SEISMIC DESIGN CONSIDERATIONS FOR STRUCTURES SUPPORTED ON ASEISMIC BEARING PADS

BY

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SUMMARY

Mitigation of the effects of earthquakes on structures may be accomplished either by providing sufficient strength and ductility in the structure or by isolating the structure from severe ground motions. A method of isolating nuclear power plants and other industrial structures from severe horizontal ground motions, using Aseismic Bearing Pads (ABP) has been presented previously by Plichon (1975) and Jolivet and Richli (1977). The ABP's comprise a neoprene pad and a friction surface. The response of the structure to seismic excitation is therefore nonlinear. The design aims to limit the horizontal accelerations in the structure. Special problems such as effects of traveling waves, differential motion, variation of friction coefficient, a more intense than design earthquake, and the associated large displacements are discussed.

INTRODUCTION

Traditional seismic design of structures such as nuclear power plants has resulted in the addition of strength to the structural elements. To preclude permanent distortions in such structures, they are designed to remain elastic with the energy absorbing capability in the inelastic range serving the purpose to prevent catastrophic failure should the design earthquake be exceeded.

The concept of isolating building structures from seismic motions has been considered on previous occasions but only in a few instances has it been implemented. Recently, seismic base isolation has received renewed interest. An overview of the various isolation schemes has been presented by Kelly (1979).

The particular isolation scheme analyzed in this paper has been presented by Plichon (1975) and Jolivet and Richli (1977) and was implemented in the design of proposed nuclear power plant structures in Iran, South Africa, and France. Extensive feasibility studies of this aseismic design have shown the concept to be a reliable means to reduce horizontal earthquake motions in the structure, thus minimizing distress

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and improving the performance of the structure in a seismic event. The purpose of the present paper is to discuss special problems related to this design concept such as the effect of traveling waves, differential settlements, combined motions, variation of friction coefficient, and the effect of earthquakes of intensities beyond the design earthquake.

DESCRIPTION OF ASEISMIC FOUNDATION SCHEME

The aseismic foundation scheme consists of a double mat system interposed with neoprene pads and slippage bearings. Figure 1, which shows cross sections through a typical two-unit nuclear power plant, illustrates this scheme.

The plant structures comprising two reactor units and the associated auxiliary Category I buildings are founded on a common upper mat to form the "Nuclear Island" which is in turn supported by a common lower mat foundation. The lower mat is cast integrally with pedestals and on top of each of them three to eight ABP's are mounted. The details of the design are presented elsewhere (Jolivet and Richli, 1977).

SEISMIC ISOLATION DESIGN PHILOSOPHY AND ITS ADVANTAGES

To effect isolation from horizontal ground motions, the ABP's are designed to have a low horizontal stiffness such as to impart a low frequency (typically about one Hertz) to the predominant horizontal mode of the Nuclear Island. Although the pads are stiff in the vertical direction and do not provide any isolation in the vertical direction, the low horizontal frequency effectively decouples the response in the horizontal and rocking modes, thus significantly reducing the associated vertical motions in the structure. The predominant mode of vibration of the structure on ABP's is thus one of pure horizontal motion with very little rocking (Plichon, 1975 and Jolivet and Richli, 1977).

During moderate earthquakes, the nuclear power plant vibrates elastically on the pads and eventually returns to rest in its original position, while in more severe earthquakes, the plant vibrates and slips on the ABP's and comes to rest with some residual displacement. The overall seismic design philosophy aims to limit the horizontal accelerations in the structure, equipment, and components by imparting a low frequency to the predominant horizontal mode thereby decoupling the horizontal and rocking modes of vibration. Furthermore, the horizontal seismic accelerations imparted to the plant are limited by providing an interface with a low friction coefficient. The concept, therefore, allows a standardized plant designed for, say, a peak acceleration of 0.2 g to be located at a site having a somewhat higher peak ground acceleration by appropriately accounting for the associated larger displacements.

RESPONSE CALCULATIONS

The incorporation of the ABP's in the foundation introduces the possibility of a nonlinear response due to horizontal ground motions as the seismic motions become severe and the Nuclear Island slips on the friction surface. Response spectrum techniques cannot, therefore, be applied directly for the computation of structural response unless an approximate inelastic response spectrum is available. Lacking this, the responses have been computed using nonlinear time domain analyses.

The seismic environment of the site under consideration herein was defined by the USNRC Regulatory Guide 1.60 (1973) response spectra for peak horizontal and vertical accelerations of 0.3 g. Structural response was evaluated using synthetic time histories which were consistent with the design response spectra. The ground motion characteristics such as peak velocity and displacements of the synthetic time histories were also consistent with those observed from real records. The three components were nearly statistically uncorrelated (Chen, 1975).

The analytical model use in the seismic analysis of the Nuclear Island was obtained by a static condensation of a detailed planar finite element model of the Nuclear Island structures. The model included mass and stiffness matrices for the structures, nonlinear slippage elements for the aseismic bearing pads, and distributed stiffness and damping parameters for the soil.

The computer code TITUS (Creusot Loire and Citra, 1971) was used for static condensation. TITUS is a general purpose finite element code and represents an industry standard in France. The MULTIGLI (Spie Batignolles, 1975) computer code, which solves for the nonlinear dynamic response by a direct numerical integration scheme, was used for the dynamic seismic analyses. Confirmatory studies of the same and other plants, were also performed in which the models were analyzed using the computer codes DAPSYS (D'Appolonia, 1977) and ANSYS (Desalvo and Swanson, 1975).

COMBINED MOTIONS

The dynamic response of the Nuclear Island structures, including the slippage elements, has been evaluated considering simultaneous input motions in two horizontal and the vertical directions. Typical response obtained from the nonlinear transient dynamic analysis is shown in Figure 2 where the total relative displacement between the top and bottom raft and the slip as a function of time are plotted. Typical values of maximum slippage of the upper raft for a 0.3 g SSE were found to be on the order of 10 centimeters for a predominant plant frequency of one Hertz and a friction coefficient of 0.2, while the residual displacement following that earthquake was computed to be about six centimeters. A few important observations of the dynamic behavior of the structure are discussed below.

Since the purely vertical frequency on the pads in much higher than the horizontal, the vertical ground motions do not significantly add to the horizontal response for design purposes. When combining two horizontal inputs, the response of the Nuclear Island (acceleration and displacement) in the two directions are related in that the maximum resultant acceleration cannot exceed the value of the coefficient of friction times the acceleration of gravity. This provides an additional degree of safety in that it limits the resultant earthquake forces on systems and components to values due to a single seismic component, only.

The horizontal and the rocking motions of the structure are decoupled. Thus the horizontal response over the entire height of the structure is almost constant. The response spectra of the horizontal in-structure motions exhibit a peak at the predominant horizontal frequency of one Hertz and indicate effective filtering of the ground motions at higher frequencies.

The following paragraphs discuss the special considerations in the design of the Aseimic Bearing isolation concept.

INDUCED TILTING AND ROCKING MOTIONS

Effects of traveling waves which impose tilting and rocking motions on the foundation mat were investigated. The tilting and rocking motions were evaluated by imposing varying vertical and horizontal time histories of motion at the support points of the lower mat consistent with the velocity of propagation of the seismic wave. The soil-structure interaction was represented by Higher Order Winkler springs (Hall et al., 1979) so as to assure correct prediction of horizontal, vertical, and rocking response simultaneously. The structural response obtained on the basis of the traveling wave assumption was compared with that obtained from the traditional assumption of vertically propagating body waves.

The study indicates that, for the cases examined, the response calculated using the traveling wave assumption is approximately equal to that calculated by the body wave assumption.

INDUCED TWISTING AND TORSIONAL MOTIONS

Relative twisting of the upper and lower rafts arising due to dynamic eccentricity, differences in the centers of gravity of structures and the seismic bearing pads, the passage of Love waves, and the spatial variations in the physical properties of the pads both in a patterned and a random fashion has been considered in the computation of the response of the structures on the Nuclear Island.

The torsional effects due to the above factors were evaluated by imposing on the structure rotational time histories consistent with each factor. The torsional response was computed using a single mass representation of the Nuclear Island structures. Maximum horizontal acceleration and relative displacements at the ends of the mat were obtained by a rigid body translation of the rotational response.

It has been concluded that the contribution to horizontal motion from twisting is about one to two orders of magnitude smaller than that from the translational motion of the raft.

EFFECTS OF UNEVEN SETTLEMENT OF BOTTOM RAFT

A differential settlement of the bottom mat causes (1) a redistribution of the vertical loads on the pads and (2) a rotation of the slippage plane for each individual pad.

Analyses have shown that the two phenomena will not affect the overall seismic response of the Nuclear Island structures. The rotation of the slippage plane is tantamount to increasing the effective coefficient of friction in one direction and decreasing it in the other. An angular rotation of about 1×10^{-3} radians causes a change in the effective coefficient of friction of ± 0.5 percent; i.e, for a friction coefficient of 0.2, the rotation results in an effective coefficient of 0.199 in one direction and 0.201 in the other. This angle corresponds to a differential settlement of about 10 centimeters in a length of 100 meters,corresponding, typically, to total settlement of 20 to 30 centimeters.

CRITICAL PIPELINE CONNECTIONS

The "critical pipes" serving the systems, such as the Essential Service Water system and the Fire-Fighting Water Distribution system which have supports both in the isolated and the non-isolated plant structures, have been designed to accommodate differential displacements between the Nuclear Island and the adjacent structures. The design incorporates articulated joints in the lines which permit anticipated differential movements without undue distress.

SAFETY BEYOND DESIGN EARTHQUAKE

In a conventional design, additional safety is derived from the ability of the structure to deform in the inelastic range, thereby absorbing the earthquake energy should the design earthquake be exceeded. Since the aseismic design precludes the inelastic action of the structure, the ABP's must be designed to assure continued performance in the event that the design earthquake is exceeded.

In the present design where the SSE was established as 0.3 g, the dimensions of the friction plates have been determined so as to confer to the system a slippage ability (allowable slippage of 27.5 centimeters) enabling it to sustain the design earthquake and its possible aftershocks as derived from a statistical study of the seismotectonic regime of the site.

Maximum total displacements for a range of values of ground acceleration are shown as a curve of displacement versus horizontal ground acceleration in Figure 3. These values were obtained using Artificial Time Histories matching the Regulatory Guide 1.60 Response Spectra. It is seen from the figure that the ABP's including the friction elements can sustain an event producing 0.45 g horizontal peak acceleration without exceeding the allowable relative displacement between the rafts of 27.5 centimeters.

Based on a statistical analysis of the seismic response of the Nuclear Island for several real earthquake records, the maximum total displacement, which is the sum of the elastic distortion of the neoprene and the slippage on the friction surface, has been obtained for the plant frequency of one Hertz as a function of peak ground acceleration normalized on the basis of the USNRC Regulatory Guide 1.60 response spectrum.

Relationships between maximum total displacement and peak ground acceleration were also compared with the results of a study by Newmark and Riddell (1979) who studied the dynamic response of non-linear systems subjected to earthquake excitation. In these calculations, the yield displacement was taken as five centimeters corresponding to a frequency of the Nuclear Island of one Hertz and a friction coefficient of 0.2. Damping was assumed to be 5 percent and the ductility factor was varied from two to eight to obtain total displacements varying from 10 to 40 centimeters. Only the elastoplastic case was investigated since this best describes the behavior of the ABP's.

The mean values of maximum total displacement obtained from the present study are compared in Figure 4 and are in good agreement with those of Newmark and Riddell based on deamplification factors, ϕ_μ, for the velocity region.

SUMMARY AND CONCLUSIONS

The aseismic foundation scheme analyzed herein has been evaluated for seismic motions defined by the USNRC Regulatory Guide 1.60. On the basis of analytical models comprising distributed parameters for soil, non-linear slippage elements for the ABP's, and mass and stiffness matrices for the Nuclear Island structures, it has been shown that using this concept of isolation, structures designed for 0.3 g could sustain horizontal ground motions of about 0.4 g. The ABP concept does not isolate vertical motion but does decouple horizontal and rocking motion with a consequential reduction in vertical motion.

Special considerations with respect to the aseismic design, such as effects of traveling waves, differential settlements, and earthquakes in excess of the design earthquake, have been investigated. The slippage elements and the piping connections can accommodate the expected relative motions between the upper and lower rafts without undue distress.

Extending the concept to sites with postulated horizontal ground motion in excess of 0.4 g is feasible although further confirmatory studies may be required.

ACKNOWLEDGMENT

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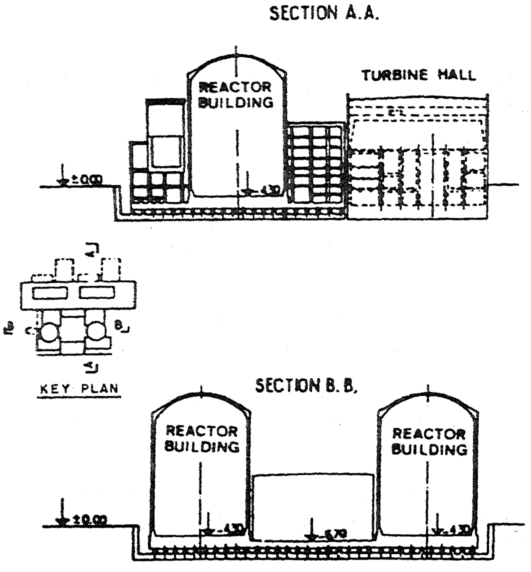

FIGURE 1 — STRUCTURAL CONFIGURATION

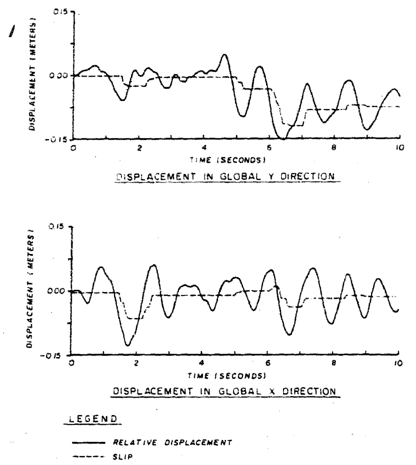

FIGURE 2 — RESULTS OF NON-LINEAR TIME DOMAIN ANALYSIS

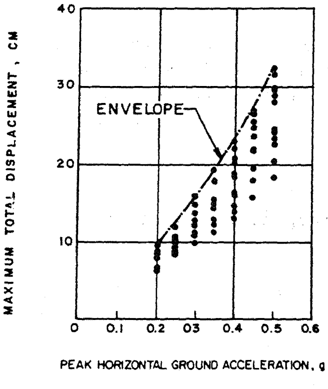

FIGURE 3 - MAXIMUM DISPLACEMENT VS. PEAK GROUND ACCELERATION SYNTHETIC TIME HISTORY

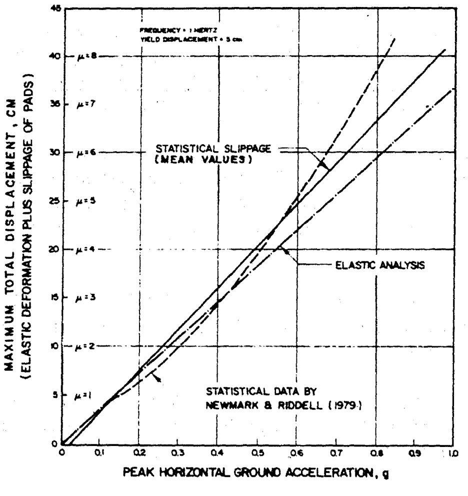

FIGURE 4 - MAXIMUM DISPLACEMENT VS. PEAK GROUND ACCELERATION REAL TIME HISTORY