Probabilistic Performance-based Optimum Seismic Design with Application to the California High-Speed Rail Prototype Bridge

Yong Li
Postdoctoral Researcher, Dept. of Structural Engineering, Univ. of California at San Diego

Joel P. Conte
Professor, Dept. of Structural Engineering, Univ. of California at San Diego

ABSTRACT: Seismic isolation provides a potentially promising strategy to mitigate the seismic risk to California High-speed Rail (CHSR) bridge structures. Notably, a proper selection of the seismic isolator properties must be carried out to strike a trade-off between the beneficial and detrimental effects of seismic isolation while accounting for the uncertainties associated with the seismic loading. Building upon a three-dimensional detailed nonlinear finite element (FE) model of a California High-speed Rail (CHSR) prototype bridge, including soil-foundation-structure interaction (modeled using the dynamic p-y approach) and rail-structure interaction, a comprehensive parametric probabilistic seismic demand hazard analysis was performed for this bridge located at San Jose, California. A proposed next-generation approach, i.e., Probabilistic Performance-based Optimum Seismic Design (PPOSD) framework, is applied to the CHSR Prototype Bridge, within the context of the Performance-Based Earthquake Engineering (PBEE) methodology developed at the Pacific Earthquake Engineering Research (PEER) center. Through the application of the PPOSD framework to the CHSR Prototype Bridge, a well-posed optimization problem is proposed for the optimal seismic isolator parameters and solved through grid-based brute-force approach.

1. INTRODUCTION

Seismic isolation aims to decouple a structure or part of structure, e.g., bridge deck, from the damaging actions of earthquakes, where isolators are inserted between the bridge deck and the top of piers and abutments (Kelly 1997). Seismic isolation reduces the transmissibility of ground motions to the structural system through shifting the fundamental period of the isolated system from the fixed-base period of the structure and from the predominant period of the ground motions (i.e., period elongation effect).

In addition, another equally important contribution from seismic isolators is the added hysteretic energy dissipation caused by the nonlinear force-deformation behavior of the seismic isolators, thereby reducing the seismic energy transmitted into other structural components. However, an undesirable consequence of using isolators is the increased seismic deformation concentrated at the isolation layer. As concluded in the state-of-the-art reviews of seismic isolation (Buckle et al. 1990, Kelly 1997, Kunde and Jangid 2003), seismic isolation is a promising effective design and rehabilitation strategy for mitigating seismic damage at various hazard levels of ground motions in earthquake-prone regions.

Widespread applications of seismic isolation can be found in the design or retrofit bridge structures. A historical survey on the seismic performance of actual isolated structures subjected to earthquakes further proved the benefits of seismic isolators (Asher et al. 1997, Matsagar and Jangid 2006). The seismic performance of isolated structures has also been evaluated through comparative analytical study of bridges with and without seismic isolation (Hwang 1994, Sarrazin et al. 2012). Seismic isolation provides a potential strategy to mitigate the seismic risk to California High-speed Rail (CHSR) bridge structures.

Notably, a proper selection of the seismic isolation properties must be carried out to strike a trade-off between the beneficial and detrimental effects of seismic isolation while accounting for the uncertainties associated with the seismic loading, which requires structural optimization for optimum probabilistic seismic performance (Austin, 1987a, b). The pertinent uncertainty can be properly addressed in the well-established conceptual framework of the Performance-Based Earthquake Engineering (PBEE) methodology developed at the Pacific Earthquake Engineering Research (PEER) center (Cornell and Krawinkler 2000, Porter 2003). This methodology provides a comprehensive framework for fully probabilistic seismic performance/risk evaluation of infrastructural system (Cornell and Krawinkler 2000, Krawinkler 2002, Moehle 2003, Porter 2003), by evaluating probabilistically the seismic intensity measure, structural response, seismic damage, and decision variables (e.g., deaths, downtime, and repair/replacement loss) in four analytical steps.

In this paper, a three-dimensional detailed nonlinear finite element (FE) model of a California High-speed Rail (CHSR) prototype bridge is developed in the open source earthquake engineering simulation framework (i.e., OpenSees), including soil-foundation-structure interaction (modeled using the dynamic *p-y* approach) and rail-structure interaction. Instead of implementing the four analytical steps of the PBEE methodology, a comprehensive parametric probabilistic seismic demand hazard analysis (i.e., the second step of the PBEE methodology) was performed for a local site in San Jose, California, due to limited statistical data available regarding the damage and repair cost required for this CHSR project. Using high performance computing technology, we have explored the topology of objective and/or constraint functions defined in terms of risk features, which are defined based on the probabilistic seismic demand hazard results associated with different Engineering Demand Parameters (EDPs) of the entire bridge system. A computationally challenging and well-posed optimization problem is proposed and solved through brute-force approach within the context of probabilistic performance-based optimum seismic design (PPOSD) framework for the selection of optimal seismic isolator parameters.

2. CHSR PROTOTYPE BRIDGE MODEL

With the support of Parsons Brinckerhoff (PB), which is assisting the State of California in planning, designing, and managing the construction of the California high-speed rail systems, a prototype bridge to be located at downtown San Jose is selected and designed for the present study of the feasibility and optimization of seismic isolation. The 9-span prototype bridge is straight consisting of three 330.0ft long and 48.0ft tall frames (3 spans 110.0ft each) with two interior structural expansion joints between the central and two end frames as well as two abutment expansion joints at both bridge ends (see Figure 1). At both ends of the bridge, the seat-type abutments are supported by 2×3 pile group foundations with cast-in-place drilled shafts, and pier columns in the middle are supported by 2×2 pile foundations.

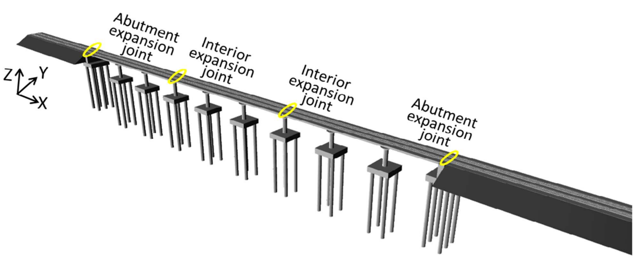

Figure 1: Isotropic view of the California High-speed Rail (CHSR) prototype bridge.

The bridge superstructure, a post-tensioning single-cell box girder (42.0ft wide at the top), is rested on eight single-column piers/bents in the middle and two seat-type abutments at both ends. The bridge deck is represented by elastic beam-column elements, considering that bridge deck is designed to remain elastic as a capacity protected component. The pier columns of circular crosssection with diameter 8.0ft are modeled using ten displacement-based beam-column elements with nonlinear fiber sections.

Twelve pairs of transversally aligned seismic isolators are inserted between the bridge deck and piers/abutments, with two pairs at each of the two interior expansion joints, one pair at each of the six continuous joints, and one pair at each of the two abutments. Since the generic isolator behavior is of interest herein and no specific isolator type is selected, each seismic isolator is modeled as a zero-length element with two uncoupled bilinear inelastic materials for horizontal behavior: one in the longitudinal direction and the other in the transverse direction of the bridge.

A pair of slotted hinge joint (SHJ) devices is incorporated at each interior expansion joint to maintain the transverse continuity of the bridge while allow the free movement of bridge deck segments in the longitudinal direction. Regarding the modeling of the SHJ device, a zero-length element coupled with nonlinear springs are used to capture the force-deformation behavior reasonably well, in which a gap-hook elastic-perfectly-plastic spring (EPP) in the longitudinal direction and two EPP springs in the transverse and vertical direction of the bridge. At the abutment expansion joints, exterior shear keys with minimum construction gap (0.5in) are designed to restrain the bridge deck in the transverse direction, i.e., limit the isolator deformation in the transverse direction of the bridge. A well-calibrated shear key model developed based on the experimental results (Megally et al. 2001) is used to model the shear keys.

The soil-structure interaction (SSI) is also accounted in the FE model developed here for the CHSR prototype bridge. The SSI effect, which can possibly occur at both bridge ends (i.e., abutments) and the foundations to support pier columns (i.e., deep pile group foundations), are captured consistently using a simplified but accurate approach. The resistance to the bridge deck in the longitudinal direction is modeled as an inelastic spring with hyperbolic backbone curve calibrated from the backfill soil properties in series with a gap element to represent the abutment expansion joint gap. The pile foundations are modeled using the well-established dynamic *p*-*y* approach (Boulanger et al. 1999).

In the FE model presented, the rail-structure interaction is also included to investigate the seismic isolation effects on the rails. The rail is modeled using linear elastic elements with specified material and section properties for rails of type 141RE in AREMA. A series of coupling springs (i.e., bilinear inelastic springs in the longitudinal direction and elastic springs in the transverse and vertical directions) on a per track basis are included to represent pairs of fasteners as the rail-structure interaction layer in the bridge model. A minimum finite length of explicit modeling of the track system beyond the bridge ends is included as well for better accounting for the boundary conditions of tracks on bridges, besides a nonlinear longitudinal spring (denoted as rail boundary spring) are added at each rail end to represent the longitudinal support of infinitely long rail supported on track slab.

Consequently, with proper representation of each structural component in the complete model and boundary conditions, a three-dimensional (3D) nonlinear finite element (FE) model of the CHSR prototype bridge considering rail-structure interaction and soil structure interaction is implemented as shown in Figure 2. This FE model with each components tagged for convenience of interpretation is used for simulating the seismic response of the CHSR bridge system, which is to generate response data sample space for the probabilistic seismic demand hazard analysis in the second step of the PBEE methodology as described in Section 4.

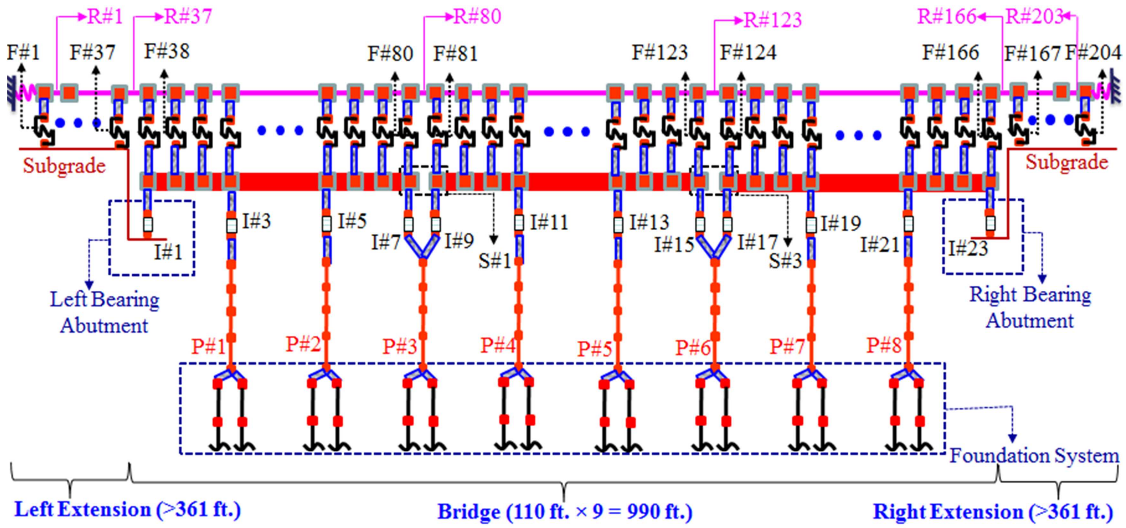

Figure 2: Isotropic view of the California High-speed Rail (CHSR) prototype bridge.

3. SEISMIC SIMULATION FOR BRIDGE RESPONSE

Since the hysteretic energy dissipation is directly considered in seismic isolation system, 2% Rayleigh damping is only applied to the structural components (i.e., excluding the seismic isolators between the bridge deck and bridge substructures). Proper dashpot in series with the elastic deformation terms in the p-y or t-z springs in the dynamic *p-y* approach are also imposed to consider the geometric radiation damping as part of the SSI effects.

Multiple-support excitation is adopted for the dynamic time history analysis for the seismic response simulation to consider the depth-varying displacement inputs along the depth of the pile foundation. For the selected ground motion records with two horizontal components, site response analysis using the equivalent linear analysis in frequency domain (e.g., Shake91) is employed to obtain the free-field ground displacement at different depths, which are assigned at the far-field ends of the soil-springs in the dynamic p-y approach.

4. PARAMETRIC PROBABILISTIC DEMAND HAZARD ANALYSIS

For a given CHSR prototype bridge with a specified seismic isolation design, probabilistic seismic demand hazard analysis can be conducted for the probabilistic performance evaluation. A comprehensive parametric probabilistic seismic demand hazard analysis is then performed over a grid in the design variable space, defined based on the proper isolator yield strength and initial elastic stiffness of the bilinear seismic isolation system, which satisfies relevant design criteria.

4.1. Probabilistic seismic hazard analysis

To estimate the probabilistic seismic demand hazard in the second step of the PBEE methodology, probabilistic seismic hazard analysis, i.e., the first step of the PBEE methodology needs to be performed first to obtain the probabilistic seismic hazard curve. The probabilistic seismic hazard curve is a probabilistic measure of the intensity measure (IM), e.g., mean annual rate of exceedance for intensity measure IM, $\nu_{IM}(im)$, where the IM is selected to be the 5% damped elastic spectral acceleration at the fundamental period of structural system with the corresponding isolator design. The web application PSHA tool (USGS 2008 Interactive De-aggregation, http://earthquake.usgs.gov/hazards/) developed by the U.S. Geological Survey (USGS) is used to conduct the seismic hazard analysis at the given site with specific soil condition (i.e., average shear wave velocity at the top 30 meters, Vs_{30} = 229m/s). This ends up with the probabilistic seismic hazard curve as well as the seismic hazard de-aggregation results with respect to the source-to-site distance R and magnitude M. Corresponding to the seismic hazard de-aggregation results, 40 ground motion records are selected and scaled uniformly by three different scaling factors to enlarge the ground motion sample for seismic response simulation.

4.2. Conditional probabilistic seismic demand hazard analysis

The conditional probabilistic seismic hazard analysis is to characterize the probabilistic properties of the structural response given a specified seismic hazard level, or given a level of the intensity measure. This step is to make use of the structural response simulated through nonlinear time history analysis of the developed FE model of the CHSR prototype bridge considered herein subjected to the 120 ground motions records.

Based on a linear regression of a structural response parameter (i.e., engineering demand parameter EDP) and the corresponding intensity measure of the ground motion record in the log-space, a statistical inference model is built to estimate the conditional mean and variance of ln(EDP) for given seismic hazard level, i.e., $\hat{\mu}_{\ln EDP|IM}$ and $\hat{\sigma}_{\ln EDP|IM}$. This is referred to as the cloud method for the conditional demand hazard analysis, as shown in Figure 3. The variance estimator in the cloud method is assumed to be independent of the IM. Together with the premise that the EDP distribution for a given seismic hazard level follows log normal distribution, the conditional cumulative distribution function is attained as below

$$P\left[EDP > edp \middle| IM\right] = 1 - \Phi\left(\frac{edp - \hat{\mu}_{\ln EDP|IM}}{\hat{\sigma}_{\ln EDP|IM}}\right) \tag{1}$$

which measures the probability exceedance of the demand under a given seismic hazard level.

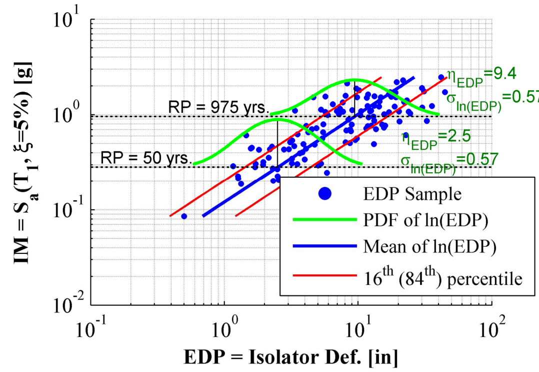

Figure 3: Conditional demand analysis of seismic isolator deformation of I #13 in the transverse direction of the CHSR prototype bridge with initial isolator design.

4.3. Unconditional probabilistic seismic demand hazard analysis

The unconditional probabilistic seismic demand hazard to compute the probabilistic seismic demand hazard curve, e.g., the mean annual rate of EDP exceeding a certain threshold value edp, $\nu_{EDP}(edp)$, or the probability of exceedance in 100 years when Poisson process is assumed. This is accomplished by convolution of the conditional probabilistic seismic demand hazard analysis results with the probabilistic seismic hazard curve as below

$$\nu_{EDP}(edp) = \int_{IM} P\left[EDP > edp \middle| IM\right] \left| d\nu_{IM}(im) \right| \tag{2}$$

4.4. Grid in the design variable space

In this study, the yield strength and initial elastic stiffness of seismic isolators are chosen to be the design variables, with post-yield stiffness ratio fixed as 0.1 as observed in elastomeric bearings and lead rubber bearings.

The parametric probabilistic seismic demand hazard analysis is to perform probabilistic seismic demand hazard analysis of the CHSR prototype bridge when varying the seismic isolator design parameters. This is to explore how the probabilistic seismic demand hazard (i.e., conditional or unconditional) will change as a function of the seismic isolator parameters for a variety of EDPs, which are of primary interest to the structural engineers to assess the seismic performance of the CHSR prototype bridge.

The design variable space of seismic isolation parameters are firstly determined based on the properties of seismic isolators, which can provide the enough axial load capacity are available in market provided the Dynamic Isolation Systems (DIS) Inc.. In addition, the design constraints on the seismic isolators for the operation of high-speed train are also applied to impose a lower bound on the isolator parameters such that the maximum braking and traction force will neither yield the isolators nor cause the relative deck displacement limit being exceeded. As a result, seismic isolators with yield strength ranging from 34.1kips to 204.7kips and pre-yield stiffness ranging from 120.0kips/in to 740.0kips/in, are used as the design variable space.

5. RISK FEATURE DEFINITIOIN AND TOPOLOGY STUDY

In performance-based seismic design philosophy, different performance objectives based on the seismic demand conditioned on two or three seismic hazard levels is usually stated explicitly. For example, the two hazard levels of interest in CHSR project, i.e., OBE hazard level with 86% probability of exceedance in 100 years, and MCE hazard level with 10% probability of exceedance in 100 years. Consequently, several risk features to measure the seismic risk imposed to the structural response can be defined based on a certain seismic hazard level, in terms of the conditional median (i.e. exponential of the mean of logarithmic of EDP when lognormal distribution of EDP is assumed), conditional mean, dispersion, and percentiles, etc. Similarly, risk features can be also defined based on the probabilistic seismic demand hazard analysis.

Figure 4 and Figure 5 shows the topology of two typical risk features: i.e., mean demand on the relative deck displacement in the transverse direction conditioned at the OBE hazard level, and the mean demand on the total base shear force in the transverse direction conditional at the OBE seismic hazard level. They show the detrimental and beneficial effect of seismic isolation respectively, in terms of the topology with respect to the seismic isolator properties. For reference, the corresponding risk feature value for non-isolated bridge (NIB) is also indicated with the black triangular marker.

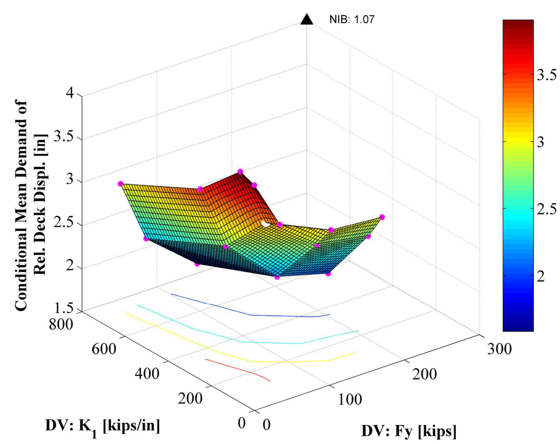

Figure 4: Risk feature exploration in terms of mean demand on the relative deck displacement in the transverse direction conditional at OBE hazard level.

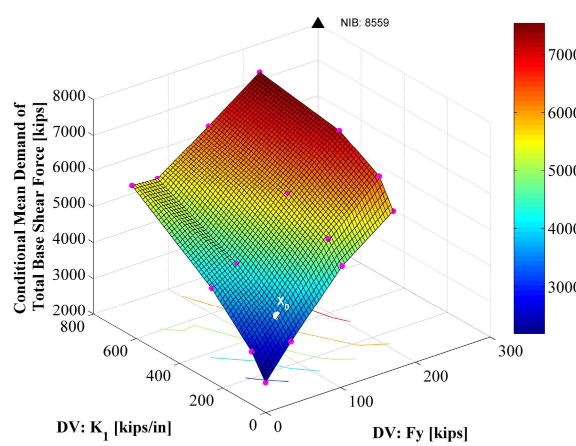

Figure 5: Risk feature exploration in terms of mean demand on total base shear force in the transverse direction conditional at OBE hazard level.

6. PROBABILISTIC PERFORMANCE-BASED OPTIMUM SEISMIC DESIGN

6.1. Mathematical formulation

The risk features defined above can be either used as objective function or constraint function in the optimization problem formulation for probabilistic performance-based optimum seismic design. For demonstration purpose, an optimization problem based on the seismic performance conditioned on the OBE hazard level is presented. Aiming at minimizing the conditional median demand on total base shear force across all columns in the transverse direction, subject to six relevant design constraints, the mathematical formulation of the optimization problem is shown in Equation (3).

$$\underset{\substack{34.1kips \le F_y \le 204.7kips \\ 120kips/in \le K_1 \le 740kips/in}}{\textbf{Minimize}} \quad \text{conditional median: } \eta\left[F_{trans.}^{\text{TBS}, \, all\ columns} \,|\, OBE\right]$$
$$\begin{aligned}
&(1)\ E\left[AA_{trans.}^{deck} \,|\, OBE\right] \le 0.35g \\
&(2)\ Pctl.^{95th}\left[AA_{trans.}^{deck} \,|\, OBE\right] \le 0.5g \\
&(3)\ Pctl.^{95th}\left[M_{trans.}^{P\#5} \,|\, OBE\right] \le M_{cr}^{pier}(1.5\times10^4 kips\text{-}ft) \\
&(4)\ Pctl.^{95th}\left[M_{trans.}^{piles,\,P\#5} \,|\, OBE\right] \le M_{cr}^{pile}(5.3\times10^3 kips\text{-}ft) \\
&(5)\ Pctl.^{95th}\left[\sigma_{P}^{rail,\ \text{abut.}} \,|\, OBE\right] \le 12.5ksi \\
&(6)\ \eta\left[\sigma_{P+M}^{rail,\ \text{abut.}} \,|\, OBE\right] \le 42.5ksi
\end{aligned} \tag{3}$$

The seismic risk to transverse deck acceleration, $AA_{trans.}^{deck}$, on OBE hazard level is limited in terms of mean value and 95th percentile (Pctl.^{95th}), denoted as constraint (1) and constraint (2) respectively. In constraints (3) and (4), the 95th percentiles of conditional demand on maximum bottom moment in pier #5 and the maximum bending moment in piles under pier #5 are enforced to be less than the cracking moment of the corresponding section capacity for higher performance objectives under OBE hazard level when seismic isolation is incorporated. Another two constraints are imposed on the rails stress to exclude the seismic isolators which can lead to excessive deck displacement and thus additional rail stress, as seen in constraints (5) and (6).

6.2. Optimization solution

Considering the highly demanding computing need for probabilistic performance optimization of large using rigorous optimization scheme, the solution to this optimization problem using grid-based brute- force approach is shown in Figure 6. The objective function is plotted as the surface and the barrier walls of constraint functions are shown to restrict the feasible domain satisfying all the prescribed constraints, and thus to shrink the feasible design space.

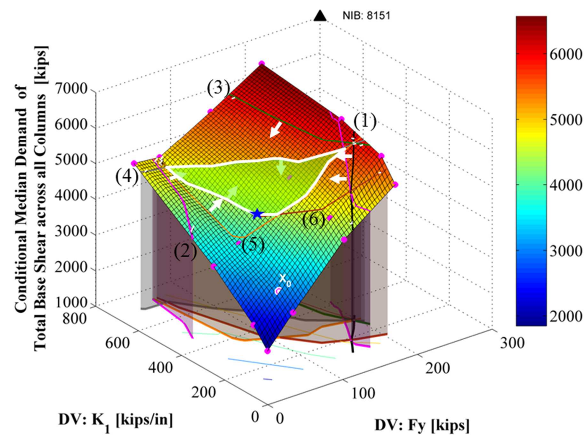

Figure 6: Demonstration of the solution to the optimization problem formulated for probabilistic performance-based optimum seismic design on given seismic hazard level (i.e., OBE).

The obtained optimum design of bilinear seismic isolator is marked out by the pentagram with yield strength 95.54kips and initial stiffness 330.8kips/in, which lies on the intersection of boundaries of the constraints on the axial rail stress and total rail stress. It indicates that all probabilistic design constraints are satisfied, and higher-level seismic performance objectives on substructures are reached. This implies that the substructure can be resized when seismic isolation is introduced.

The well-posed optimization problem is solved herein using grid-based brute-force approach based on the parametric analysis over the grid in the design variable space, considering the highly extensive computational cost. However, it is planned to extend this study to solve the optimization problems using rigorous optimization algorithms when computational cost is not an obstacle.

7. CONCLUSIONS

This paper presents the parametric probabilistic seismic demand hazard analysis based on an isolated California High-Speed Rail (CHSR) prototype bridge when varying the characteristic properties of seismic isolation. To accomplish this task, a three-dimensional detailed nonlinear finite element model for the CHSR prototype bridge is developed, including rail-structure interaction and soil-foundation-structure interaction. Risk features are defined based on the conditional probabilistic demand hazard analysis results, to measure the seismic risk imposed to bridge response and rail response. The topology of the risk features is used to explore the beneficial and detrimental effects of seismic isolation on the CHSR prototype bridge. In the context of probabilistic performance-based optimum seismic design (PPBOSD) framework, a well-posed optimization problem is proposed and solved using grid-based brute-force approach. Such optimization problems are expected to be solved using computational optimization algorithms for future work.

8. REFERENCES

Asher, J. W., Hoskere, S. N., Ewing, R. D., Mayes, R. L., Button, M. R., and Van Volkinburg, D. R. (1997). "Performance of seismically isolated structures in the 1994 Northridge and 1995 Kobe earthquakes." *Proceedings of Structures Congress*, vol. XV, ASCE, 1997.

Austin, M., Pister, K., and Mahin, S. A. (1987a). "Probabilistic design of moment-resistant frames under seismic loading." Journal of Structural Engineering, 113(8), 1660 - 1677.

Austin, M., Pister, K., and Mahin, S. A. (1987b). "Probabilistic design of earthquake-resistant structures." Journal of Structural Engineering, 113(8), 1642 - 1659.

Boulanger, R.W., Curras, C.J., Kutter, B.L., Wilson, D.W., and Abghari, A. (1999). "Seismic soil-pile-structure interaction experiments and analysis." Journal of Geotechnical and Geo-environmental Engineering, 125(9), 750-759.

Buckle, I., and Mayes, R. (1990). "Seismic isolation: history, application, and performance-a world view." *Earthquake Spectra*. 6(2), 161-201.

Cornell, C., and Krawinkler, H. (2000). "Progress and challenges in seismic performance." *PEER Center News*, 3(2).

Hwang, J., Sheng, L., and Gates, J. (1994). "Practical analysis of bridges on isolation bearings with bi-linear hysteresis characteristics." *Earthquake Spectra*, 10(4), 705 – 727.

Kelly, J. M. (1997). *Earthquake-Resistant Design with Rubber*, Springer, Berlin.

Krawinkler, H. (2002). "A General Approach to Seismic Performance Assessment." International Conference on Advances and New Challenges in Earthquake Engineering, Hong Kong.

Kunde, M. C., and Jangid, R. S. (2003). "Seismic behavior of isolated bridges: A-state-of-the-art review." *Electronic Journal of Structural Engineering*, 3, 140–170.

Matsagar, V., and Jangid, R. (2006). "Seismic response of simply supported base-isolated bridge with different isolators." *International Journal of Applied Science and Engineering*, 53–69.

Megally, S. H., Silva, P. F., and Seible, F. (2001). "Seismic response of sacrificial shear keys in bridge abutments." *Rep. No. SSRP-2001/23*, Dept. of Structural Engineering, Univ. of California, San Diego.

Moehle, J. P. (2003). "A framework for performance-based earthquake engineering." Proceedings of ATC-15-9 Workshop on the Improvement of Building Structural Design and Construction Practices, Maui, HI, June.

Porter, K. A. (2003). "An overview of PEER's performance-based earthquake engineering methodology." Conference on Applications of Statistics and Probability in Civil Engineering (ICASP9), Civil Engineering Risk and Reliability Association (CERRA), San Francisco, California, July 6–9.

Sarrazin, M., Moroni, O., Neira, C., and Venegas, B. (2012). "Performance of bridges with seismic isolation bearings during the Maule earthquake, Chile." *Soil Dynamics and Earthquake Engineering*, 1–15.