Seismic Directionality Effects on In-Structure Response Spectra in Seismic Probabilistic Risk Assessment

S. Jarernprasert, E. Bazan-Zurita, P. C. Rizzo

Abstract—Currently, seismic probabilistic risk assessments (SPRA) for nuclear facilities use In-Structure Response Spectra (ISRS) in the calculation of fragilities for systems and components. ISRS are calculated via dynamic analyses of the host building subjected to two orthogonal components of horizontal ground motion. Each component is defined as the median motion in any horizontal direction. Structural engineers applied the components along selected X and Y Cartesian axes. The ISRS at different locations in the building are also calculated in the X and Y directions. The choice of the directions of X and Y are not specified by the ground motion model with respect to geographic coordinates, and are rather arbitrarily selected by the structural engineer. Normally, X and Y coincide with the "principal" axes of the building, in the understanding that this practice is generally conservative. For SPRA purposes, however, it is desirable to remove any conservatism in the estimates of median ISRS. This paper examines the effects of the direction of horizontal seismic motion on the ISRS on typical nuclear structure. We also evaluate the variability of ISRS calculated along different horizontal directions. Our results indicate that some central measures of the ISRS provide robust estimates that are practically independent of the selection of the directions of the horizontal Cartesian axes.

Keywords—Seismic, Directionality, In-Structure Response Spectra, Probabilistic Risk Assessment.

I. INTRODUCTION

FOR use in SPRA, the calculation of In-Structure Response Spectra involves the following tasks:

1. Seismic hazard analyses to define the seismic ground motion in terms of the frequency of exceedance during a prescribed period;
2. Site response analysis provide the site free field horizontal ground motion response spectra (GMRS) at the outcropping bedrock;
3. Development of a structural model;
4. Seismic dynamic analyses to calculate time histories of floor accelerations; and
5. Calculation of ISRS for specified damping ratios and frequency range.

In the horizontal plane, coordinate X and Y axes are utilized to define 1) the building geometry, 2) the orientation of the horizontal components of the seismic input, and 3) the directions to output horizontal ISRS. The choice of a particular orientation for X and Y is somewhat arbitrary and

depends on the judgment of the analyst, but often corresponds to the sides of the building rectangular footprint. However, it is equally appropriate to use any other set of X-Y axes rotated within the horizontal plane. This study focuses on steps 4 and 5, and aims to assess the effects of changing the direction of horizontal motion on ISRS at a prescribed direction.

II. SEISMIC INPUT

The seismic hazard analyses and the site response analysis provide the site free field horizontal ground motion response spectra (GMRS) at the outcropping bedrock. The GMRS selected for this study is based on the EPRI 2004-06 ground motion models [1], [2] and updated Central and Eastern United States (CEUS) seismic source characterization [3]. The GMRS develops uniform hazard spectra following the guidelines in RG 1.208 [4], and represents an equal risk foundation input response spectrum (FIRS) at the building foundation level.
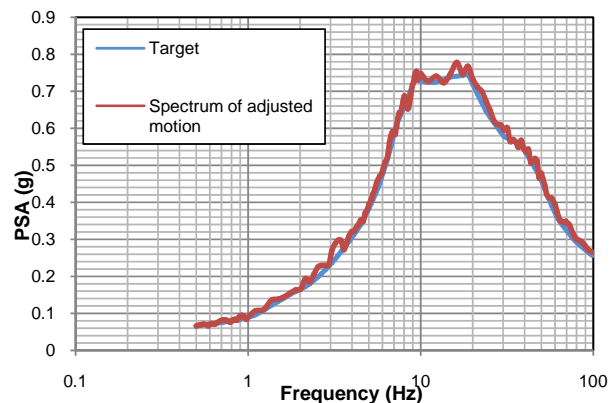

Fig. 1 Comparison of computed spectrum to the target spectrum

We consider only horizontal ground motion, because our interest is to assess the effects of changing systematically the directions of horizontal seismic input. For input to the dynamic analyses, the ground motion is represented by a synthetic time history in the horizontal direction. This time history was developed based selected seed records adjusted iteratively using wavelet functions so that the response spectrum of the resulting time history matches the target FIRS shown on Fig. 1. The matching is consistent with the criteria in NRC's Standard Review Plan (SRP) Section 3.7.2 [5]. This FIRS corresponds to a soft rock site with shear wave velocity of about 5000 ft/s. However, because the dynamic analyses are limited to elastic behavior, our conclusion should hold for

S. Jarernprasert is with Rizzo Associates, Inc., Pittsburgh, PA 15235 USA (phone: 66-91-832-1550; e-mail: eakcmu@gmail.com).

E. Bazan-Zurita and P. C. Rizzo are with Rizzo Associates, Inc., Pittsburgh, PA 15235 USA (e-mail: enriquez.bazanz@rizzoassoc.com, paul.rizzo@rizzoassoc.com).

other spectra and time histories.

III. STRUCTURAL MODELS

We have use three-dimensional finite element models of the building selected for our study. However, our observations and conclusions should hold for simpler structural models. Since fragility evaluations are based on the median response, the structural models were developed using median values of structure stiffness, mass and damping characteristics. Criteria in the American Society of Civil Engineers (ASCE) Standards 4-13 [6] and 43-05 [7] were utilized in developing the finite element models using the computer code SAP2000 [8].

IV. ISRS CALCULATION

Seismic responses of each structure were calculated utilizing step-by-step modal synthesis using finite element models. The numbers of modes used in the analyses were sufficient to yield total modal mass participations of at least 99 percent in the two directions of analyses. The same time history was used separately as seismic input in two horizontal orthogonal directions. For each of the two components of ground motion, time histories in the X and Y horizontal axes were obtained at representative points on the floors of the structures. The time histories were used to calculate in-structure response spectra (ISRS) at the selected points on the floors. Five percent of critical damping was used in the calculation of the ISRS. This effort produces four spectra at each selected point. The two co-directional spectra (one for each direction of ground motion) were combined by the SRSS rule following the criteria of Regulatory Guide 1.92, "Combining Modal Responses and Spatial Components in Seismic Response Analysis," by the Nuclear Regulatory Commission [9]

V. EFFECTS OF DIRECTIONS OF SEISMIC INPUTS

To account for uncertainty in the directionality of the horizontal input motion, we have calculated the ISRS along prescribed (original) X and Y directions with the seismic input also in the X and Y directions. Then, the ISRS along X and Y has been re-calculated by rotating the input acceleration in increments of 10 degrees from 0 to 90 degrees. Fig. 2 shows the resulting ISRS in the X direction due to a component of horizontal earthquake motion applied at an angle α with the original X axis. As anticipated, these ISRS exhibit very significant differences. The same conclusion is extracted from Fig. 3 depicting the ISRS in the X direction due to a component of horizontal earthquake motion applied at an angle α with the original Y axis (equal to an angle $\beta = \alpha + 90$ with respect to the X axis).

Nevertheless, the spectra obtained from separate application of two orthogonal components of ground motion must be combined following the criteria of Regulatory Guide 1.92 [9]. The most widely used procedure in practice is the so called SRSS (square root of the sum of squares). The ISRS resulting from the application of this rule are presented in Fig. 4. It is remarkable that practically no differences occur in the

combined ISRS due to changes in the direction of application of the horizontal components of ground motion. These results indicate that the ISRS in a prescribed direction due to the combined effects of two component of horizontal ground motion is insensitive to the selection of horizontal axes used to apply the seismic input.
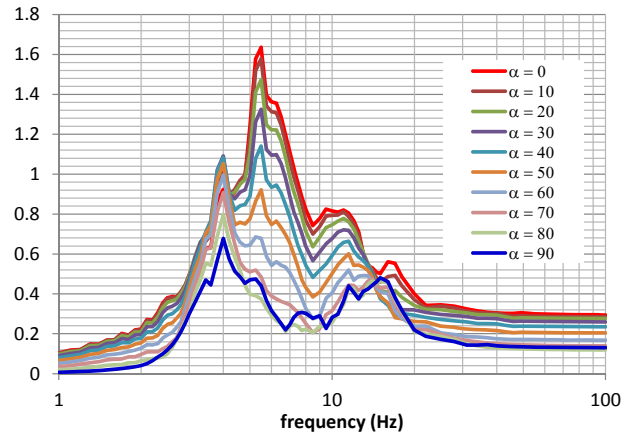

Fig. 2 ISRS in the Original X-Direction due to a Horizontal Component of Ground Motion Applied at an Angle a with Respect to the X Axis
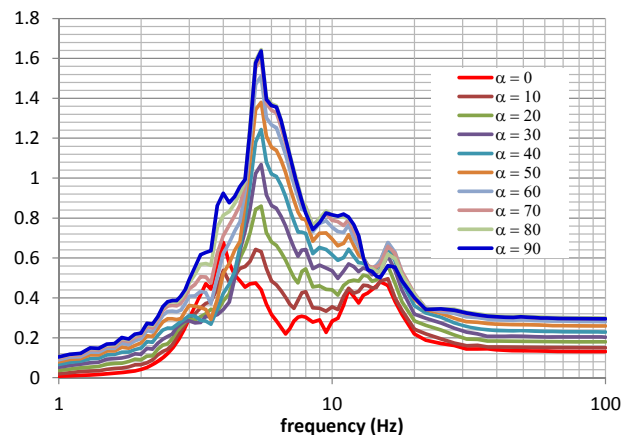

Fig. 3 ISRS in the Original X-Direction due to a Horizontal Component of Ground Motion Applied at an Angle a with Respect to the Y Axis

VI. EFFECTS OF DIRECTIONS OF ISRS CALCULATION

To examine the effects of the direction where the horizontal ISRS are calculated we have calculated ISRS corresponding to a horizontal direction that forms an angle α with the original Y axis. Again, the angle varied in increments of 10 degrees from 0 to 90 degrees. Fig. 5 shows the resulting ISRS in the various directions due to a component of horizontal earthquake motion applied in the original direction X. Similarly, Fig. 6 shows the resulting ISRS in the same direction as before but due to a component of horizontal earthquake motion applied in the original direction Y. The ISRS in both figures show substantial differences.
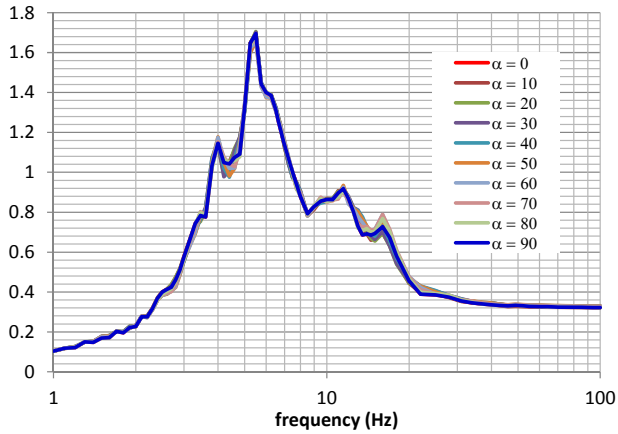
Fig. 4 ISRS in the Original X-Direction due to Two Horizontal Components of Ground Combined with the SRSS Rule
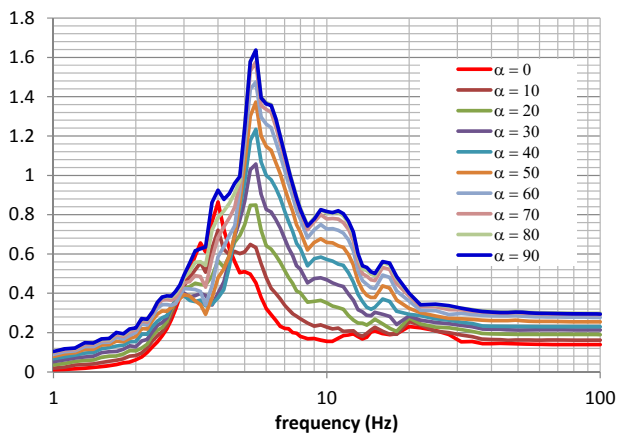

Fig. 5 ISRS along an Angle α with Respect to the Original Y Axis due to a Horizontal Component of Ground Motion Applied along the Original X Axis
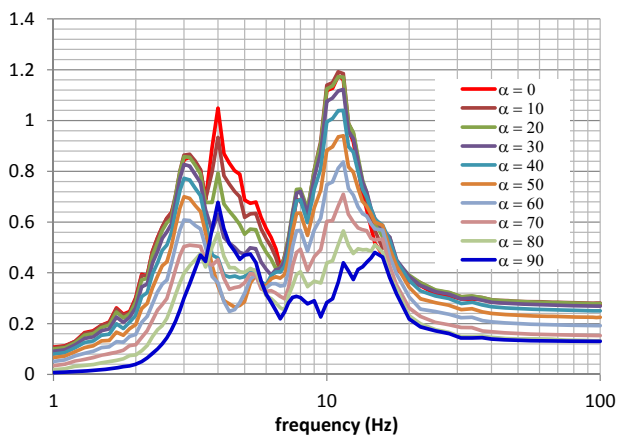

Fig. 6 ISRS along an Angle α with Respect to the Original Y Axis due to a Horizontal Component of Ground Motion Applied along the Original Y Axis

Again, the spectra obtained from separate application of two orthogonal (X and Y) components of ground motion have been combined the SRSS rule. The combined ISRS are presented in Figs. 7 and 8. This time, very appreciable differences appear due to changes in the direction of calculation of the horizontal ISRS.
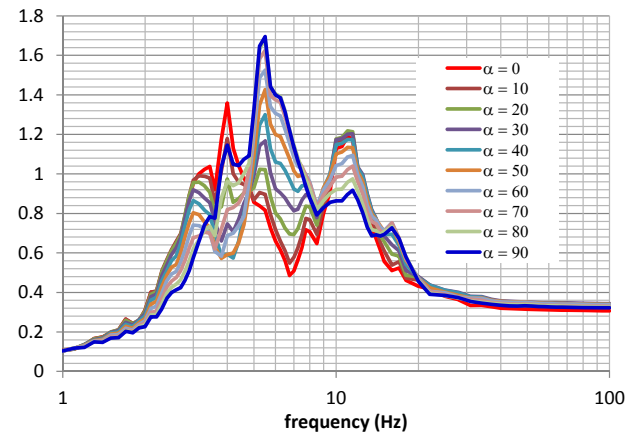

Fig. 7 ISRS along an Angle α with Respect to the Original Y Axis due to Combined Horizontal Two (Original X-Y) Components of Ground Motion
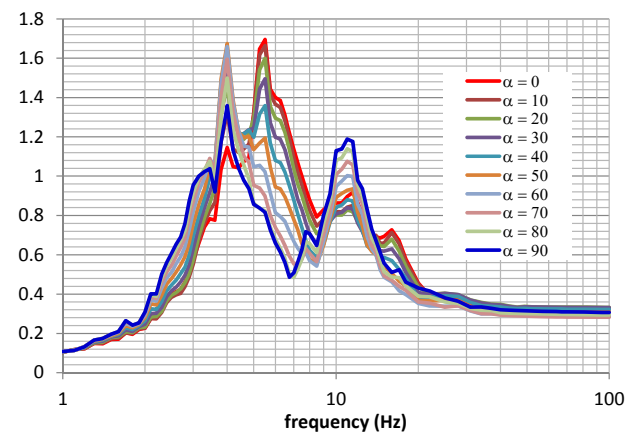

Fig. 8 ISRS along an Angle α with Respect to the Original X Axis due to Combined Horizontal Two (Original X-Y) Components of Ground Motion

VII. OPTIONAL IN-STRUCTURE RESPONSE SPECTRA

Typically, the X and Y direction ISRS are applied in the equipment longitudinal and transverse direction to extract the worst loading case. Our previous results show that ISRS are relatively insensitive to the definition of the coordinate axes used to define the seismic input. However, for a given set of input motions, the ISRS calculated along different orientations, e.g. equipment local longitudinal and transverse directions are expected appreciably different. A sufficiently robust methodology should be envisaged to minimize the impact of subjective choices for the orientation of axes for output ISRS. In this regard, alternate definitions of ISRS are proposed in the following paragraphs.

A. Resultants ISRS

Because accelerations are vector quantities, a "resultant" spectrum can be defined as the square root of the sum of squares of the two orthogonal components. It is noted that because the maximum components accelerations are unlikely to occur simultaneously, the resultant spectra developed in this manner are somewhat conservative. We have calculated the "resultant" of the ISRS presented in Figs. 7 and 8. The results, depicted in Fig. 9, show that the "resultant: ISRS are insensitive to the direction selected to calculate the individual ISRS.
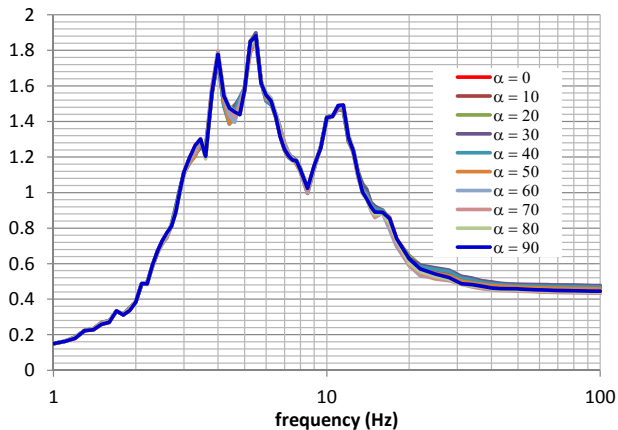

Fig. 9 "Resultant" of two Orthogonal ISRS along an Angle α with Respect to the Original X Axis due to Two Combined Horizontal Components of Ground Motion
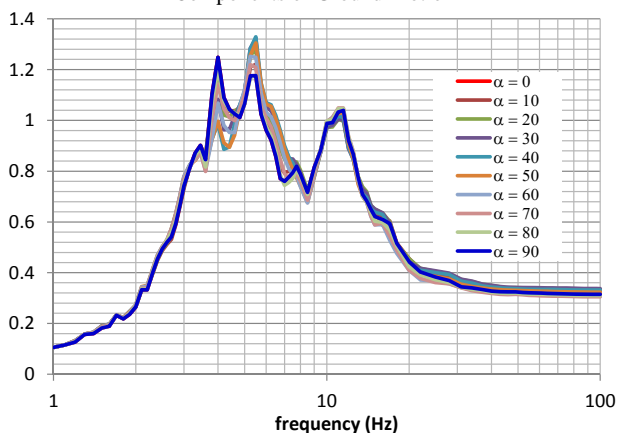

Fig. 10 Geometric Mean of two Orthogonal ISRS along an Angle α with Respect to the Original X Axis due to Two Combined Horizontal Components of Ground Motion

A. Mean ISRS

We have also calculated the geometric mean of the ISRS presented in Figs. 7 and 8. The results, depicted in Fig. 10, show that the geometric mean ISRS are also insensitive to the direction selected to calculate the individual ISRS. Again, there is excellent agreement between results for different angles of calculation of ISRS demonstrating geometric mean spectra also remain practically unchanged regardless of the axes orientation. It is also noticeable the closeness of the

shapes of the ISRS in Figs. 9 and 10 showing very close agreements in the location of peaks and of the relative values for all frequencies. In fact, not shown herein for brevity, the mean spectra are practically identical to the resultant spectra divided by the square root of 2. This means that the decomposition of the resultant spectra in two equal orthogonal components is an excellent estimate of the geometric mean spectra.

VIII. CONCLUDING AND REMARKS

The results of the study reported here indicate that the use of "resultant horizontal ISRS" (based on X and Y direction ISRS) would offset the effects of directional uncertainties. The results presented in this paper, as well as other conducted with different ground motions and different buildings, demonstrate that the resultant ISRS are practically insensitive to the orientation of coordinate axes selected for analysis. The above result suggest the possibility of using the resultant ISRS or its equal orthogonal components (resultant divided by square root of 2) for use in the calculation of component fragilities. The equal orthogonal components provide a very good estimate of the average horizontal ISRS. The results presented above are based on fixed base analysis. However, analyses of some building with significant soil structure interaction effects are consistent with our conclusions. We trust that these conclusions will be substantiated by additional confirmatory analyses.

REFERENCES

[1] EPRI, 2004, "CEUS Ground Motion Project Final Report: TR 1009684 2004, Electric Power Research Institute, December 2004.
[2] EPRI, 2006, "Program on Technology Innovation: Truncation of the Lognormal Distribution and Value of the Standard Deviation for Ground Motion Models in the Central and Eastern United States," TR 1014381, Electric Power Research Institute, August 2006.
[3] NRC, 2012, NUREG-2115, "Central and Eastern United States Seismic Source Characterization for Nuclear Facilities," Nuclear Regulatory Commission, 2012.
[4] NRC, 2006, Regulatory Guide 1.208, "A Performance-Based Approach to Define The Site-Specific Earthquake Ground Motion," Nuclear Regulatory Commission, March 2007.
[5] NRC, 2007, NUREG-0800 "Standard Review Plan Section 3.7.2 - Seismic System Analysis", Nuclear Regulatory Commission, March 2007.
[6] ASCE, 2013, "Seismic Analysis of Safety-Related Nuclear Structures," Standards ASCE 4-13, American Society of Civil Engineers, 2013.
[7] ASCE, 2005, "Seismic Design Criteria for Structures, Systems and Components in Nuclear Facilities," ASCE/SEI Standard 43-05, American Society of Civil Engineers, 2005.
[8] CSI, 2007, "Reference Manual for SAP – Version 14," Computers and Structures, Inc., 2007.
[9] NRC, 2006, Regulatory Guide 1.92, "Combining Modal Responses and Spatial Components in Seismic Response Analysis," Nuclear Regulatory Commission, July 2006.