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Analysis of High-Frequency Seismic Effects

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ABSTRACT

This paper presents results of a project conducted for the Electric Power Research Institute (EPRI) to investigate the potentially damaging effects of high-frequency seismic ground motions on nuclear power plant (NPP) components (Reed et al., 1991). The study was performed to develop a rational procedure for reducing input to high-frequency components which are being evaluated for earthquake response spectra rich in high-frequency energy. The final results from the study are intended for use in the Individual Plant Examination for External Events (IPEEE) to resolve NRC Severe Accident Policy (SAP) issues. In addition, the results will be useful for developing site-specific design response spectra that are based on uniform hazard spectra (UHS) with significant high-frequency energy.

1 INTRODUCTION

The results of recent seismic hazard analyses conducted for the eastern U.S.(EUS) indicate that UHS have relatively large high-frequency spectral acceleration content above approximately 10 Hz. This is in contrast to typical NPP design or seismic margins-type input, such as the NRC Regulatory Guide (R.G.) 1.60 or NUREG/CR-0098 ground response spectra. However, these same UHS have significantly lower spectral acceleration content at the low-frequency end of the response spectrum (i.e., between about 1 and 10 Hz), which indicates to the seismic engineering community that these motions are less damaging than traditional design or evaluation-type input.

Uniform hazard spectra are in sharp contrast to typical plant design or evaluation spectra which have been used in the past by engineers to assess the seismic safety of nuclear power plants. Design response spectra for all EUS nuclear power plants since the mid-1960's do not have significant energy in the high frequencies. These design spectra have their peak spectral accelerations at frequencies less than 10 Hz and typically return to the peak ground acceleration at frequencies between 30 and 40 Hz. The shape of these design spectra is based upon the characteristics of western North America (WNA) earthquake ground motions which have been of sufficient amplitude to be potentially damaging to engineered structures and/or equipment.

Most nuclear power plant structures have fundamental frequencies in the 1 to 10 Hz range and have sufficient interstory drift capacity to drop their effective frequency below 4 Hz before severe distress will develop. Based upon nonlinear studies such as presented in Kennedy et al. 1984 and 1988 and other similar studies, it is widely accepted among knowledgeable engineers that ground motion must have substantial spectral acceleration content in the 1 to 4 Hz range to be potentially damaging to nuclear power plant structures, and that higher spectral accelerations at frequencies in excess of about 10 Hz are of little or no interest in the design of such structures, unless a very severely poorly designed and constructed link exists within the structure.

Most equipment within a nuclear power plant has fundamental frequencies in the 5 to 25 Hz range. Some analysts compute equipment fundamental frequencies substantially in excess of 25 Hz. However, this situation occurs only when the analyst has either ignored or mistakenly estimated the flexibility of the attachment of the equipment to the structure. It is nearly impossible to mount a piece of equipment sufficiently rigidly in a structure to produce a fundamental frequency substantially in excess of 25 Hz at high shaking levels, unless the equipment has trivial mass and thus is not vulnerable to seismic-induced distress (relay chatter may be an exception). Thus, for equipment, the primary concern is spectral accelerations up to about 25 Hz.

All but the most brittle equipment has sufficient distortion capability to quickly drop its effective frequency to well below 25 Hz before it is severely damaged. In most cases, the attachment of the equipment to the structure must undergo a minimum distortion of at least 0.06 to 0.12 inches before its load transfer capability is fully mobilized.

Even if all of the distortion is concentrated into a single element, this element will not fail if its distortion capability exceeds the spectral displacement of the input motion at the effective frequency of the equipment. Since the weak-link elements of most items of rugged industrial equipment can accommodate distortions of at least 0.1 inch, spectral accelerations of less than 1g at frequencies of 10 Hz and greater are unlikely to result in equipment failure. Therefore, it is reasonable to conclude that the damaging frequency range for most items of equipment is less than 10 Hz, with the exception of relay chatter during the shaking.

A more critical potential exception occurs when a very strong piece of equipment is attached to the supporting structure through a stiff but weak anchorage. In this case the entire load path except for the anchorage remains elastic, and all of the nonlinear distortion must be accommodated within the weak anchorage. Based upon a review of common anchorage schemes, it was concluded that fillet welds loaded transverse to the welds represented the anchorage approach with the least distortion capability.

The ground motion response spectrum estimated from seismological studies represents the elastic response of simple oscillators mounted on a small lightweight pad on the free ground surface. These are not the motions "seen" by a large massive structure founded on a substantial size basemat. Comparison of response spectra obtained from motions measured on the basemat of large structures with those obtained from motions measured on small lightweight pads show substantial differences, particularly at frequencies in excess of 5 Hz (for instance, see Chang et al. 1986). At frequencies of 10 Hz and greater the spectral accelerations obtained on the basemat of large structures are often more than a factor of two less than those obtained on a small pad at the free ground surface. This is due to spatial variation and incoherence of the ground motion.

High-frequency incoherency reduction factors should be applied in addition to the inelastic-energy-absorption reduction factors described in this paper. In fact, an incoherency reduction factor should be applied first, since it represents a reduction in the motion input to the structure and to equipment mounted therein. Then, the inelastic-energy-absorption correction factor as discussed in the following should be applied to this reduced motion.

2 MOTIVATION FOR CURRENT STUDY

Most high-frequency components in nuclear power plants are very strong. If components have high fundamental frequencies (i.e., relatively stiff compared to their mass) they also have high strength, since stiffness and strength are correlated. In addition to being strong most high-frequency components in nuclear power plants also have ample ductile capacity to resist the small displacements associated with high-frequency motions. Examples include the casing on a vertical pump motor and the exterior shell on a small heat exchanger. These types of components are also ductile, and small displacements associated with high-frequency motions can be safely accommodated if the yield capacity is exceeded.

A class of high-frequency components which have potentially limiting capacities are stiff electrical cabinets supported at their base, where the anchorage system is potentially the weak link (e.g., welded or secured with expansion anchors). An investigation was performed to find examples of real electrical cabinets which have high fundamental frequencies based on actual testing (i.e., 15 Hz and higher). However, the high-frequency cabinet examples which were found had very strong stiff supports (overstrength welds or anchor bolts).

In this study a limiting capacity case is postulated where an electrical cabinet is assumed to have a high fundamental fixed-base frequency, and the anchorage is sized exactly to resist the input earthquake. The total structural system, including the cabinet and anchorage, has a fundamental frequency lower than the fixed-base frequency, and in some cases may no longer be classified as a "high-frequency" component. In any case, the anchorage strength was no larger than required to resist the design earthquake. From this viewpoint limiting components can be thought of as having high fixed-base frequencies (i.e., 10 Hz and higher) with minimum strength anchorage. This class of components was assumed to represent the critical case for all high-frequency nuclear power plant components and was investigated in detail. In general, the models analyzed in the high-frequency study are very conservative relative to the general population of high-frequency components found in nuclear power plants.

The only source of non-linear behavior which was assumed to occur in the study was the anchorage system at the cabinet base. Other factors which would also reduce the load on the anchorage system include the following:

- Non-linear response in the cabinet (e.g., buckling in the side panels or local flexibility in the cabinet material near the anchorage)
- Non-linear response at the connection between the electrical devices and cabinet shell
- Non-linear response in the devices themselves
- Reduction to high-frequency motions in nuclear power plant structures caused by incoherence of the ground motion (see discussion above)

These sources of reduction exist for real electrical cabinets; however, it was conservatively assumed in the study that all potential non-linear behavior is concentrated in the equipment anchorage. This assumption allowed the study to be focused on systematically investigating the various parameters that influence the results. The disadvantage of this approach is that the additional margin which exists for high-frequency components was not quantified.

It was determined early in the investigations that welded anchorages are more brittle than bolted anchorages. Expansion anchors have ultimate displacement capacities in the range of approximately 0.1 to 0.5 inches, while small fillet welds loaded in shear were found to have corresponding capacities in the range of about 0.01 to 0.1 inches. It is clear from the results of this study, and past investigations Kennedy et al. 1984, that seismic capacity is limited by the displacement capacity of the weakest element. Thus, all the analyses were performed assuming welded anchorages. This represents another source of conservatism in the study.

The effect of nonlinear anchorage distortion is to lower the effective frequency of the equipment and to increase the energy dissipation capability Kennedy et al. 1984. Both effects are commonly defined in terms of a ductility scale factor (also called inelastic energy absorption factor), F_μ, by which the elastic computed demand (spectral acceleration demand) can exceed the yield capacity (spectral acceleration capacity) without failure. Then, to maintain a consistent margin of safety, the elastic spectral accelerations for an evaluation earthquake input Sa_e associated with a fixed-base frequency f_f and damping β_f should be reduced by a ductility scale factor F_μ, to obtain a reduced spectral acceleration Sa_r. Thus:

$$Sa_r = \frac{Sa_e}{F_\mu}$$

Note that F_μ also is dependent on f_f and β_f, as well as on other parameters.

For a 5 Hz piece of equipment subjected to ground motion, the lowering of the effective frequency and increase in energy dissipation due to a 0.01 inch anchorage distortion is negligible, because the elastic distortion of the 5 Hz piece of equipment is many times greater than 0.01 inch. Thus, at 5 Hz, F_μ is approximately equal to 1.0 and there is no benefit from inelastic anchorage distortion. Therefore, engineers have come to treat anchorages as "brittle" and have traditionally defined design spectral acceleration as being equal to the elastic spectral acceleration.

However, for a 25 Hz piece of equipment, the lowering of the effective frequency and increase of energy dissipation due to a 0.01 inch nonlinear anchorage distortion is substantial because such a nonlinear distortion is no longer small when compared to the elastic distortion of the equipment. For EUS UHS both the lowering of the effective frequency and the increasing of energy dissipation associated with a 0.01 inch nonlinear distortion are substantial. The net effect is that F_μ is significantly greater than unity, and the evaluation spectral acceleration at 25 Hz should be much less than the elastic EUS UHS at 25 Hz. However, for WNA ground motions the lowering of the effective frequency below 25 Hz actually increases the spectral acceleration input, which counters the benefit gained from the increased energy dissipation, and F_μ is again close to unity.

Because, in the past, NPP design response spectra have always been low-frequency content spectra, and because small nonlinear distortions such as 0.01 inch do not produce an F_μ significantly greater than unity for such spectra, even at 25 Hz, engineers have typically not modified such spectra. However, when dealing with a high-frequency content EUS UHS, this spectrum should be modified by the appropriate F_μ associated with at least some minimal nonlinear distortion such as 0.01 inch. Making such a modification will produce spectra more similar in shape to the design spectra which have been used in the past. The recommended procedure for calculating F_μ is given in Reed et al. 1991.

3 RECOMMENDATIONS FOR REDUCING GROUND RESPONSE SPECTRA

It is recommended that spectral reduction factors used to reduce an evaluation or a design response spectrum for analyzing high-frequency components be obtained using the simplified sliding model presented in Reed et al. 1991. The following guidance is given when applying this recommendation:

1. The reduction should be performed for frequencies above 10 Hz, and the reduced response spectrum should be reconnected to the evaluation spectrum at 8 Hz.

2. The reduced response spectrum should not be reduced below a response spectrum value equal to the peak evaluation spectral acceleration at 10 percent damping divided by 1.6, or the elastic spectral acceleration at frequencies greater than that at which the elastic spectrum peaks, whichever is less, unless additional cases are considered as discussed in Reed et al. 1991.

3. In the evaluation mode for equipment mounted at the ground the minimum safety margin, F_{SM}, should be equal to 1.5, and for equipment up in a building F_{SM} should be 3.0.

   In the design mode for equipment mounted at the ground F_{SM} should be equal to 2.0 and for equipment up in a building F_{SM} should be 4.0.

A minimum weld size of 3/16-inch weld should be used to develop the reduction factors. It is assumed in selecting a 3/16-inch weld that there may be 1/8-inch welds used to attach the sides of electrical cabinets to embedded floor plates. However, there are other sources of flexibility in this type of component that are equivalent to the models used in the high-frequency study which assumed 3/16-inch welds. Thus, the use of a 3/16-inch weld size also represents these cases. For plants where the minimum weld size is larger than 3/16-inch, it may be possible to base the spectrum reduction factors on the actual minimum weld size used in the plant. However, the capacity of electrical cabinets anchored with nominal welds in the plant must be considered in justifying a larger weld size.

The analyst should realize when performing a seismic margin analysis (SMA) evaluation using reduced response spectra as input that the portion of the reduced response spectrum above 8 Hz takes credit for ductile capacity.

Figure 1 shows example reduced ground response spectra for a rock site UHS anchored to 0.3 g pga based on the sliding model following the above recommendations. The spectra based on F_{SM} values of 1.5 and 3.0 and would be used for an SMA evaluation for equipment at the ground and for developing in-structure response spectra, respectively.

The spectra in Figure 1 based on F_{SM} of 2.0 and 4.0 are examples of reduced spectra for use in design where the required minimum design to yield margin is determined to be 2.0. The reduced response spectrum corresponding to F_{SM} equal to 2.0 would be used for design of equipment mounted at the ground and the top one (i.e., F_{SM} equal to 4.0) would be used for developing in-structure design response spectra.

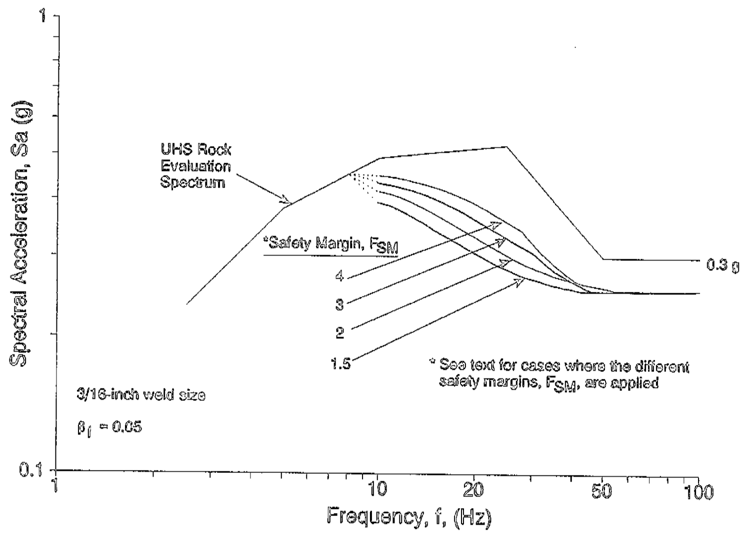

Figure 1 Example Reduced Response Spectra for Rock UHS Anchored to 0.3 g PGA.

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