Influence of soil structure interaction on the fragility of an isolated bridge-soil-foundation system

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SUMMARY:
This paper investigates the effects of soil-structure interaction (SSI) and liquefaction on the fragility of both an un-retrofitted and an isolated bridge-soil-foundation system. Stiff soils and soft soils are considered. The soft soils are also used to investigate the liquefaction effect by changing water elevations. The results show that the failure probability of the isolated system is less than that of the non-isolated one for both soil types. However, SSI tends to decrease the isolation effectiveness. The failure probability is higher for soft soils compared to stiff soils, highlighting that soft soils decrease the isolation efficiency. However, results also show that liquefaction provides an effective natural isolation by reducing the curvature demands on the columns while it increases the isolation bearing displacement. Therefore, SSI should be considered in the design of isolated bridges, and isolation can still be used in liquefiable sites if lateral spreading and slope instability are prevented.

Keywords: bridge-soil-foundation system; isolation; liquefaction; fragility curves; soil-structure interaction

1. INTRODUCTION

The destructive effects of past large earthquakes on bridges due to shear or flexural failure of the columns, and damage of steel bearings among other failure modes (Dicleli and Buddaram 2006; Mander et al. 1996), has led to an increase of seismic isolation design and implementation to minimize the seismic risk on bridge structures. Isolation has been suggested as the most effective retrofit option for multi-span continuous steel (MSCS) bridges in past vulnerability studies for the central and eastern United States (CEUS) based on a lumped spring foundation model (Padgett and DesRoches 2008). However, as loose sands/soils in alluvial deposits, especially along the Mississippi Valley, make this CEUS region susceptible to liquefaction during a large earthquake, the effectiveness of isolation in reducing fragility for bridges with soil structure interaction (SSI) and liquefaction effects needs to be explored.

Soil-structure interaction (SSI) effects and the contribution of higher modes of vibration are commonly ignored in the earthquake resistant analysis and design of seismically isolated bridges (Dicleli et al. 2005). In recent years, a number of studies have investigated the effectiveness of isolation devices for the seismic design or retrofit of bridges (Bessason and Haflidason 2004; Dicleli et al. 2005; Eroz and DesRoches 2008) and have evaluated the influence of SSI on the seismic response of conventionally designed bridges (Elgamal et al. 2008; Aygün et al. 2011; Jeremić et al. 2009). However, only a few publications are available in the literature that explore the impacts of SSI on the seismic response of isolated bridges. Vlassis and Spyrakos (2001) analyzed the influence of SSI on the dynamic response of a seismic isolated bridge pier using a two degree-of-freedom linear elastic model. The authors found that the fundamental period of the bridge structure increases significantly when SSI is considered and that SSI effects reduced the base shear of the bridge obtained from the AASHTO design procedures. Tongaon-kar and Jangid (2003) investigated the effects of SSI on the peak responses of a three-span continuous deck bridge seismically isolated with elastomeric bearings and observed that the effects of SSI are more pronounced for stiff bridges in comparison to the flexible bridges and the bearing displacements at abutment locations were underestimated when the SSI effects were not considered. Dicleli et al. (2005) investigated the effects of SSI on two types of isolated bridges that had different superstructure and substructure weights. The analysis of results showed that

SSI can be neglected for isolated bridges with a heavy superstructure and light substructure constructed on stiff soil. However, SSI needs to be considered for bridges with a light superstructure and heavy substructures regardless of the stiffness of the soil. They also found that SSI effects need to be considered in soft soil conditions regardless of the bridge type. Ucak and Tsopelas (2008) also analyzed two bridge systems, one representative of short stiff highway overpasses and another representative of tall flexible multi-span highway bridges. The results showed that SSI causes higher isolation system drifts as well as, in many cases, higher pier shears when compared to the bridges without SSI.

The dynamic response of a coupled bridge soil foundation (CBSF) system with isolation bearings is complex, especially for soft and liquefiable soils which experience highly nonlinear response during seismic excitations. Therefore, it is necessary to use realistic yet computationally feasible models to simulate the seismic response of CBSF systems, particularly in probabilistic response analyses. A number of approximations, such as two degrees of freedom systems to represent the complex three dimensional (3D) bridge models (Vlassis and Spyrakos 2001), lumped spring models (Dicleli et al. 2005) or closed form solutions to model the SSI system (Ucak and Tsopelas 2008) have been introduced in previous work. However, a major standing question is how these effects (nonlinear behaviour of the soils and approximate modelling assumptions) interact with the nonlinear behavior of the isolators for realistic bridge foundations (Olmos and Roesset 2008). Therefore, more accurate structural models of seismically-isolated bridges considering SSI that can improve the prediction of the seismic response and retain computational feasibility should be used.

All of the above mentioned studies that have evaluated the effectiveness of isolation systems on the seismic response of bridges are deterministic studies. Since the effectiveness of seismic isolation highly depends on the frequency characteristics of structures and earthquake motions, the deterministic approach, employing design seismic spectra and a few ground motion records as input, is limited in its ability to provide a comprehensive evaluation of the system response while accounting for the uncertainties of ground motions (Zhang and Huo 2009). Relatively little work has been done to evaluate the effect of seismic isolation on bridge fragility. As an example, Karim and Yamazaki (2007) have assessed the impact of isolation on bridge fragility using a simplified methodology for bridges in Japan. They observed that the failure probability for the isolated system is less than that of the non-isolated one for low pier height while the failure probability for the isolated system is found to be greater for high pier height compared to the non-isolated system. Additionally, Zhang and Huo (2009) utilized the fragility function method to investigate the effectiveness and optimum isolation design for typical highway bridges in California. An extensive parametric study is carried out under the fragility analysis framework to identify the optimum isolation parameters as a function of structural properties and damage states. However, none of the above studies considers SSI effects. In addition, no studies have investigated the effect of liquefaction on the seismic response of isolated bridges to the authors' knowledge. However, it is important to know whether isolation can be used on liquefiable soil sites, and how liquefaction impacts the seismic response of isolated bridges and associated components. Thus, more studies are needed to investigate the effect of SSI and liquefaction on the fragility of isolated bridges.

The purpose of this study is to develop fragility curves for isolated bridges and to compare them with the ones of non-isolated bridges to explore the effectiveness of isolation in reducing fragility for bridges in the CEUS region with soil structure interaction (SSI) and liquefaction effects. A detailed CBSF system with a three-dimensional bridge superstructure, two-dimensional soil domain and one-dimensional *p-y*, *t-z*, and *q-z* springs is first constructed. The bridges are then analyzed using nonlinear time history analysis taking into account the nonlinear behavior of the seismic-isolation system, other bridge components, and SSI effects. The analyses are performed for stiff and soft foundation soil conditions in Section 3. Next, seismic fragility with dry sands and saturated sands by changing water elevations are compared to assess the effect of liquefaction on the efficiency of the isolation bearings in Section 4. The last section concludes the paper.

2. DESCRIPTION OF THE ISOLATED CBSF SYSTEM AND INPUT GROUND MOTIONS

Nielson (2005) performed a fragility assessment of different classes of bridges in CEUS and concluded that MSCS girder bridges were among the most vulnerable to seismic damage. In addition, previous research identified significant vulnerabilities of the steel fixed and rocker bearings employed in these bridges to seismic loads (Mander et al. 1996). Seismic isolation of MSCS girder bridges via replacing the existing steel bearings may be an effective tool for improving the earthquake performance. A MSCS girder bridge typical in CEUS is used to explore the effect of SSI on the seismic response of the isolated CBSF system. Lead Rubber bearings (LRBs) are considered for the retrofitting in the seismic isolation design to reduce the vulnerability of the MSCS girder bridges. The seismic isolation of the bridge is achieved via placing LRBs under each of the typical eight girders for this MSCS bridge type above the piers and abutments. The elevation view of the chosen bridge with two types of soil profiles and cross Section of several key components is shown in Fig. 2.1.

The Open System for Earthquake Engineering Simulation (OpenSees) is used to perform the nonlinear dynamic analyses for the CBSF system. Only the seismic design and OpenSees model of the LRBs is discussed in detail below. Detailed information on the CBSF modeling approach for other components is presented by Wang et al. (2012 a), who couples one-dimentional (1D) *p-y*, *t-z*, and *q-z* springs with two-dimensional (2D) soils and three-dimensional (3D) bridge superstructure models. This 1D/2D/3D modeling strategy can be used to efficiently simulate SSI with non-liquefiable soils, and liquefiable soils without lateral spreading and slope instability, which has been verified by the authors through the more complex and computationally intensive 2D soil modeling approach (Wang et al. 2012 a). The 1D/2D/3D modeling strategy offers an improvement compared with using lumped springs to replace the SSI effect or just using fixed boundary conditions as typically done for probabilistic seismic risk analysis of bridges (Nielson 2005).

2.1. Seismic Isolation Design

A bilinear model is often used to represent the nonlinear inelastic hysteretic property of lead rubber bearings. As depicted in Fig. 2.2, the parameters that determine the behavior of LRBs are the yield strength F_y, the elastic stiffness K_u and the post-yielding stiffness K_d. The post-yield stiffness is taken as 10% of the initial stiffness for isolation bearing in this study. The choice of K_d and F_y will determine the level of the force transmitted into the pier, and the peak displacement that the isolation system will experience (Ucak and Tsopelas 2008).

Different from traditional seismic isolation design to achieve a target fundamental period, LRBs are designed for a target design displacement in this study. The period elongation generally brings an increase of response displacement of the deck. Hence, in the design of seismic isolation bearings, the natural period should not be excessively increased. In this study, since the width of the expansion joints at the abutments is only 7.7 cm for the as-built bridge, the displacement of the deck is limited to avoid significant pounding between deck and the abutment which could induce undesirable damage and inhibit the effectiveness of isolation. Therefore, the parameters of the LRBs are selected such that the displacement of the deck is limited to 7.7 cm (Table 2.1), corresponding to the spectral response at Charleston, SC, while assuming that the site class is E and following a general design process as described in the current AASHTO specifications (AASHTO 2010). The response spectra corresponding to a hazard level earthquake with 7% probability of exceedance in 75 years in Charleston for 5% damping are given in Fig. 2.3.

2.2. Input Ground Motions

When assessing the bridge seismic response at a particular region, a large number of ground motion time histories that are representative of the area are needed. However, strong ground motions records for the CEUS do not exist. Therefore, synthetic acceleration time histories must be used instead. Fernandez and Rix (2006) developed 240 ground motions for selected cities within the Upper Mississippi Embayment including Memphis, TN; Jonesboro, AR; Jackson, TN; Blytheville, AR; Paducah, KY; Cape Girardeau, MO, and Little Rock, AR. These ground motions are probabilistic motions consistent with hazard levels of 10%, 5% and 2% probability of exceedance in 50 years, corresponding to return periods of 475, 975 and 2475 years, respectively. Sixty of the 240 motions (20 motions for each hazard level) selected at random are used in this study to perform the nonlinear time history analyses.

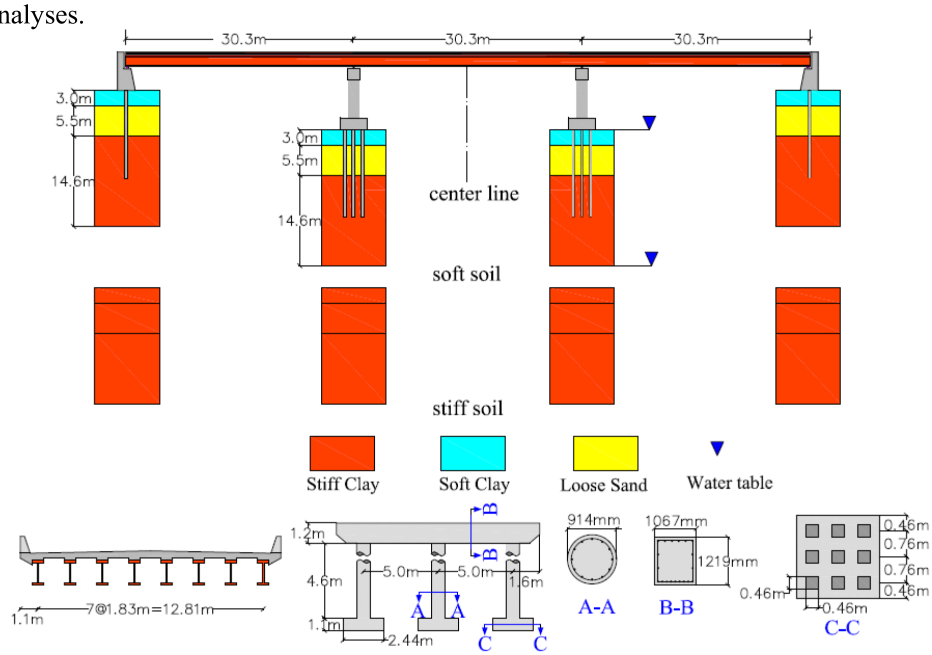

Fig. 2.1 Layout of MSCS girder bridge for CEUS on soft soil (dry or saturated) and stiff soil

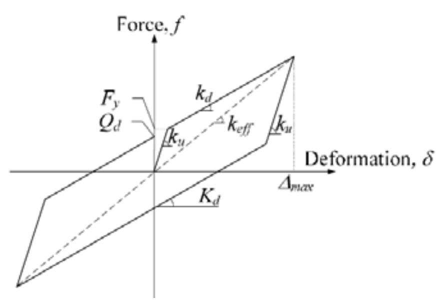

Fig.2.2 Characteristics of bilinear isolation bearings as per AASHTO Guide Specifications (AASHTO 2010)

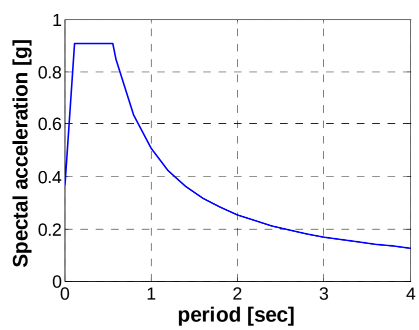

Fig. 2.3 Design response spectrum for Charleston, SC

Table 2.1. Parameters of bilinear modeling for LRBs at the abutments and the bents.

LRB location	K_e (kN/m)	K_b (kN/m)	F_y (kN)
abutment	2 204	220.4	21.3
bent	5 973	597.3	57.6

3. FRAGILITY ANALYSIS FOR KEY COMPONENTS OF THE CBSF SYSTEMS

Fragility curves capture the conditional probability of a structure to reach or exceed predefined damage states given a hazard intensity measure (IM). Fragility curves are developed here for bridges using the results of nonlinear time history analysis in the demand modeling. The supports at the column base and the abutments are first considered fixed, and then the 3D/2D/1D models are used to consider SSI effects for stiff and soft soil conditions. Nonlinear time history analyses are performed and bridge response variables monitored, including the curvature of the columns, the displacement of the bearings at the bents, and the displacement of the bearings at the abutments. After each nonlinear time history analysis, the maximum demand-capacity ratios are recorded and a probabilistic seismic demand model (PSDM) is constructed. This PSDM establishes a relationship between maximum demand-capacity ratio and the IM the in the form of a power law (Cornell et al.2002). The choice of IMs plays a crucial role in the fragility analysis since it is related to the uncertainty in the PSDM analysis. A previous study shows that *PGV* is an optimal IM based on its efficiency, practicality, sufficiency and hazard computability for both liquefiable and non-liquefiable soils (Wang et al. 2012 b). Therefore *PGV* is used as the IM in this study.

If both the demand and the capacity of the structural components are assumed to follow a lognormal distribution (Nielson 2005), the conditional probability of failure can be defined as:

$$P\left[\frac{D}{C}\geq 1|\,\mathrm{IM}\right]=\Phi\left(\frac{\ln\left(\frac{S_D}{S_C}\right)}{\sqrt{\beta_{D/C}^2+\beta_C^2}}\right) \tag{3.1}$$

where $\Phi(\cdot)$ is the standard normal cumulative distribution function; D is the structural demand; C is the structural capacity; S_C is the median value of structural capacity; S_D is the median value of structural demand; $\beta_{D/C}$ is the logarithmic standard deviation of the demand-capacity ratio; and β_C is the logarithmic standard deviation of the capacity. If capacities are estimated for each bridge component, in addition to the demand models, then fragility curves can be generated using Eqn. 3.1. The capacities for the components are discussed in the next Section.

3.1. Limit States for Bridge Component Fragility Analysis

Limit states for bridge components combine a qualitative description of their level of damage and associated traffic closure times with a quantitative metric of their physical state (Nielson and DesRoches 2007). Often, four damage states—slight, moderate, extensive and complete—are defined for the fragility analysis of bridges and their components. A summary of the capacity limit states for each damage state of key CBSF components is shown in Table 3.1. The following sub-sections describe the adopted limit states.

3.1.1. Columns

The damage states for columns are quantified using curvature ductility which is defined as the maximum realized curvature divided by curvature at the yielding point of the outer most steel reinforcing bar. The quantitative limit states along with their variability presented in Table 3.1 are adopted from Nielson (2005) for the poorly confined columns common in the CEUS region.

3.1.2. Steel bearings

The damage states of high-type steel bearings are usually based on experimental data. Typically, the bearing displacement is used to describe its damage states. The median values and dispersions of the prescriptive limit states previously used in the work by Nielson (2005) are used in this study to define the limit states of the fixed bearings at the bent and the expansion bearings at the abutment as listed in Table 3.1. These limit states values are based on the tests by Mander et al. (1996).

3.1.3. Lead rubber bearings

The damage states of isolation bearings are usually determined based on experimental studies. In addition, the displacements of the bearings cannot be too large in order to avoid pounding and unseating. For lead rubber bearings, shear strain is often used to describe the damage states since it can characterize well the bearing behavior due to the direct dependence of the shear modulus and damping of rubber on shear strain (Zhang and Huo 2009). Current AASHTO specifications (AASHTO 2010) require that the shear strain of LRBs should not exceed 250% with the consideration of the resulting pounding and unseating. Therefore, complete damage of the LRB is defined as the shear strain exceeding 250%. Other limit states are defined based on the response characteristics of the rubber material. For instance, previous experimental studies showed that material behavior of the rubber compound remains almost linear up to a shear strain of 100% while the damping will decrease when shear strain exceeds 200% due to hardening of elastomeric material (Naeim and Kelly 1999). This paper assumes a coefficient of variation of 0.25 for slight and moderate damage states and 0.5 for extensive and complete damage states for the LRBs based on the authors' judgment and literature review. The adopted limit states of the LRBs in this study are consistent with previous studies (Zhang and Huo 2009).

Table 3.1. Limit states for the CBSF system components

Bridge component	Monitored Component Response	Slight Damage		Moderate Damage		Extensive Damage		Complete Damage	
		Med (S_c)	Disp (β_c)	Med (S_c)	Disp (β_c)	Med (S_c)	Disp (β_c)	Med (S_c)	Disp (β_c)
Column (*)	Curvature ductility	1.29	0.59	2.10	0.51	3.52	0.64	5.24	0.65
Fixed bearing (*)	Longitudinal displacement (mm)	6.0	0.25	20.0	0.25	40.0	0.47	186.6	0.65
Expansion bearing (*)	Longitudinal displacement (mm)	34.4	0.60	104.2	0.55	136.1	0.59	186.6	0.65
LRB	Shear strain	100%	0.25	150%	0.25	200%	0.5	250%	0.5

* Nielson, 2005; Med: median value; Disp: dispersion

3.2. Component Fragility Curves for Both Isolated and As-built CBSF Systems

The methodology described in the previous Section is used to derive the fragility curves of the as-built highway MSCS bridges in the CEUS and the retrofitted bridges using LRBs. Fig. 3.1, 3.2 and 3.3 show the fragility curves for the column, the bearings at the bents, and the bearings at the abutments for the fixed base, stiff soil type and dry soft soil without liquefaction cases. It can be seen that isolation reduces the column and abutment bearing failure probability for all four damage states regardless of the type of boundary conditions (i.e., SSI or fixed base). However, the bearings at the bents experience a higher failure probability for the isolated bridge than that of the as-built bridge especially for moderate, extensive and complete damage states. The reason that the failure probability of the bearings at the bents is higher for the isolated bridge than the as-built bridge is that the displacements of the fixed bearings at the bents of the as-built bridge are very small and isolation increases the displacement of the LRBs at the bents. Therefore, the system damage state may be underestimated if only the damage in columns is considered. In addition, it is observed that SSI has significant effects on the response of the isolated bridges, and tends to decrease the effectiveness of the isolation system. The level of failure probability for the columns and bearings is found to be higher for soft soil types compared to stiff soil types and fixed base cases, highlighting that soft soils decrease the efficiency of the isolation system. For instance, *PGV*s corresponding to the median fragility of the column are 87.6cm (fixed base), 53.6cm (stiff soil) and 47.5cm (dry soft soil) for moderate damage states, respectively. Even for stiff soil whose response would be expected to close to the fixed base condition, the median *PGVs* decrease by 38.8% for the moderate damage state compared to the fixed base case. For soft soils, the median *PGVs* decrease further by 11.3% compared to the stiff soil case. The median *PGV*s of the abutment bearings decrease by 62.9% for the moderate damage state compared to the fixed base case, while for the soft soil its median *PGV*s decreases further by 22.1% compared to the stiff soil case. This observation demonstrates that neglecting the SSI effect may significantly underestimate the failure probability of isolated bridges, and that isolation is more effective for a bridge built on stiff soils, while it is less effective for a bridge built on soft soils. The

SSI effects need to be considered in the design of isolated bridge even for stiff type soil considerations. In addition, results from this study shows that multiple components of the isolated system should be used for system-level fragility evaluation because only considering the response of the columns may underestimate the failure probability of the system.

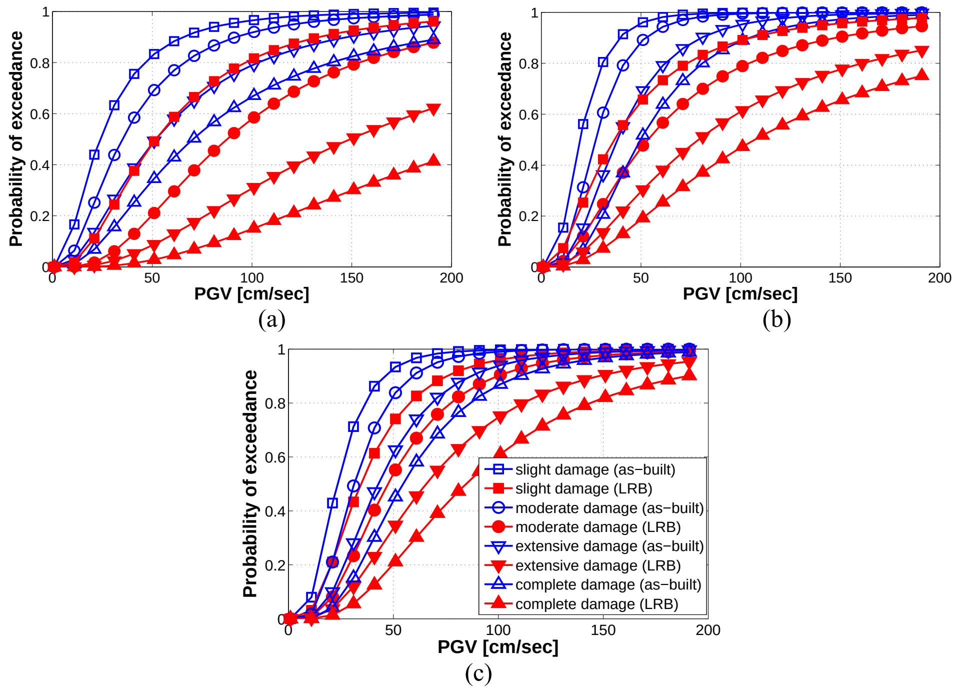

Fig. 3.1 Fragility curves of the columns for the as-built and isolated CBSF system: (a) fixed base; (b) stiff soil; (c) dry soft soil

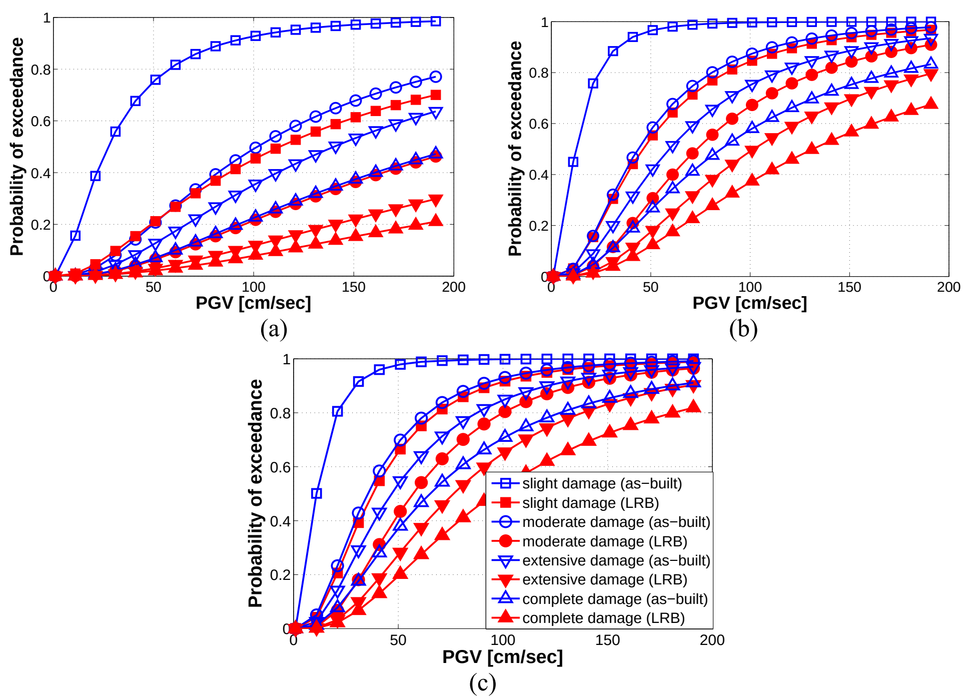

Fig. 3.2 Fragility curves of the bearings at the abutment for the as-built and isolated CBSF system: (a) fixed base; (b) stiff soil; (c) dry soft soil

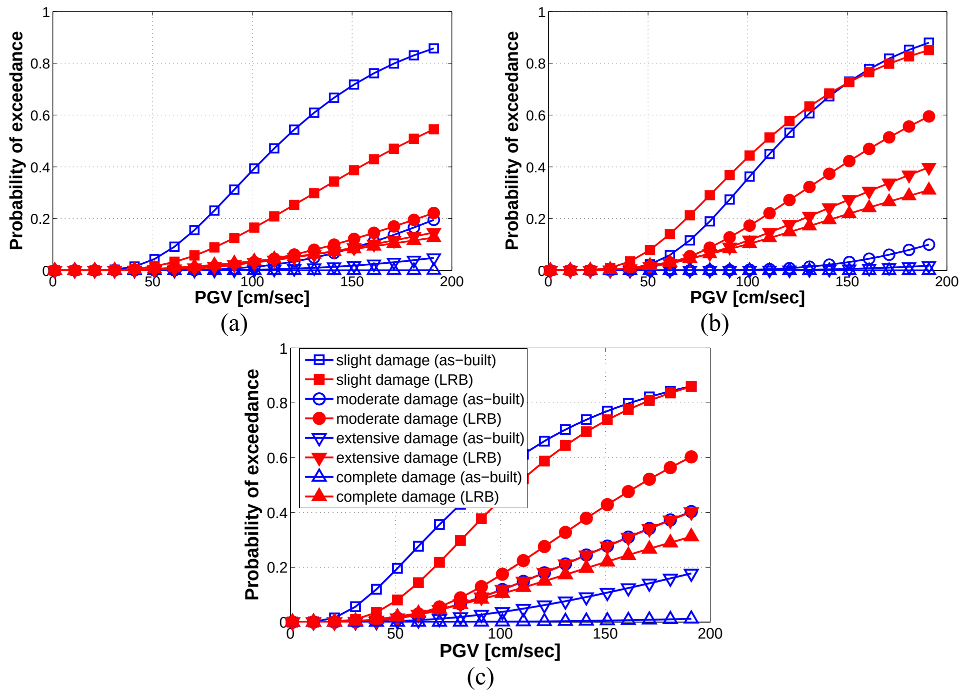

Fig.3.3 Fragility curves of the bearings at the bents for the as-built and isolated CBSF system: (a) fixed base; (b) stiff soil; (c) dry soft soil

4. EFFECTS OF LIQUEFACTION ON THE SEISMIC ISOLATED BRIDGE

Another related issue of interest is to assess the influence of liquefaction on the seismic efficiency and fragility of the isolated bridge compared to non-liquefiable SSI effects. In order to isolate the impact of liquefaction effects, the same nonlinear time history analyses to develop the fragility curves in Section 3 are repeated by changing the dry sand to saturated sand conditions for the bridge sites. Fig. 4.1 shows the fragility curves of the moderate damage state for the columns, the LRBs at the bents and the LRBs at the abutments for the dry soft soil and saturated soft soil along with the stiff clay and fixed base cases. For the purpose of comparison, the fragility curves of key components of the as-built bridge on the saturated sands are also shown in Fig. 4.1. For other damage states, similar trends are observed regarding the influence of liquefaction on fragility. From this figure it is observed that isolation is still very effective on liquefiable soils by increasing the median *PGV*s of the columns and the bearings at the abutments by 59.3% and 88.6% respectively while liquefaction decreases the median *PGV*s of the bearings at the bents by 31.6% compared to the as-built bridge. Since the overall failure probability of the bearings at the bents is very small, isolation can effectively reduce the failure probability of the CBSF system on liquefiable soils due to typical dominance of columns in system-level fragility. For dry sands condition, isolation is less effective than the liquefaction case by increasing the median *PGVs* of the columns only by 14.6% compared to the as-built bridge. In addition, the failure probability of the columns of the isolated bridge on liquefiable soil which would be expected to be the highest is even smaller than that on the stiff clay. Liquefaction provides a means of natural base isolation decreasing the curvature demands on the columns, which is similar to the effect of a base isolator in accordance with previous studies (Mylonakis and Gazetas 2000; Kwon et al. 2008). This phenomenon demonstrates that isolation bearings can be used on liquefiable soil if lateral spreading and slope instability are managed. However, attention should be paid to the design of the isolation bearings since liquefaction may increase the displacement of the isolation bearings. For instance, in this study, LRBs at the bents experience an 18.1% increase in median fragility at the moderate damage states compared to the non-liquefiable condition. The above study confirms that isolation is an effective retrofit option for MSCS bridges in the CEUS region even if liquefaction occurs.

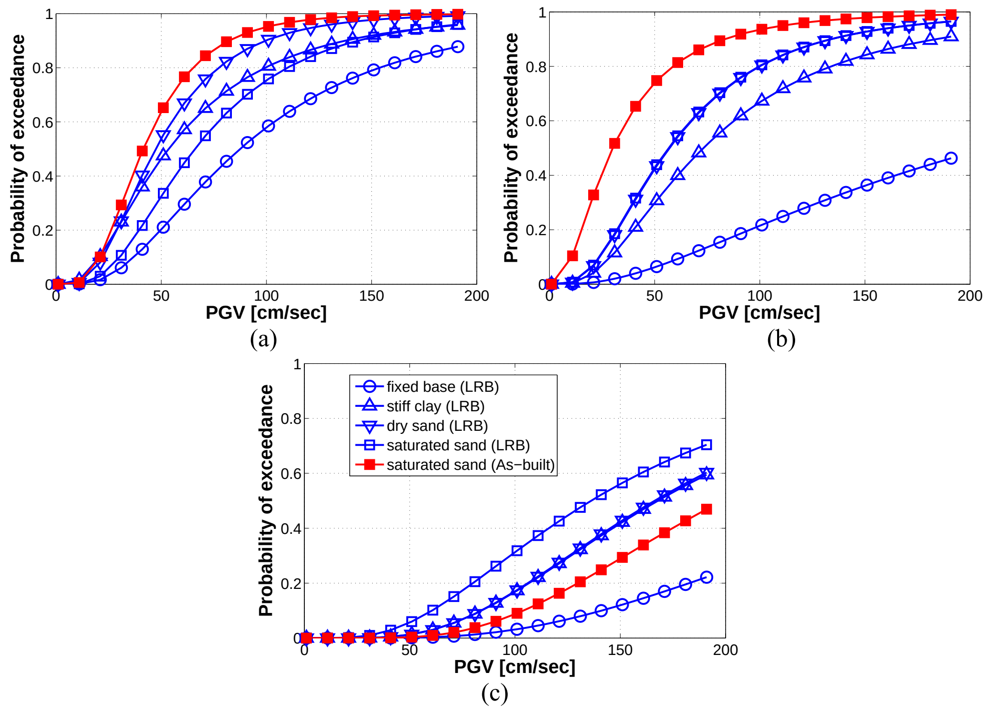

Fig. 4.1 Comparison of fragility curves of components of the isolated CBSF system for moderate damage state: (a) column; (b) LRBs at the abutments; (c) LRBs at the bents

5. SUMMARY AND CONCLUSIONS

This paper investigates the effects of SSI and liquefaction on the seismic performance of both an un-retrofitted multi-span continuous steel (MSCS) girder bridge typical of the central and eastern United States and a seismically isolated version of it. An advanced model of the coupled bridge soil foundation (CBSF) system with a three-dimensional bridge superstructure, two-dimensional soil domain, and one-dimensional set of *p-y*, *t-z*, and *q-z* springs is built in OpenSees to efficiently incorporate SSI and liquefaction effects. Two soil profiles are considered, one representative of stiff type soils and another representative of soft type soils which are also used to investigate the liquefaction effects by changing the water elevation. Nonlinear time history analyses of the bridges are then conducted to derive key component fragility curves of the CBSF system. The analysis of results shows that isolation reduces the failure probability of key components for both fixed base and SSI cases. However, SSI tends to reduce the efficiency of the LRBs and increase the failure probability of the isolated bridges. Even for stiff clay, SSI should also be considered because the failure probability of key components of the CBSF system may be significantly underestimated if the SSI effects are not considered. It is also found that isolation is more effective for a bridge built on stiff soils, as opposed to soft soils. The fragility analysis results of the CBSF system show that liquefaction has a beneficial effect on the fragility of the columns, by providing a means of natural base isolation that decreases the curvature demands on the columns. However, liquefaction may increase the displacement of the isolation bearings by more than 18%. This study shows that isolation bearings can still be effectively used in liquefiable sites if lateral spreading and slope instability are prevented. Traditional bridge seismic design that neglects SSI will underestimate the failure probability of certain components of the CBSF system. The results suggest that the effects of SSI should be more explicitly considered in the fragility analysis of isolated bridges and their critical components, especially for soft soil conditions. This study also shows that isolation offers a viable retrofit option by reducing the column demands and replacing the vulnerable steel bearings in the CEUS region even if liquefaction occurs.

AKCNOWLEDGEMENT

The authors gratefully acknowledge the support of this research by the National Science Foundation through Grants CMMI-0728040 and CMMI-0923493, as well as the Department of Civil and Environmental Engineering at Rice University. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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