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Probabilistic Vector-Valued Ground Motion Intensity Measures and Engineering Demand Measures for the PEER Van Nuys Holiday Inn PBEE Testbed

Collaborative Project between SCEC and PEER

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Introduction

In a joint SCEC-PEER project that is now nearing completion, the P.I.'s, in collaboration with Professor Allin Cornell of Stanford University, have developed the capability to perform probabilistic vector-valued hazard calculations, and applied that capability to evaluation of the nonlinear dynamic response of the Van Nuys Holiday Inn, one of the PEER Testbeds for Performance Based Seismic Engineering. The use of vector-valued hazard is expected to improve the accuracy and the efficiency of prediction of building response. The project is being performed within the context of the PEER PBE Methodology Testbed Program, specifically, the Van Nuys Holiday Inn Testbed. In this program, ground motions are being specified using the conventional scalar-valued hazard approach. The goal of this project is to concurrently test the application of vector-valued hazard to this project, and compare its efficacy with that of the standard scalar-valued hazard approach.

Scalar-Valued Ground Motion Hazard

Conventional probabilistic seismic hazard analysis provides the annual frequency of occurrence of only one ground motion intensity measure at a time, so we refer to it as scalar-valued PSHA. The intensity measure is usually a peak value or a response spectral value. Although PSHA often produces a probabilistic response spectrum that is defined at multiple periods, these are independent estimates whose joint probability of occurrence is not defined.

Vector-Valued Ground Motion Hazard

The objective of vector-valued probabilistic seismic hazard analysis (VPSHA) is to provide the annual frequency of the joint occurrence of more than one ground motion intensity measure. This approach should prove superior when the response of a structure to ground shaking is strongly dependent on more than one ground motion intensity measure. For example, higher modes contribute significantly to the response of tall structures; for them, specifying the joint frequency of occurrence of spectral accelerations having specified levels at the fundamental mode and at the first higher mode will provide a more accurate representation of the response of the structure.

PEER Methodology Testbed Program

The PEER Testbeds are real facilities to which PEER performance based earthquake engineering assessment (PBEE) and design methodologies are being applied. The primary focus of the Testbeds is to assess the applicability of the methodologies and to foster their refinement. The testbeds will serve supplementary purposes such as focusing and integrating the research, promoting multidisciplinary research interactions, emphasizing systems level research, and involving interested earthquake professionals and decision makers.

The focus of this project is on the Van Nuys Holiday Inn testbed. This building was chosen because it was damaged by both the 1971 San Fernando and 1994 Northridge earthquakes. It is a non-ductile concrete moment frame building, a category of structures whose seismic safety has been of major concern for some time.

The PEER Methodology involves the following four steps:

- Select Intensity Measures, IMs (e.g. response spectral acceleration for fundamental and first mode period of building, or directivity pulse period and amplitude)
- Select Engineering Demand Parameters, EDPs (e.g. inter-story drift: the relative horizontal displacement of adjacent floors of a building))

- Select Damage Measures and Decision Variables (e.g. collapse; down time)
- Document the Detailed Analysis Methodology

The focus of this project is on the first two areas, namely the ground motion intensity measures and the engineering demand parameters, and their relationship.

Results

An approach to vector-valued probabilistic seismic hazard analysis, and its application to probabilistic engineering demand analysis, was developed by Bazzuro, Shome, and Cornell, and reported recently in Bazzurro and Cornell (2002). Vector-valued PSHA requires applying the VPSHA code to each selected vector IM. In a joint SCEC-PEER project in collaboration with Professor Allin Cornell of Stanford University, we have developed and applied vector-valued hazard calculations to the Van Nuys Holiday Inn, one of the PEER Testbeds for Performance Based Seismic Engineering. VPSHA was developed and applied following the method of Bazzurro and Cornell (2002).

Step 1. VPSHA Software Development (SCEC)

Our starting point for vector-valued probabilistic seismic hazard analysis (VPSHA) was a computer program for scalar-valued probabilistic seismic hazard analysis written by Norm Abrahamson. We modified the program so that it computes the vector-valued hazard, i.e. the frequency of joint occurrence of two or more ground motion parameters. At present, we have developed the code for pairs of response spectral periods, and plan to extend it to a vector or rank larger than two. The program was also modified to generate the deaggregation of the vector valued seismic hazard by magnitude and distance.

Step 2. Collect Structural Models (PEER)

Structural, computer-based models of the Van Nuys Holiday Inn were collected. Initially the DRAIN-2D model that was developed by Cornell's current PEER project was used. Since then, the PEER Testbed models in OpenSees (the PEER dynamic analysis framework) have been used. The models are non-linear and consider strength degradation, including cyclic degradation (which may be duration sensitive).

Step 3. Provide Ground Motion Records for Nonlinear Dynamic Analyses (SCEC)

The record sets for three annual probabilities (50% in 50 years, 10% in 50 years, and 2% in 50 years), corresponding to return periods of 72, 475, and 2,475 years, prepared for the Van Nuys Holiday Inn Testbed, were provided for use in nonlinear dynamic response analyses.

Step 4. Nonlinear Dynamic Analyses (PEER)

For each of the record sets and each of the models, a nonlinear time-history analysis was done. All Engineering Demand Parameters (EDPs) of potential interest (story drift, inter-story drifts, floor accelerations, etc.) were recorded and saved for processing.

The DRAIN-2D model of the structure has been subjected to many records and many ground motion levels for each record. The record sets for three different annual probabilities of exceedance for the Van Nuys Holiday Inn Testbed were used in non-linear dynamic analyses of the structure using the OpenSees software. The results of OpenSees analyses of this structure were reviewed and processed to study the means and correlations among the engineering demand parameters (EDPs) of PEER PBEE interest (i.e., the interstory drifts and floor accelerations). From this review, the value and interest of investigating not just one EDP at a time, but the vector of EDP's, was recognized. The current results give the moments (including correlations) given a ground motion with a specified (scalar) spectral acceleration at a given period. In the vector-valued IM context we give such moments (including correlations) conditioned on a ground motion with a vector of specified spectral accelerations. The behavior of these correlations as the IM changes from scalar to vector are therefore a new element of our study.

In addition to using the Van Nuys Testbed structure for the study of vector-valued intensity measures, Prof. Cornell and his student, Jack Baker, made use of a large new data base developed by Mr. Ricardo Medina, a Ph. D. student of Prof. Helmut Krawinkler of Stanford. Developed for PEER, the data base includes the results of many nonlinear analyses of a systematic suite of multi-storied building frames models representing a range of periods, number of stories, nonlinear member models, etc. These frame models were subjected to a sample of forty records or more, each scaled to a range of amplitudes; and the results of many different demand measures (roof displacement, inter-story drifts, energy measures, etc., were placed in a data base for systematic extraction and study. Access to this data base, kindly provided by Prof. Krawinkler, permitted this study of vector-value IM's to proceed over a much wider set of cases permitting far broader conclusions.

Step 5. Identify Candidate Intensity Measures (IMs) - Scalars and Vectors; Conduct Regressions of EDPs on IMs (Joint PEER/SCEC)

For current candidate scalar IMs (S_A at first mode period, etc.) and for vector IMs (multiple S_A values), regression analyses of interesting combinations of EDPs vs. IMs were run. These represent the necessary information for the second factor in the PEER framing equation: the conditional distribution of EDP given IM. Although the focus was on (log) linear functional forms for the mean of (log) EDP given (log) IM, the value of the dispersion (standard deviation of residuals of logs) was also recorded as a measure of the efficiency of the IM.

Step 6. Optimal Spectral Acceleration Vectors (PEER)

The vector IMs that were analyzed include pairs of spectral accelerations at various response spectral periods. A search algorithm was developed to determine, for a given EDP, the optimal pair of response spectral periods. Such results provide valuable insights into nonlinear structural behavior and its relationship to ground motion properties.

Step 7. Sufficiency Assessment (Joint PEER/SCEC)

Regression analyses of the EDPs were performed on certain of the IM candidates and other independent variables such as M (magnitude), R (distance), and _ (epsilon), to establish if there remains conditional dependence of the EDP on these variables given the IM. If not, the IM is said to be "sufficient" and is more likely to produce accurate EDP hazard curves (Luco and Cornell, 2001). Vector-valued IMs are expected to be more sufficient than similar scalars, because they use more information about the ground motion characteristics of a given record. No significant residual dependence on magnitude or distance was found, but there was a significant residual dependence on epsilon. Epsilon is the number of standard deviations of an IM of a given record away from the median value of the IM as given by a ground motion model. Accordingly, vector valued calculations of drift hazard were performed using the vector IM consisting of Sa_{T1} and epsilon, where Sa_{T1} is the spectral acceleration at the fundamental period of the building. These results are shown in Figure 2 and described in more detail in Step 11.

Step 8. Evaluate Candidate IMs (PEER)

Given the dispersion, which is a measure of efficiency, i.e., the number of records that must be run to provide adequate estimates of the regressions, and the degree of sufficiency, we can evaluate the relative merits of different IM candidates.

Step 9. Vector-Valued Attenuation Relations (SCEC)

Vector valued hazard analysis for response spectral acceleration requires supplementing existing Sa attenuation relations with correlation coefficients between the residuals of Sa pairs.

We initially used the correlation coefficients derived by Inoue (1990) from a set of strong motion recordings. We are now using an updated set of correlation coefficients derived by Abrahamson et al. (2003) using a much large set of strong motion recordings.

Step 10. Conduct VPSHA (SCEC)

Vector-valued PSHA requires applying the VPSHA code to each selected vector IM. An example of the result of our calculations for the Van Nuys Holiday Inn is shown in Figure 1. Individual scalar hazard curves for the two response spectral periods of interest, 0.8 Hz and 1.0 sec, are shown in Figure 1a. These hazard curves describe the annual frequency of occurrence of the individual response spectral values, but do not describe their joint frequency of occurrence. The vector hazard surface, which describes the joint frequency of occurrence, is shown in Figure 1b. For a given annual probability of occurrence, there is an ellipse-shaped line along which pairs of the two ground motion parameter values are jointly specified.

Step 11. Conduct VPSDA (PEER)

Vector-valued probabilistic demand analysis (VPSDA) was performed by numerically convolving the VPSHA distribution (Step 10) and the conditional distribution of EDP given IM (Step 5) to obtain the annual probability of the structure experiencing EDP larger than a given value. The black line in Figure 2 shows the annual frequency of exceedance of an EDP (maximum interstory drift) based on a scalar IM (Sa at 0.8Hz), and the blue line shows the corresponding relation for the same EDP based on a vector IM (Sa at 0.8 Hz and 1.0 Hz). In this case, the more realistic estimate of the engineering demand parameter obtained by the vector valued hazard is lower than the demand estimate provided by the conventional scalar valued hazard; the latter demand estimate is thus shown to be needlessly conservative. The same is true of the IM vector consisting of the spectral acceleration at the fundamental period of the building and epsilon, shown by the red line.

Step 12. Recommendations (Joint SCEC-PEER)

Conclusions as to most effective vector IMs and their relationship to this structure will be prepared, and the effectiveness of the vector hazard approach will be evaluated by comparing the probabilistic demand obtained using scalar and vector representations of the hazard (Figure 2).

References

Bazzuro, P. and C. A. Cornell (2002). Vector-valued probabilistic seismic hazard analysis (VPSHA). Proceedings, 7th U.S. National Conference on Earthquake Engineering, Boston, MA, July 21-25.

Luco, N. and C. A. Cornell (2001), Structure-Specific Scalar Intensity Measures for Near-Source and Ordinary Earthquake Ground Motions, *Earthquake Spectra*, Submitted, 2001.

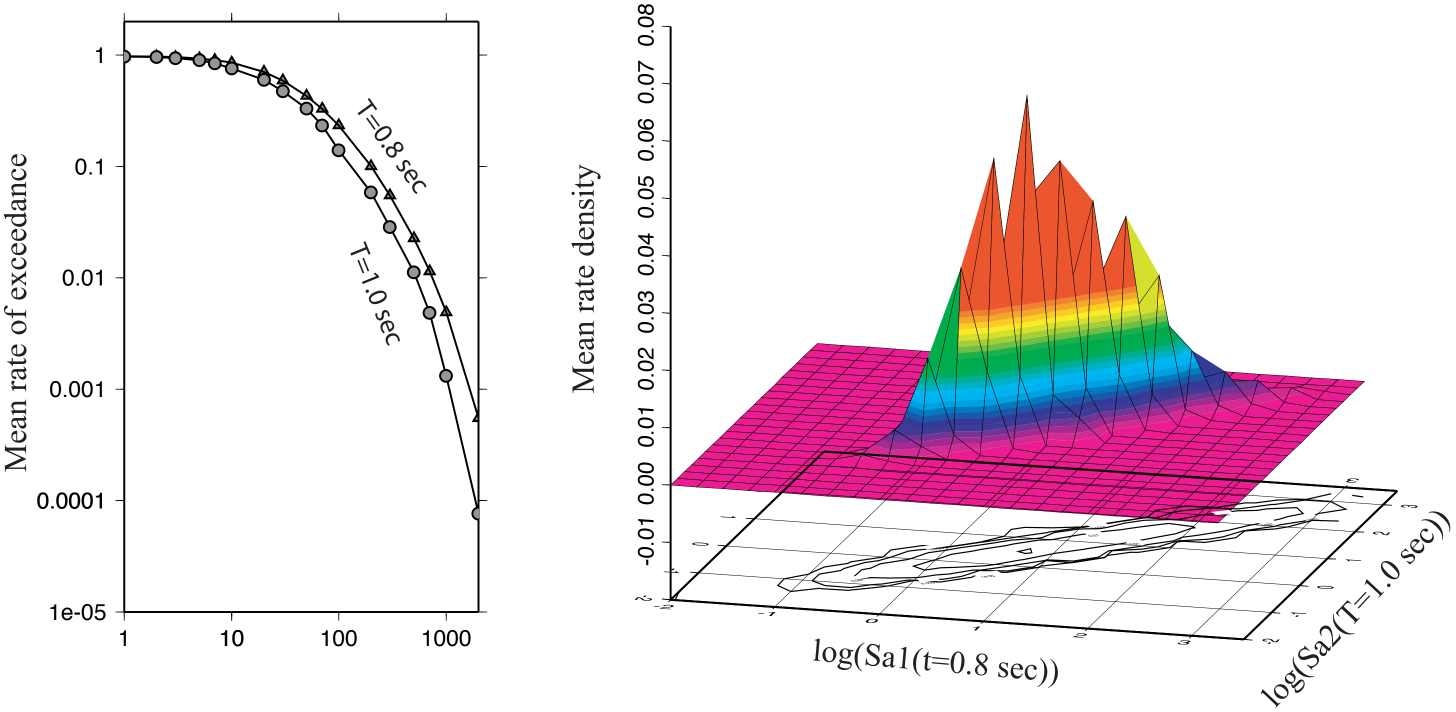

Figure 1. Scalar (left) and vector (right) probabilistic seismic hazard for the Van Nuys hotel.

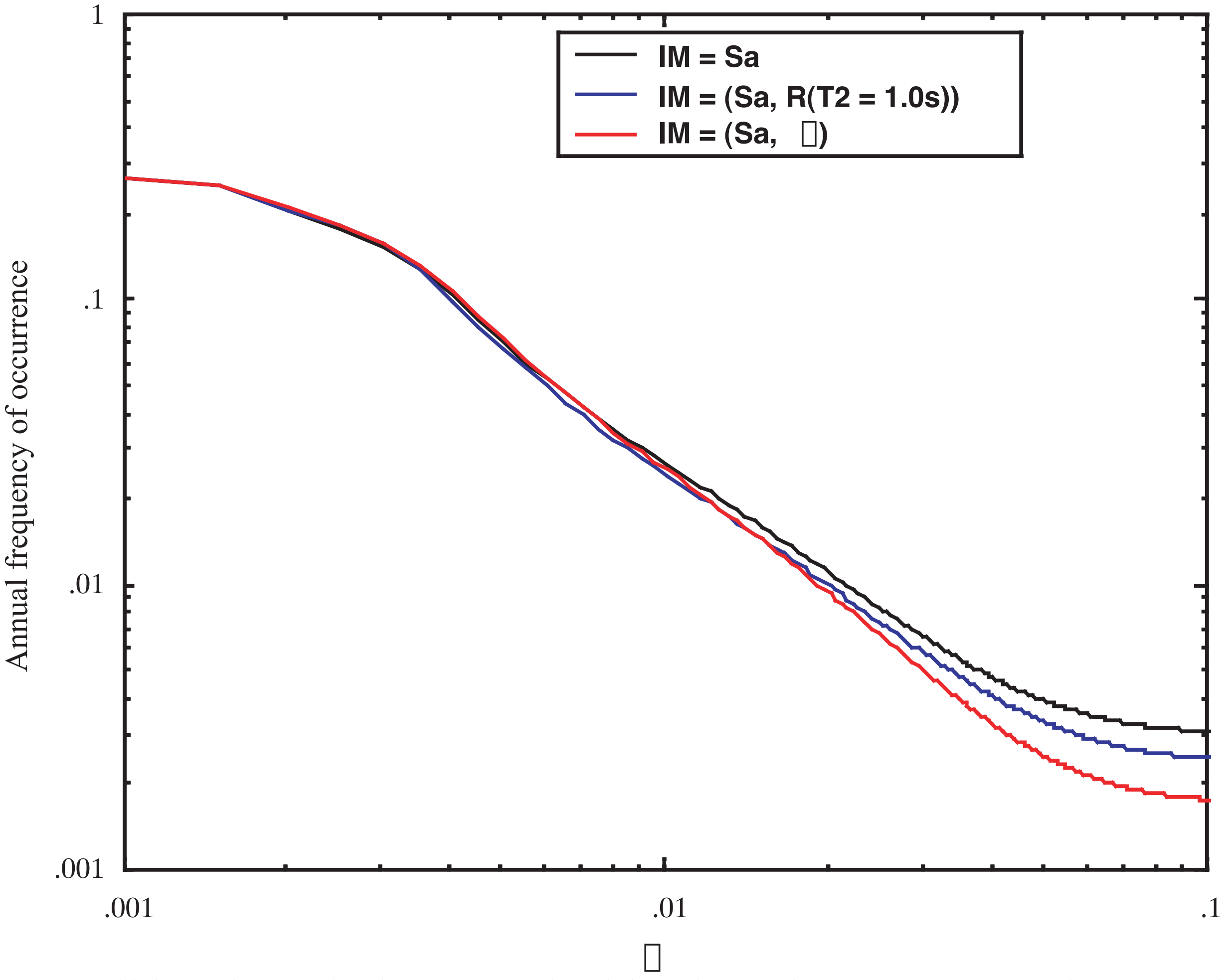

Figure 2. Drift hazard curve for the Van Nuys hotel. based on scalar (upper curve), and vector analyses. The vector results are for two period pairs (0.8 and 1.0 sec) (middle curve) and one period (T=0.8 sec) and (lower curve).