Research Journal of Applied Sciences, Engineering and Technology 4(19): 3791-3800, 2012
ISSN: 2040-7467

Submitted: April 03, 2012 Accepted: April 30, 2012 Published: October 01, 2012

Seismic Demands for Pile-Supported Wharf Structures with Batter Piles

[1]Rouhollah Amirabadi, [2]Khosrow Bargi and [2]Hamid Heidary Torkamani
[1]Member of Civil Engineering Department, University of Maragheh, Maraghe, Iran
[2]Member of Civil Engineering Department, School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran, P.O. Box 11155-4563

Abstract: This study develops an optimal Probabilistic Seismic Demand Model (PSDM) for pile-supported wharves whit batter plies. Four bins with twenty non-near-field ground motions and three typical pile-supported wharf structures from western United States ports are used to determine an optimal PSDM by using Probabilistic Seismic Demand Analysis (PSDA). PSDA is used to compute the relationship between Engineering Demand Parameters (EDPs) and earthquake Intensity Measures (IMs). An optimal PSDM should be practical, sufficient, effective and efficient-all tested through several IM-EDP pairs. It has been found that for these types of structures, the optimal model comprises a spectral IM, such as spectral acceleration and one of several EDPs. These EDPs are considered for local (moment curvature ductility factor), intermediate (displacement ductility factor and horizontal displacement of embankment) and global (differential settlement between deck and behind land) response quantities. The considered PSDMs are a critical component in performance-based seismic design and seismic risk assessment. Results can be used in probabilistic framework for performance-based design developed by Pacific Earthquake Engineering Research (PEER) center.

Keywords: Intensity measure, performance based design, pile-supported wharf, probabilistic seismic demand analysis, seismic demand

INTRODUCTION

Probabilistic Seismic Demand Model (PSDM) is one component of the second-generation Performance Based Earthquake Engineering (PBEE-2) framework developed by Pacific Earthquake Engineering Research (PEER) center. A probabilistic model, directly relates the deciding variables to the measures describing the site seismicity. This study addresses one component of de-aggregated PEER-PBEE equation, an interim demand model, or the relation between structural demand and earthquake intensity. Probabilistic Seismic Demand Model (PSDM) is used in order to estimate the mean annual frequency (ν) of exceeding a given structural engineering demand measure (EDP>edp) in a postulated hazard environment (IM = im), expressed as follows (Cornell and Krawinkler, 2000):

$$v\left(EDP \geq edp\right) = \int_{edp} G\left(EDP \geq edp \middle| IM = im\right) \left| d\lambda(im) \right| \qquad (1)$$

where,

G(EDP≥edp|IM = im): Demand model, to predict the exceeding probability of engineering demand parameter (edp) for seismic hazard intensity measure (im).

λ(im): Seismic hazard model, to predict the annual exceeding probability of seismic hazard intensity measure (im) in the seismic hazard environment.

Many researchers have indicated the disadvantages of the traditional static procedures for seismic design (Gardoni *et al*., 2003; Goel and Chopra, 2004; Kunnath and Kalkan, 2004; Kalkan and Kunnath, 2006; Akkar and Metin, 2007; Goel, 2007; Zhong *et al*., 2008). In addition, the necessity for incorporating Performance-Based Engineering (PBE) concepts into seismic design has been widely recognized (Cornell and Krawinkler, 2000; Mackie and Stojadinovic, 2003; Moehle and Deierlein, 2004).

A great deal of research was carried out to develop the probabilistic seismic demand models for bridge and building structures; however less effort was made in the case of port structures.

Luco (2002) used a combination of two intensity measures to account for the effect of the near-field ground motions on the nonlinear structural responses. Gardoni *et al*. (2002) proposed a general Bayesian methodology to construct probabilistic models that account for any source of information, including field measurements, laboratory data and engineering judgment. Mackie and Stojadinovic (2003) conducted a sensitivity analysis to explore the

Corresponding Author: Rouhollah Amirabadi, Student, Member of Civil Engineering Department, University of Maragheh, Maraghe, Iran, Tel: +982123015683

effect of different ground motion intensities on the seismic demands of RC bridges. Gardoni *et al*.(2003) and Zhong *et al*.(2008) constructed probabilistic seismic demand models for Reinforced Concrete (RC) bridges that account for the prevailing uncertainties such as uncertainties in the structural properties, statistical uncertainties and model errors. Zhong *et al*. (2008) developed demand models for RC bridges with two-column bents. Gardoni *et al*. (2003) and Zhong *et al*. (2008) used limited laboratory data on RC bents and one numerical model of a full bridge to calibrate the proposed demand models. Quindan *et al*. (2010) developed probabilistic seismic demand models for Reinforced Concrete highway bridges with one single-column bent in addition they proposed bivariate deformation-shear fragility.

Considering few efforts for development of probabilistic seismic demand models for port structures, this study aims to develop PSDM for pile-supported wharves. Focusing on pile-supported wharves whit batter plies, commonly used in western United States ports, this study develops an optimal Probabilistic Seismic Demand Model (PSDM). Probabilistic Seismic Demand Analysis (PSDA) was used to determine the relationship between Engineering Demand Parameters (EDPs) and earthquake Intensity Measures (IMs).

Among numerous possible combinations of IM-EDP pairs, optimal PSDM was driven based on practicality, sufficiency, effectiveness and efficiency. For these structures, the optimal model comprises a spectral IM, such as spectral acceleration and one of several EDPs. These EDPs are considered for local (moment curvature ductility factor), intermediate (displacement ductility factor and horizontal displacement of embankment) and global (differential settlement between deck and behind land) response quantities.

DEVELOPING PROBABILISTIC SEISMIC DEMAND MODEL STEP BY STEP

The required steps for developing PSDM for a pile-supported wharf whit batter pile is proposed as follows:

- Choose a pool of representative ground motions near the site as earthquake events for PSDA analysis. They are categorized according to their magnitudes and closest distances.
- The typical structures are selected and the proper EDPs are determined to assess the performance of structures under considered ground motions.
- Construct the numerical model of chosen target wharf structures, a nonlinear model using FLAC-2D is generated to evaluate the seismic performance of structures.
- The nonlinear dynamic analyses are performed for all ground motions (here eighty ground motion records) and structures.
- A demand model is formulated between the resulting IMs and EDPs.

Based on these steps, a procedure to construct the PSDM for pile-supported wharves whit batter piles are proposed in the following sections.

Ground motions: To select representative ground motions for the PSDA of wharf structures at a particular site, records are better to select obtained from stations with similar geologic conditions to that site. The number of ground motions should be sufficient to yield response quantity statistics. In addition, the selected ground motion records should capture the characteristics of the possible seismic hazards (Krawinkler *et al*., 2003). In present study, eighty ground motions were selected as representative ground motions for the PSDA. The details are in; http://peer. berkeley.edu/peer_ ground_ motion_ database.

Following bin approach proposed by Shome and Cornell (1999), the selected eighty ground motions are subdivided into four bins whit twenty earthquakes, based on their moment Magnitude (M) and the closest distance between the record location and the fault (R). Each bin represents specific combinations of the earthquake characteristics and the collection of all bins captures all possible characteristics. Thus, each bin should have sufficient earthquakes to capture the variability of the characteristics of that bin and the same number of ground motions as each of the other bins to provide an even representation of the possible characteristics without introducing bias into the ground motion characteristic or the assessment of the seismic demand variables of interest. Furthermore, ground motions within bins can be scaled up to higher intensities, without introducing bias. We consider the following four bins:

- **Bin (1) LMLR:** Large Magnitude and Large R ($M>6.5$ & $R>30$)
- **Bin (2) LMSR:** Large Magnitude and Small R ($M>6.5$ & $15<R<30$)
- **Bin (3) SMLR:** Small Magnitude and Large R ($M<6.5$ & $R>30$)
- **Bin (4) SMSR:** Small Magnitude and Small R ($M<6.5$ & $15<R<30$)

Figure 1 shows the distribution of selected ground motion records in M-R space. The specific selected records were similar to those used by (Mackei) in a companion PEER research project related to California highway bridges (Mackie and Stojadinovic, 2003).

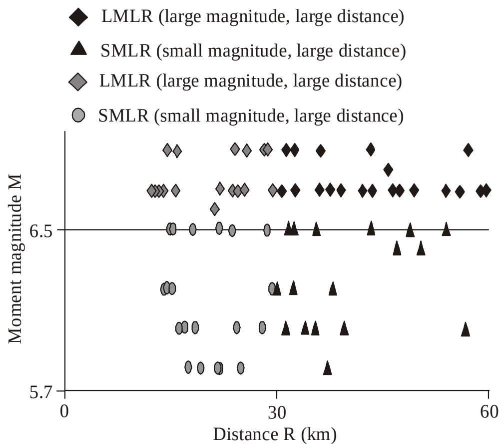

Fig. 1: Distribution of ground motion records in M-R space

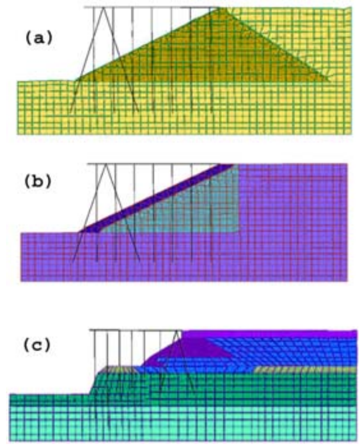

Fig. 2: Cross section of FLAC numerical modeling, a) SMS02 b) JCB01 c) POOAK

Characteristics of pile-supported wharf structures: Two centrifuge models SMS02 (Boland *et al*., 2001a) and JCB01 (Boland *et al*., 2001b) and 7th Street terminal at the Port of Oakland (POOAK), were selected as typical pile-supported wharves with batter piles. POOAK that damaged seriously in Loma Prieta earthquake (1989), was selected as an example of existing pile-supported wharf with batter piles (Egan *et al*., 1992). The centrifuge models were carried out at the geotechnical-modeling center of California University, (UC Davis), to evaluate the seismic performance of pile-supported wharf structures. Detailed information regarding the geotechnical parameters values, structural element properties and model geometry can be easily found in Boland *et al*. (2001a) and Boland *et al*. (2001b).

Numerical simulation: A two-Dimensional (2D) finite difference model has been constructed to simulate seismic performance of pile-supported wharf structures. In order to construct nonlinear numerical model, the software FLAC2D (Fast Lagrangian Analysis of Continua) has been used Itasca (2000). Cross section of two-dimensional models is shown in Fig. 2.

Different analyses: Herein, three different analyses were performed for each three pile-supported wharf structures;

- Validation analysis for calibrating the input data and verifying the output data with centrifuge models results or observed values in past earthquake for POOAK;
- Static pushover analysis for obtaining yield values;
- Dynamic time-history analysis for seismic demand values determination.

Static analysis: A pushover analysis was performed for all structures in order to evaluate:

Table 1: Pushover analysis results of PSDA models

Parameter	PSDA models SMS02	JCB01	POOAK
d_y (m)	0.20	0.3	0.070
P_y (kN)	4070.00	3590.0	1113.000
d_u (m)	1.39	1.4	0.245
P_u (kN)	5830.00	4962.0	1390.000

- Yield values of structural elements
- The yield sequence of structure
- The transition from elastic response to final state of failure

The yield lateral force value (P_y) was determined as the break-point in the curve and the ultimate lateral force value (P_u) as the point at which the double plastic hinge is developed in the initial pile (at the pile cap and embedded portion of the pile). The yield lateral displacement (d_y), P_y, ultimate lateral displacement (d_u) and P_u were presented for all PSDA models in Table 1.

Dynamic analysis: In order to determine seismic demands, dynamic analyses were performed for all ground motions and structures. In these analyses, each of wharf structures were subjected to eighty ground motions time history record and the values of Engineering Demand Parameters (EDPs) were determined through non-linear dynamic time history analyses. It should be mentioned that firstly, a static analysis was performed to allow application of the gravity loads. Numerous quantities of EDPs were monitored to extract IM-EDP pairs, which are mentioned in the following sections.

Different IMs and EDPs for PSDA: In PSDA the relation between structural EDPs and specific IMs is formulated by statistic nonlinear time-history analysis and finally all interested analyses are combined into PSDMs. Whit this in mind, we need to determine suitable EDPs and IMs. In theses IMs, the characteristics such as spectral quantities, duration, energy related quantities and frequency content are all included. According to literature of filed damage date during past earthquakes, the pile-supported wharf EDPs were derived (Werner, 1998). Different EDPs were considered for local, intermediate and global response quantities and described in the following sections.

Defining optimal PSDM: Here, optimal is defined as being practical, sufficient, effective and efficient. An IM-EDP pair is practical if it has some direct correlations with known engineering quantities and makes engineering sense. Specifically, the practical IMs and EDPs are the ones which derived from known ground motion parameters and nonlinear analysis, respectively. Such demand models, having no conditional dependence, are sufficient (Cornell *et al*., 2002). The effectiveness of a demand model is determined by evaluating the Eq. (1) in a closed form. In this regard the EDPs are assumed to follow a log-normal distribution (Cornell and Krawinkler, 2000) and the demand model is described as follows:

$$EDP = a(IM)^b \tag{6}$$

The coefficients are determined by applying a linear or piecewise-linear regression in log-log space.

Different PSDM: Considering possible combination of IM-EDP pairs the different PSDM were developed for all selected structures, as proposed in the following sections.

Optimal PSDMs resulted from local EDPs: Local EDPs describe the damage in the elements of pile-supported wharf structure or in certain locations. Based on the type of structure (with or without batter piles) and expected failure modes there are many varieties in these parameters (Yang, 1999).

In order to maintain comparability of EDPs, a PSDM was first developed at the landward vertical pile for μ_Φ. In this regard, the results for structures with batter pile are shown in Fig. 3. They produced very efficient fits and their dispersions are shown at the bottom of figures.

In all figures, The Sa refers to spectral acceleration at the natural period of wharf structure. As well, the values of dispersions were displayed in the parentheses in which, the first value refers to JCB01, second value refers to SMS01 and the last values refers to the dispersion representing the POOAK.

Since the structural damages of pile-supported wharf are governed by stress/strain state rather than displacement, so a PSDM is developed using maximum compression strain of top of landward vertical piles (ϵ_{max}) as local EDP and spectral acceleration as IM. The resulted PSDMs are shown in Fig. 4. These models were efficient and effective, as expected.

Batter piles are the most efficient structural components for resisting lateral load caused by earthquake, mooring and berthing and crane operation. Large stress concentrations and shear failures of concrete batter piles have been observed during past earthquakes. With this in mind, the maximum axial force ratio at critical pile cross section of batter pile selected as another local EDP, Fig. 5.

Very low dispersion, shown in Fig. 5, indicates that maximum axial force ratio is very efficient. Computed dispersion for each of them shows that if we use deformation indices we will face more than 100% increasing in dispersion by using internal forces indices. On the other hand, because the stress-strain relations of structural materials in all models have been considered as bilinear, the internal forces indices have ultimate limit. When internal forces indices reach their ultimate limit in specified earthquake intensity, they do not increase by

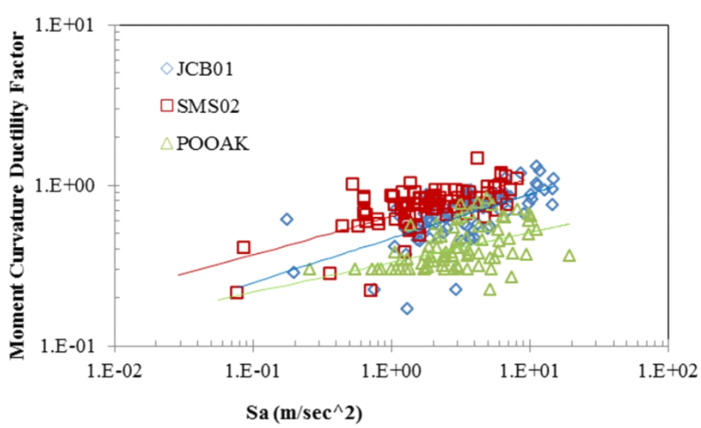

Fig. 3: Sa-μ_Φ (σ = 0.35, 0.24, 0.27)

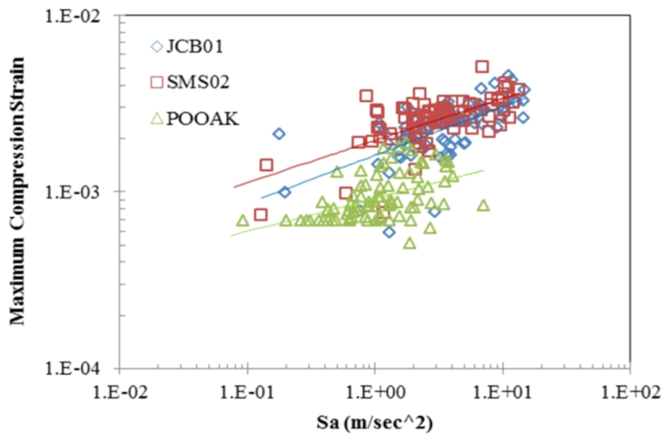

Fig. 4: Sa-ϵ_{max} (σ = 0.35, 0.27, 0.32)

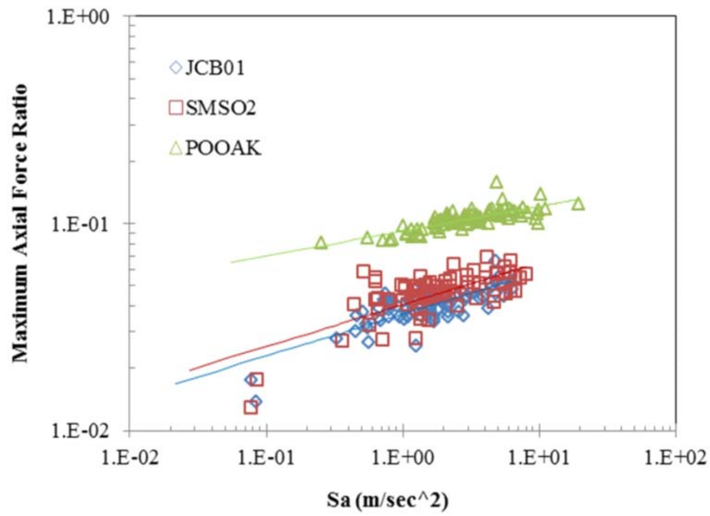

Fig. 5: Sa-axial force ratio of piles (σ = 0.14, 0.18, 0.07)

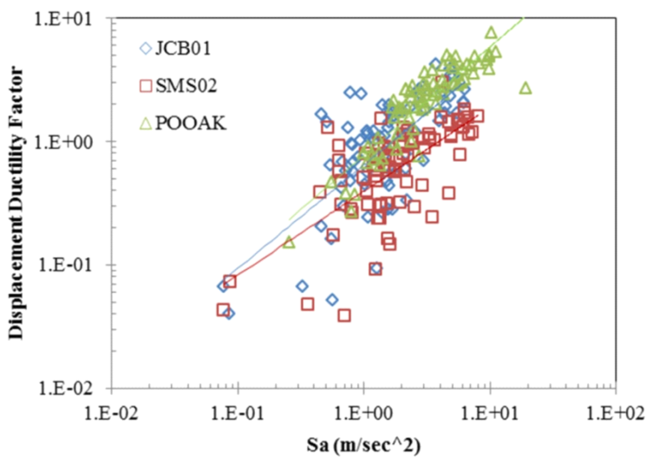

Fig. 6: Sa-μ_d (ó = 0.31, 0.29, 0.23)

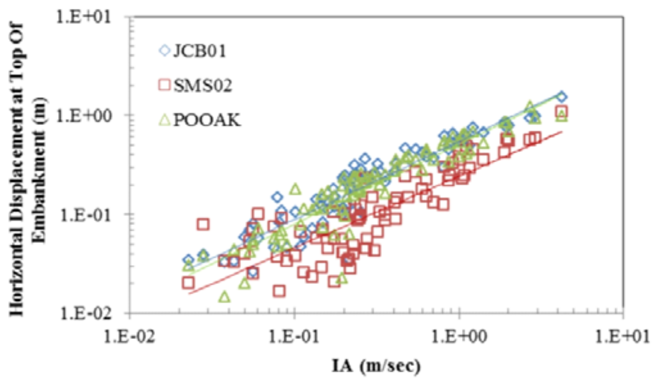

Fig. 7: Arias intensity (I_A)-horizontal displacement at the top of embankment (σ = 0.26, 0.30, 0.22)

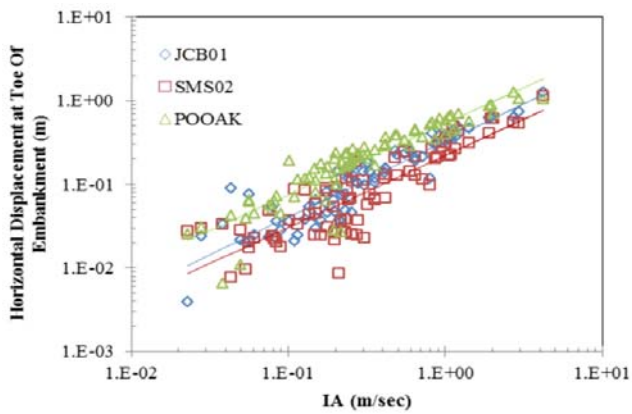

Fig. 8: Arias intensity (I_A)-horizontal displacement at the toe of embankment (σ = 0.29, 0.34, 0.25)

enhancement of earthquake intensity. This discussion confirms that the intermediate and global EDPs should be focused.

Optimal PSDMs resulted from intermediate EDPs: Intermediate EDPs estimate the state of structure or dike/slope. Intermediate EDPs are defined as follows;

- Intermediate EDPs based on local EDPs.
- The settlement and horizontal displacement of rock dike at head and toe.
- The difference between vertical displacement of the first and end points of deck.

The first intermediate EDPs are estimated as a weighted average of local EDPs and dissipated energy at each element is usually used as the weighting function. The optimal IM is Sa (spectral quantities can be used interchangeably).

Fig. 6 shows the PSDM using displacement ductility factor (μ_d) as EDP and Sa as IM. In case of using Spectral acceleration (Sa) or Spectral displacement (Sd) instead of arias Intensity (I_A), the dispersion will increase 30% in average (Fig. 7). In some models, this fact causes problems in the efficiency for examining optimal PSDM. However, Sa is more practical than IA. Therefore, to eliminate Sa intensity shifts due to the variation in natural periods of structures, the use of IA is offered. The PSDMs for horizontal displacement at the toe of embankment/slope are shown in Fig. 8, IA as the IM. The last PSDM was developed for differential settlement at the deck. The optimal model was obtained using Sa as IM for pile-supported wharf structures with batter piles, Fig. 9.

Optimal PSDMs resulted from global EDPs: The overall state of structure and dike/slope are estimated altogether by Global EDPs. There are three engineering demand parameters classified as the global EDPs;

- Differential settlement between deck and behind land
- Global normalized dissipated energy
- Park and Ang's global damage index

The final PSDM was developed for differential settlement between deck and behind land. The optimal model was obtained by using Sa as shown in Fig. 10.

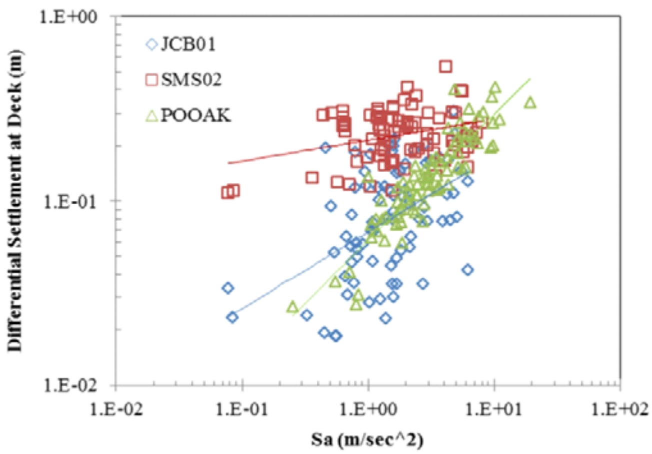

Fig. 9: Sa-differential settlement at deck (σ = 0.61, 0.32, 0.26)

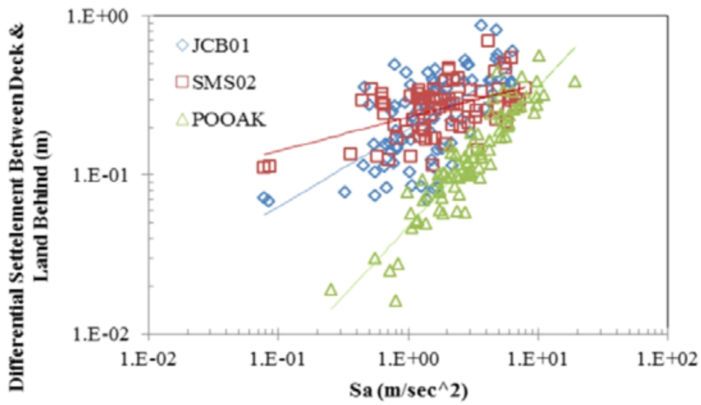

Fig. 10: Sa-differential settlement between deck and behind land: (σ = 0.35, 0.28, 0.22)

Other possibilities are incorporating SED, PGV as the IM. These options increase dispersions by approximately 20-40% comparing with those in using Sa. However, dispersion decreases about 20% by using I_A as IM in comparison to the case of using Sa.

VERIFICATION OF OPTIMAL IM-EDP PAIRS

In order to investigate the optimality for obtained PSDMs, the relationship between Sa and displacement ductility factors were selected to investigate other demand model properties. In addition to the mean, calculated for the models, here $\mu \pm 1\sigma$ (16^{th} and 84^{th} percentile) distribution stripes can be generated as well:

$$EDP_{\pm 1\sigma, j} = \sqrt{\sigma \left((1+N)^{-1} + \frac{\left[IM_j - \mu(IM)\right]^2}{\sum_{i=1}^{N}\left[IM_i - \mu(IM)\right]^2} \right)} \tag{8}$$

The probability distributions were studied in the above mentioned example and shown in Fig. 11. So far, the efficiency and effectiveness have been established; however; the sufficiency and practicality should be confirmed. The classification of practicality is, unfortunately, a subjective exercise. In most port structures guideline, μ_d is used for evaluating seismic performance of pile-supported wharf structures (Werner, 1998: OCDI, 2009). In other words, displacement ductility factor is one of the practical EDPs. The sufficiency is needed to determine whether total probability theorem can be used for de-aggregating various components of PEER framework equation.

The regression was performed on the IM-EDP pair residuals, conditioned on magnitude of ground shaking (M_w), closest distance from fault (R) in order to assess the sufficiency. The resulting sufficiency plots for interested PSDM are shown in Fig. 12 and 13. Figure 12 takes M_w from the database of IMs and plots it versus the residual of the chosen IM-EDP fit for both subgroup structures.

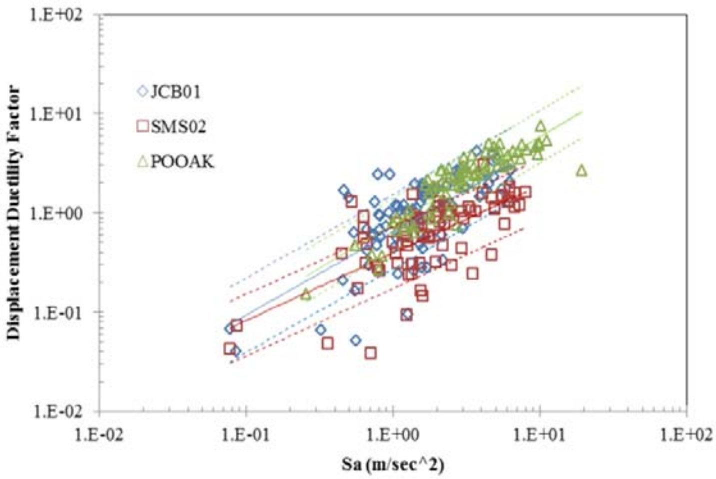

Fig. 11: μ±1σ strippes (Sa-μ_d) (σ = 0.31, 0.29, 0.23)

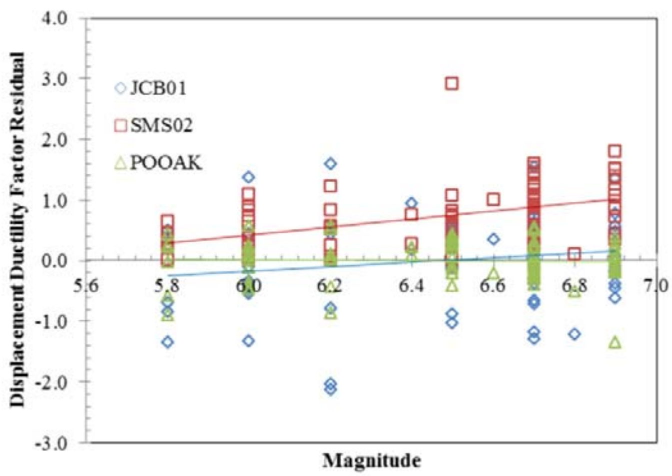

Fig. 12: Magnitude (M_W) dependence (Sa-μ_d) (slope = 0.26, 0.46, 0.04)

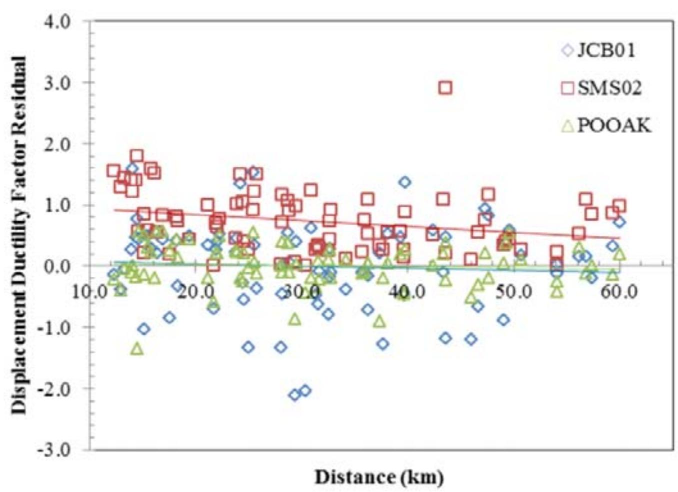

Fig. 13: Distance dependence (Sa-μ_d) (D = -0.003, -0.009, -0.002)

Similarly, Fig. 13, the residuals are plotted versus R, for both subgroup structures. The slopes of linear regression lines are shown at the bottom of each plot. Small slope values of all parameters indicate that the demand models have the sufficiency required to neglect the conditional probability. A more rigorous definition of sufficiency can be used where the regression lines are ambiguous. The fitting of residual data is equivalent to the multivariate linear regression shown in the Eq. (9):

$$\ln(EDP) = A+B\ \ln(IM)+C(M)+D(R) \quad (9)$$

The median coefficient values are shown in the plots; however, the statistics can be obtained for an arbitrary confidence interval. If there is no residual dependence on M_w and R, the coefficients C and D (i.e., slopes) are zero somewhere within the defined confidence interval. Regarding the purposes of this study, no residual dependence on 80% confidence interval is sufficient.

In short, the spectral values (Sa, Sd) were found as the optimal existing IM when coupled with a variety of EDPs. These EDPs include local measures (curvature ductility factor), intermediate measures (displacement ductility factor and horizontal displacement of embankment) and global measures (differential settlement between deck and land behind). With a small trade-off in practically, the use of period-independent Arias intensity as the IM was also acceptable as an optimal IM. The spectral values can be considered as superior IM quantities as they not only incorporate measures of the motion frequency content, but are directly related to modal response of the given structure. Arias intensity does not include this structure-dependent information, but does include the cumulative effect of energy input from the ground motion. There are several practical reasons to utilize Arias intensity though, given that it can be used to compare structures at constant intensity levels and has been recently described by an attenuation relationship (Travasarou *et al*., 2003).

RESULTS AND DISCUSSION

The optimal PSDMs were selected out of huge IM-EDP pairs based on practicality, effectiveness, efficiency and sufficiency. By practicality, PSDM is realistic in an engineering sense; the effectiveness describes its ability to fit a linear or piecewise linear form to the data for use in the closed-form solutions of Eq. (1). The dispersion around these linear fits is described by its efficiency. PSDM should be robust, effective and efficient across all interested periods in order to be used as a design tool. Finally, a sufficient model has no residual dependence on Mw and R, allowing hazard de-aggregation. In all considered models, the spectral quantities (Sa, Sv, Sd) produced optimal models. The optimal period-independent IM in the resulting PSDMs can met similar conclusions by Arias intensity as well. The period-independent IMs can be effectively employed in the above PSDMs in order to identify the design trends more clearly. The complementary EDPs were coupled with these IMs and separated based on the scope of response quantity. The optimal PSDMs were determined as moment curvature ductility factor (μ_Φ) for local EDPs. Maximum axial force ratio was determined as optimal local EDPs, especially for the structures with batter piles. The intermediate EDPs are considered as displacement ductility factor (μ_d) and the horizontal displacement at top and toe of embankment. Finally, the optimal global EDP quantity is the differential settlement between deck and behind land.

CONCLUSION

In this research, several EDPs describing seismic performance of pile-supported wharf structures and possible IMs were proposed. EDPs are related to IMs by PSDM, in the PEER-PBEE framework. The mentioned PSDMs are one component of PEER-PBEE framework.

Focusing on typical pile-supported wharves whit batter piles as commonly used in the ports of western United States, PSDMs were developed by using PSDA. Two centrifuge models tested at UC Davis and 7th Street terminal at the Port of Oakland were selected to determine the optimal PSDM.

PSDMs for a class of structures provide information about the probability of exceeding critical levels of chosen structural EDPs in a given seismic hazard. PSDMs, by themselves are design tools; they provide information on how variations in structural and geotechnical design parameters can change the expected demand on the structure. They can also be used in a PBEE framework, such as the one developed by PEER. In such design frameworks, PSDMs are coupled with both ground motion intensity models and structural element fragility models to yield probabilities of exceeding structural performance levels in certain seismic hazard.

The occurrence of no shear failure in the piles, especially in the batter piles, was not correctly assumed. Shear interaction was not considered due to the FLAC limitations. This is an inherent limitation in the PSDMs, presented in this study. However, bending failure precedes shear failure in structural component, based on PIANC (2001).

REFERENCES

Akkar, S. and A. Metin, 2007. Assessment of improved nonlinear static procedures in FEMA-440. J. Struct. Eng., 133(9): 1237-1246.

Boland J.C., S.M. Schlechter, S.E. Dickenson, B.L. Kutter and D.W. Wilson, 2001a. Pile-Supported Wharf Centrifuge Model (SMS02). Data report for centrifuge modeling studies funded by the Pacific Earthquake Engineering Research Center and National Science Foundation, OSU Geotechnical Engineering Report No.GEG04-2000, approx. pp: 200.

Boland J.C., S.M. Schlechter, S.E. Dickenson, B.L. Kutter and D.W. Wilson, 2001b. Pile-Supported Wharf Centrifuge Model (JCB01). Data report for centrifuge modeling studies funded by the Pacific Earthquake Engineering Research Center and National Science Foundation, OSU Geotechnical Engineering Report No. GEG04-2000, approx, pp: 200.

Cornell C.A. and H. Krawinkler, 2000. Progress and Challenges in Seismic Performance Assessment. PEER Center News, 3(2).

Cornell C.A., F. Jalayer, R.O. Hamburger and D.A. Foutch, 2002. Probabilistic basis for 2000 SAC/FEMA steel moment frame guidelines. J. Struct. Eng., 128(4): 526-533.

Egan J.A., R.F. Hayden, L.L. Scheibel, M. Otus and G.M. Serventi, 1992. Seismic repair at seventh street marine terminal. Grouting, Soil Improvement and Geosynthetics. ASCE Geotech. Spec. Public., 2(30): 867-878.

Gardoni, P., A.D. Kiureghian and K.M. Mosalam, 2002. Probabilistic capacity models and fragility estimates for reinforced concrete columns based on experimental observations. J. Eng. Mech., 128(10): 1024-1038.

Gardoni, P., K.M. Mosalam and A.D. Kiureghian, 2003. Probabilistic seismic demand models and fragility estimates for RC bridges. J. Earthq. Eng., 7(1): 79-106.

Goel, R.K. and A.K. Chopra, 2004. Evaluation of modal and FEMA pushover analysis: SAC buildings. Earthq. Spectra, 20(1): 225-254.

Goel, R.K., 2007. Evaluation of current nonlinear static procedures using strong motion records. Structures Congress 2007, ASCE, Reston,Va.

Itasca., 2000. FLAC version 4. 0 User's Manual. Itasca Consulting Group, Minneapolis, MN.

Kalkan, E. and S. Kunnath, 2006. Adaptive modal combination procedure for nonlinear static analysis of building structures. J. Struct. Eng., 132(11): 1721-1731.

Krawinkler, H., R. Medina and B. Alavi, 2003. Seismic drift and ductility demands and their dependence on ground motions. Eng. Struct., 25(5): 637-653.

Kunnath, S. and E. Kalkan, 2004. Evaluation of seismic deformation demands using nonlinear procedures in multistory steel and concrete moment frames. ISET J. Earthq. Technol., 41(1): 159-182.

Luco, N., 2002. Probabilistic seismic demand analysis, SMRF connection fractures and near-source effects. Ph.D. thesis, Dept. of Civil and Environmental Engineering, Stanford Univ., Stanford, Calif.

Mackie, K. and B. Stojadinovic (2003). Seismic Demands for Performance-Based Design of Bridges. PEER report No. 2003/16.

Moehle, J. and G.G. Deierlein, 2004. A framework methodology for performance-based earthquake engineering. Proceeding, 13th World Conf. on Earthquake Engineering, Vancouver, Canada.

Quindan, H., G. Paolo and H. Stefan, 2010. Probabilistic seismic demand models and fragility estimates for reinforced concrete highway bridges with one single-column bent. J. Eng. Mech., 136(11): 1340-1353.

Shome, N. and C.A. Cornell, 1999. Probabilistic Seismic Demand Analysis of Nonlinear Structures. Reliability of Marine Structures Report No. RMS-35, Dept. of Civil and Environment. Engineering, Stanford University, California.

Technical Standard for Port and Harbour Facilities in Japan (OCDI), 2009. Ministry of Transport, Japan.

Travasarou, T., J.D. Bray and N.A. Abrahamson, 2003. Empirical attenuation relationship for arias intensity. J. Earthq. Eng. Struct. Dyn.. 32(7): 1133-1155.

Werner, S., 1998. Seismic Guidelines for Ports. Ports Committee of the Technical Council on Lifeline Earthquake Engineering (TCLEE), Reston, VA, ASCE.

Yang, D.S., 1999. Deformation-Based Seismic Design Models for Waterfront Structures. Dissertation. Oregon State University, Corvallis, OR.

Zhong, J., P. Gardoni, D. Rosowsky and T. Haukaas, 2008. Probabilistic seismic demand models and fragility estimates for reinforced concrete bridges with two-column bents. J. Eng. Mech., 134(6): 495-504.