedures. The very adoption of the seismic isolation concept itself representing a significant licensing issue, any other major deviation from current methodologies and currently approved practices should be avoided in using this new concept, as much as possible, so as not to further complicate and delay the licensing process.

In addition, it is again imperative, in order to be given approval by the authorities, that the seismic isolation design meet basic requirements related to the performance characteristics and the material properties of the isolation system itself.

In the following, we shall address successively the requirements related to the predictability of behavior of the isolated structure and to the performance of the isolation system itself.

2.1 Predictability of Behavior

To fit in the existing codes, the elements of the seismic isolation of the nuclear power plant must have the following properties:

2.1.1 First Property

The vertical (axial) stiffness of the elements of the seismic isolation and their spacing as well as the vertical (flexural) and the horizontal (axial) stiffness of the foundation mat must be such that, as far as vertical loads are concerned, the use of isolation does not alter the character of the soil/structure interaction.

In that manner, the established load input and the procedures to evaluate the soil reactions can be used. To achieve this, the following requirements have to be met:

(a) the vertical axial stiffness of the load transferring isolation elements has to be maximal;
(b) the softer the soil, the greater the horizontal axial stiffness of the foundation mat has to be;
(c) the softer the soil and the stiffer the structure, the smaller the spacing between isolation elements and the greater the vertical (flexural) stiffness of the foundation mat have to be.

In that way, as far as vertical stiffness is concerned, the isolation elements , the foundation mat and the soil form a system with the same characteristics as the soil of an unisolated nuclear power plant. The vertical deformations of the soil and of the base of the structure -- i.e., above the isolation level -- resulting from the dead loads will substantially be the same as those in an unisolated plant.

The above requirements (a) and in part (c) concern properties of the method of seismic isolation applied.

2.1.2 Second Property

Each isolation bearing element must be able to transfer highly variable vertical loads.

In the structural analysis of a nuclear power plant supported on the ground in the classical way -- i.e., without seismic isolation -- we assume that the soil reacts with forces whose extreme distributions on the surface of the foundation result in a large variety of patterns according to the design of the whole plant, and more specifically to its foundation structural system, and to its size and loading. This variation in the force distribution at the surface of the foundation, which of course changes with the time, is mainly the result of two factors. On the one hand, it results from the statistical character of the properties of the ground and on the other hand, of the inadequacy of the existing methods of analysis to predict accurately these forces. In the case of (in part) uniformly distributed vertical loads -- e.g., (in part) uniformly distributed dead loads of the nuclear buildings -- the relative variety of load distributions is limited to a minimum. In this case, the most economic design for the foundation of the plant is that which provides a distribution of the soil reactions similar to that of the vertical loads, as far as possible. If horizontal loads of great intensity are added to the vertical loads -- e.g., the horizontal loads resulting from intensive earthquakes -- , the behavior of the materials of the structural system as well as of the ground becomes quite nonlinear. The knowledge of the properties of the materials is more questionable and the methods of analysis and design less reliable which has as a result that more extreme patterns of distribution of the forces have to be considered. This means that still heavier loads to be transferred by each definite area of the foundation surface must be assumed and this is accounted for in the design of the structural system of the plant and the verification of the soil strength.

If the plant is seismically isolated, the elements which constitute the seismic isolation system are located between the soil and the structure on the surface of a foundation mat. To be efficient the isolation system has to reduce the horizontal seismic forces as well as the overturning moments by a factor of from 10 to 20 in the case of a severe real earthquake. As a consequence, (1) the variation of soil loading due to the earthquake is minimized also since the loading of the soil during the earthquake is not much different from the loading by the vertical loads acting alone; (2) pronounced nonlinearities in the behavior of the material disappear; and (3) the methods of analysis remain reliable. It is expected that this will be felt as an advantage by the authorities and that in the future it will not be necessary for an isolated structure that the same extreme distribution patterns be taken into account. But since the establishing of criteria for a new structural design requires a very long procedure, an isolation system in order to be licensed today must be able to transfer the highly variable forces of the most extreme cases of distribution described in the previous paragraph exactly as a classical structure.

2.1.3 Third Property

For the same reasons as above, the elements of the seismic isolation system which are in fact an extension or projection of the soil must not be influenced by a possible partial loss of contact with the structure.

Of course a main reason for such a loss of contact is the strong seismic overturning moments and, as they are minimized when seismic isolation is applied, one could think that the provision of such a property is superfluous and can be overlooked. But in order to facilitate the licensing process, it is not advisable that this favorable feature be taken into account. Consequently, the isolation system must be able to function without problems even if a partial loss of contact on some foundation areas occurs. Besides, there is always the possibility of differential settlements due to variations in actual loads or soil properties or to seismic surface waves, and the ability to handle these cases of loss of contact can prove quite useful.

2.1.4 Fourth Property

Currently, the existing seismic input is developed for substantially force-dependent structural systems and its suitability for the prediction of strongly displacement-dependent systems may be questionable. Most likely it will need to be thoroughly verified and even be replaced by new seismic input. Again, this need may result in excessive delays in obtaining licensing acceptance.

To avoid or minimize this delay, the displacement of the top of the isolation elements as a whole in relation to their base support must be substantially force-dependent -- i.e., base shear-dependent --. Then the well documented existing seismic input produced currently and used for the force-dependent oscillations of classical structures and the established associated analytical methods can be used also for the prediction of the seismic response (displacements-forces) of the isolated structure.

The damping (viscous coulomb) characteristics of the isolation system must be of the same order as those usually encountered in the common classical plants when loaded in the elastic range of stresses so that the reliability of the seismic response predicted be maximal.

2.1.5 Fifth Property

In the event of an earthquake, the isolated part of the structure translates in the horizontal direction in relation to the foundation. Synchronously the base of the translating structure deforms in the vertical direction as well as the soil surface, i.e., the foundation mat. The vertical inclinations (or rotations about horizontal axis) of each of the vertically coupled areas of the translating base and the foundation mat do not necessarily coincide and therefore the isolation system must provide for unrestrained accommodation of the inclination differences between the base of the superstructure and the foundation mat.

A related problem also arises under normal loading due to (a) the difference between the vertical stiffness of the superstructure and that of the foundation and (b) the different distributions of the superstructure loads and of the pressure exerted on the soil surface by the foundation mat. In view of this also, the above provision is indispensable.

2.2 Isolation Basic Requirements

2.2.1 Performance of the Isolation System

The structure must remain stable even when experiencing the large expected relative displacements associated to high efficiency, that is, the isolation system support must be able to safely transfer the vertical loads despite the horizontal relative displacements without any damage (buckling), and substantially return to its original position after a severe earthquake, that is, the system must include strong centering forces. The remaining displacements have to be non-cumulative to prevent a one-directional "walk" of the structure in the case of a sequence of earthquakes and strong aftershocks (see also ref. 16, p. 44).

The elements of the isolation system must remain substantially unstressed by contractions and expansions of the superstructure and the foundation due to thermal expansion/contraction or similar effects. This is necessary to protect them from a continuous stressing for the whole life of the structure, which would have a degrading influence on their long-term function.

2.2.2 Properties of Materials

It is necessary to know perfectly the properties of the materials and components of the isolation system in order to be able to provide a reliable prediction of the behavior of the isolated structure.

Therefore, the materials used for the construction of the components of the system have to be well known and must have been used repeatedly, and for a long period of time, in similar environments in elements performing similar functions. That is, one must accumulate much material and literature related to the analysis and the testing of long-term physical, chemical and mechanical properties of materials proposed for use.

The successful and reliable performance of the function required from each element of the system for the whole time period of its use must be guaranteed. These elements must have performed successfully the same function for long in major structures located in similar environments. Among the mechanical properties of each component, those which are essential to the isolation system must be easily verifiable, both before and during their use in the structure. This verification must not weaken their performance ability and should be relatively easy to do.

2.2.3 In-Situ Verification of the Mechanical Properties of the Whole System

In addition to the verification of the mechanical properties of its different elements, the system must be able to allow an easy and economic in-situ verification of the mechanical properties of the whole system of isolation. This should be possible at various stages of construction, especially when the main buildings have been constructed. Such an in-situ testing is considered indispensable, given the specificity of the nuclear power plant. Moreover, it must be possible to easily rectify any problems uncovered by testing the whole system.

2.2.4 Redundancy

The isolation system in an isolated plant plays a role of first importance regarding its safety since it supports the whole plant. In effect, we transfer attention, from a safety point of view, from the structure to the isolation system. In view of this, it must be so designed that there is a great plurality of isolation components, i.e., the transferring of all vertical and horizontal loads to the foundation must be distributed to a great number of components so that an unexpected failure of one or more of them (despite the checking of their properties before and during their use) does not influence the functioning of the whole isolation system.

3. Efficiency of Seismic Isolation in a Nuclear Power Plant

In view of

(a) the very special function performed by the nuclear power plants and the very special fuel they process,

(b) the public opinion concern about their safety and potential pollution of the environment resulting from failure,

(c) the frequent revision to higher levels of the seismicity of many sites (as a result of which, e.g., NRC suspended the operating license of a nuclear power plant built years earlier, causing the loss of billions of dollars and bringing again to a sharp focus the reliability of seismic input) and the uncertainty factor in the establishing of the relative seismic criteria,

(d) the high cost of a nuclear power plant, and

(e) the subsequent need for a standardized design, abolishing its dependence on the site seismicity and site different soil and geological conditions,

it is a basic requirement that high seismic input margins be provided to nuclear power plants.

We believe that an isolation system provides a reasonable efficiency if it can limit the seismic base shear to 10 % of the weight of the plant for all the recorded high intensity seismic accelerograms scaled to 1.50 g peak acceleration minimum.

4. Adaptability to New Seismic Conditions

Considering the constant evolution of improved seismic maps throughout the world (based on the accumulation of new seismic data), it can never be completely sure that a significant increase in the seismicity of an area will not occur.

In view of this, it is desirable that the isolation system be provided with the property of adaptability to new and greater seismic input.

5. Conclusion

This paper reviewed several properties that a realistic isolated nuclear power plant design should possess in order to obtain undelayed licences and to provide high seismic safety margins.

(1) Since the very adoption of the isolation design represents an important licensing issue, any other innovation with respect to the current licensing practices should be avoided. The new structural system should fit in the existing codes and its behavior should be predictable by means of the established analysis procedures.

(2) Since the incorporation of seismic isolation in a nuclear power plant involves a concentration of the safety concerns on the isolation system, the latter must comply with the most severe requirements with regard to the verification of its performance, the properties of its materials, etc.., The isolation system should ensure a perfect stability of the structure and its components.

(3) To satisfy the need for high seismic safety margins, an isolation system should not allow the seismic base shear to exceed 10 % of the weight of the structure for all recorded accelerograms scaled to 1.50 g peak acceleration minimum. This last property also makes possible the standardization of the nuclear power plants design.

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