Probabilistic Seismic Demand Models of PEER-PBEE framework for Pile and Deck Structures

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ABSTRACT

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 representative relation between intensity measures (IMs) and engineering demand parameters (EDPs) forms the basis of the PSDM. This study aims to develop an optimal PSDM for typical pile-supported wharf structures using 2D numerical model of 5 centrifuge models tested at UC Davis campus and performing probabilistic seismic demand analysis (PSDA) under a pool of ground motion records. In PSDA the relation between certain EDPs and specific IMs is formulated by statistic nonlinear time-history analysis. For these structures, the optimal PSDM derived through several IM_EDP pairs, should be practical, sufficient, effective and efficient. According to these criteria, in resulted IM-EDP pairs, Sa determined as the optimal IM and moment curvature ductility factor (µΦ), horizontal displacement of embankment and differential settlement between deck and behind land are considered for optimal local, intermediate and global EDP quantities, respectively. The Sa-displacement ductility factor (µd) determined as the best optimal IM-EDP pair. The results are useful to owners and designers for assessment seismic performance of pile-supported wharf structures.

Keywords: Performance based earthquake engineering (PBEE), Probabilistic seismic demand model (PSDM), Pile–Supported Wharf, Engineering demand parameters (EDP), Intensity measure (IM).

1. Introduction

The PEER-PBEE methodology is expressed through a framework equation that estimates the mean annual frequency of events where a specified decision variable exceeds a given threshold (Cornell and Krawinkler 2000). Performance-based earthquake engineering (PBEE) describes a quantitative means for designers to achieve predetermined performance levels in a specific hazard levels. PEER performance-based design framework utilizes the total probability theorem to de-aggregate the PBEE problem into several interim probabilistic models. This de-aggregation involves global or component damage measures (DM), structural or nonstructural engineering demand parameters (EDP), and seismic hazard intensity measures (IM).Probabilistic seismic demand model (PSDM) is one component of de-aggregated PEER-PBEE equation, and relates EDPs to IMs.

The principal objective of this research is to develop optimal probabilistic seismic demands models (PSDMs) for pile supported wharves by using probabilistic seismic demand analysis. In PSDA the relation between certain EDPs and specific IMs is formulated by statistic
nonlinear time-history analysis and finally all interested analyses are combined into PSDMs. Regarding to this purpose, firstly different EDPs describing seismic performance of pile supported wharf structure, and possible intensity measures (IMs), representing ground motion characteristics are proposed. Then considered EDPs were derived using FLAC two-dimensional model of five centrifuge models of pile-supported wharves tested at UC Davis campus, and performing through non-linear time history analysis under eighty non-near field ground motion records. Finally, EDPs were related to IMs according to PEER framework. After development of PSDMs for possible combination of IM-EDP pairs, optimal PSDM were determined.

For these type of structures, optimal PSDM should be practical, sufficient, effective and efficient. In PSDA the relation between class-specific structural EDPs and specific ground motion intensity measures (IMs) is formulated by statistic nonlinear time-history analysis and finally all interested analyses are combined into PSDMs.

1. Pile-Supported wharf Structures

Five centrifuge models, structures on vertical pile -NJM01, NJM02, SMS01- (McCullough 2000), and with batter pile -SMS02 and JCB01 -(McCullough 2001), are the selected structures for developing optimal PSDMs. These models were carried out at the Center for Geotechnical Modeling- University of California, Davis campus (UC Davis) to evaluate seismic performance of pile-supported wharf structures. The detailed information of centrifuge models- geometry, soil and structural elements properties, and simulation methodology has been represented by (McCullough N. J. 2003).

2. Ground Motions

To evaluate the engineering seismic demand (EDP) values of interest and their associated uncertainties, it is critical to select representative ground motions for the virtual experiments. 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, 2003). In present paper, 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 (Shome and Cornell, 1999), the eighty selected ground motions are subdivided into four bins with 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:

1) Bin(1) =LMLR: Large Magnitude & Large R (M>6.5 & R>30)
2) Bin(2) =LMSR: Large Magnitude & Small R (M>6.5 & 15<R<30)
3) Bin(3) =SMLR: Small Magnitude & Large R (M<6.5 & R>30)
4) Bin(4) =SMSR: Small Magnitude & Small R (M<6.5 & 15<R<30)
The specific selected records were similar to those used by (Mackei) in a companion PEER research project related to California highway bridges.

3. Numerical Simulation

In this research, a two-dimensional (2D) reference model has been developed 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. The detailed information regarding steps of numerical modeling and model properties have been presented by (Amirabadi, 2011). Note that in all models, the Finn and Byrne model of FLAC 2D has been used to carry out semi-coupled dynamic groundwater flow calculations. Two dimensional models of each five centrifuge models are shown in figure 1.

![Numerical models showing soil layers, piles and deck elements](attachment:image)

**Figure 1:** Numerical models showing soil layers, piles and deck elements a)SMS01 b)SMS02 c)NJM01 d) NJM02 e) JCB01

4. PSDA Analysis

For each nonlinear model, three different analyses were performed:

1. Validation analysis to calibrate the input data and verify the output data with centrifuge models results.
2. A pushover analysis to evaluate: a) yield values of structural elements; b) The yield sequence of structure; c) The transition from elastic response to final state of failure
3. Dynamic analysis to determine seismic demands. Firstly a static analysis was performed to allow application of the gravity loads. Numerous quantities were monitored to extract IM-EDP pairs.

Pushover curve is shown in figure 2.
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 2.

Table 2: Pushover analysis result

| Parameter               | Models          |
|-------------------------|-----------------|
|                         | NJM01 | NJM02 | SMS01 | SMS02 | JCB0 |
| $d_y$ (m)               | yield lateral displacement | 0.23  | 0.22  | 0.23  | 0.20  | 0.30 |
| $P_y$ (KN)              | yield lateral force     | 3040  | 2400  | 2400  | 4070  | 3590 |
| $d_u$ (m)               | ultimate lateral displacement | 1.56  | 1.12  | 1.12  | 1.39  | 1.40 |
| $P_u$ (KN)              | ultimate lateral force     | 4331  | 3789  | 3744  | 5830  | 4962 |

5. Different IM-EDP Pairs

There are many IMs representing characteristics of a specific ground motion, such as ($S_a$, PGA, PGV etc.) also there are many EDPs to present seismic performance of a wharf structure (such as Drift ratio, Residual tilting etc.). In PSDA the relation between class-specific structural EDPs and specific ground motion intensity measures (IMs) is formulated by statistic nonlinear time-history analysis and finally all interested analyses are combined into PSDMs. Hence, in order to develop PSDM firstly we need to propose proper EDPs describing seismic performance of pile-supported wharf structures and possible IMs representing ground motion properties.
Table 2: Different IMs

| Intensity Measure (IM) | Name                                      |
|------------------------|-------------------------------------------|
| D                      | Duration                                  |
| Mw                    | Magnitude                                 |
| R                      | Epicentral distance                       |
| Td                     | Strong motion duration                    |
| PGA                    | Peak ground acceleration                  |
| PGV                    | Peak ground velocity                      |
| PGD                    | Peak ground displacement                  |
| Sa                     | Elastic spectral acceleration, 5% damping  |
| Ss                     | Elastic spectral velocity, 5% damping      |
| Sd                     | Elastic spectral displacement, 5% damping  |
| Sa, Cordova            | Sa predictor [Cordova 2000]               |
| IA                     | Arias Intensity                           |
| IV                     | Velocity Intensity                        |
| CAV                    | Cumulative absolute velocity              |
| CAD                    | Cumulative absolute displacement          |
| Arms                   | Root mean square acceleration             |
| Vrms                   | Root mean square velocity                 |
| Drms                   | Root mean square displacement             |
| Ic                     | Characteristic intensity                  |
| SED                    | Specific Energy Density                   |
| FR1                    | Frequency ratio 1                         |
| FR2                    | Frequency ratio 2                         |

Table 2 and 3 describes different IMs and EDPs used in this study, respectively. In these IMs, the characteristics such as spectral quantities, duration, energy related quantities and frequency content are all included.

Different EDPs derived through documented damage during past earthquakes (Seismic Design Guideline for Port Structure. 2000), (Werner S., ed. 1998), and considered for local, intermediate, and global response quantities. 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 D.S. 1999). Intermediate EDPs estimate the overall state of structure or dike/slope. The overall state of structure and dike/slope are estimated altogether by Global EDPs.

Table 3: Classified Structural EDPs

| Class of EDP | Engineering Demand Parameter (EDP)                          |
|--------------|-------------------------------------------------------------|
| Local        | Park and Ang’s local damage index (DPA)                     |
|              | Normalized dissipated energy (ED)                           |
|              | Residual Displacement Index (RDI)                           |
|              | Drift ratio (D)                                             |
|              | Plastic Rotation (θP)                                       |
|              | Residual Tilting (α)                                        |
|              | Moment curvature ductility factor (μk)                      |
Maximum compressive strain ($\varepsilon_{\text{max}}$)  
Axial force ratio of piles

| Intermediate | Park and Ang’s local damage index ($DPA$) | Normalized dissipated energy ($E_N$) | Residual Displacement Index ($RDI$) | Drift ratio ($D$) | Plastic Rotation ($\theta_p$) | Residual Tilting ($\alpha$) | Moment curvature ductility factor ($\mu_{\phi}$) | Displacement ductility factor ($\mu_d$) | Horizontal displacement at the top of embankment | Horizontal displacement at the toe of embankment | Differential settlement at deck |
|--------------|------------------------------------------|-----------------------------------|---------------------------------|-----------------|----------------------------|-------------------------|---------------------------------|---------------------------------|------------------------------------------------|------------------------------------------------|----------------------------------|
| Global       | Global normalized dissipated energy      | Park and Ang’s global damage index | Differential settlement between deck and behind land |

3. Defining Optimal IM-EDP Pairs

A principal milestone in developing PSDM for pile-supported wharf structure is searching for optimal IM-EDP pairs. As mentioned above, there was a wide array of combination of IMs and EDPs for every analysis. Therefore, it is critical to select an optimal PSDM (i.e. optimal IM-EDP pair) to narrow the amount of data. In order to determine the optimal PSDM, at first we need to define that what optimal means here.

There are 4 criteria to determine a PSDM as optimal:

1. **Practicality**: 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.

2. **Sufficiency**: If IM-EDP pair has no statistical dependence on the ground motion characteristics, such as magnitude and distance (i.e. having no conditional dependence) are sufficient (Cornell C. A., Jalayer F., Hamburger R. O., Foutch D. A. 2002).

3. **Effectiveness**: The effectiveness of a demand model is determined by evaluating the PEER-PBEE equation in a closed form. In this regard the EDPs are assumed to follow a log-normal distribution (Shome N, Cornell CA, 1999) and the demand model is described as follows:

$$EDP = a(IM)^b$$  
Eq. 1

The coefficients are determined by applying a linear or piecewise-linear regression in log-log space.
4. **Efficiency**: Efficiency is the variability between EDP and IM and is evaluated by the dispersion, defined as the standard deviation of demand model residuals logarithm (Shome N, Cornell CA, 1999), presented as:

\[
\sigma = \sqrt{\frac{\sum_{i=1}^{n} \left( \ln(EDP_{i,fit}) - \ln(EDP_{i}) \right)^2}{n-3}}
\]

Eq. 2

In addition, there is two important points to choose optimal PSDMs;

1. Efficiency is not the only measure for evaluating optimality. Some models exhibit lower dispersions than others do; however, this fact by itself does not make them optimal, and practicality, effectiveness, and sufficiency should be considered, carefully.

2. Among the resulted optimal models, which are practical, effective, and sufficient, dispersion is the measure for considering the PSDM as the best. The PSDMs with dispersions of 0.20-0.35 are superior.

**4. Different Combination of IMs and EDPs**

The considered EDPs (table 3) derived through nonlinear dynamic analysis, performed for each numerical model under eighty ground motion records. The resulted EDPs were plotted versus considered IMs in log-log scale for each subsequent PSDM figure with the IM on the horizontal and EDP on the vertical axes. Note that this is a standard method for plotting any IM-EDP relationship. In the following sections, PSMDs using different IM-EDP pairs are demonstrated. And then we determine the Optimal PSDM among resulted different PSDMs.

**4.1. Spectral Acceleration versus Moment Curvature Ductility Factor (Sa-\(\mu\Phi\))**

Firstly, a PSDM developed at the landward vertical pile for \(\mu\Phi\) and the results are shown in figure 3. They produced very efficient fits and their dispersions are shown at the bottom of figures. Pile-supported wharf structures with and without batter piles have different seismic performance. Structures without batter pile resist the earthquake-induced lateral loads/displacement by bending the pile and associate moment resistance, while Pile-supported wharves with batter piles resist by tensile and compression that induced in batter piles. Due to different seismic performance, as seen in figure 3, the \(\mu\Phi\) values in landward vertical piles of the structures with batter piles are lower in comparison to those of the structures without batter piles. According to figure 3 (b), in some earthquake intensities, \(\mu\Phi\) is greater than one, indicating that the curvature ductility factor is greater than elastic amount.
Sa is dependent on natural period of structure. Therefore, the sought IM was necessarily independent of the period, but still exhibited the properties of optimal PSDM. Based on the obtained results SED or PGV are used as the period-independent IMs yield models with the dispersions of approximately 20% higher than Sa. However, IA, as the period-independent IMs yield models with dispersions, is approximately equal to Sa.

4.2. Spectral Acceleration versus Maximum Compressive Strain (Sa- $\varepsilon_{\text{max}}$)

Since the structural damages of pile-supported wharf are governed by stress/strain state rather than displacement, so a PSDM is developed using maximum compressive strain of the top of landward vertical piles ($\varepsilon_{\text{max}}$) as local EDP and Sa as IM. The resulting PSDMs are shown for the structures with and without batter piles, in figure 4.These models were efficient and effective, as expected. It should be mentioned that due to a weak layer of Bay Mud in NJM02 and SMS01 models, the maximum bending moment occurred due to the pile pinning at the pile cross section that was situated in this layer. The bending moment at this pile cross section is much larger than the bending moment created in the top of the pile.

Figure 4: Sa-$\varepsilon_{\text{max}}$: a) The structures with batter piles ($\sigma=0.35, 0.27, 0.32$); b) The structures without batter piles ($\sigma=0.38, 0.35, 0.32, 0.30$).
4.3. Spectral Acceleration versus Maximum Axial Force Ratio

Batter piles are the most efficient structural components for resisting lateral load caused by earthquake, mooring, berthing and crane operation. The frame resulting from batter pile-deck system is much more rigid than that of vertical piles. 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, figure 5.

Very low dispersion, shown in figure 5, indicates that maximum axial force ratio is very efficient. By comparing PSDMs resulting from local EDPs, we can find out that while all PSDMs show good effectiveness and efficiency, only one of them (maximum compression strain) is practical from engineering testing standpoint. Considering local level, strain is the only measure that can be quantified during experimentation. The analytical material models would be needed for deriving stress/force from mentioned quantity.

![Figure 5: Sa-Axial force ratio for the structures with batter piles (σ=0.14, 0.18, 0.07).](image)

4.4. Spectral Acceleration versus Displacement Ductility Factor (Sa-µd)

The PSDMs for Sa-µd pair have been developed for both subgroup structures in figure 6.

![Figure 6: Sa-µd: a) The structures with batter piles (σ=0.31, 0.29, 0.23); b) The structures without batter piles (σ=0.34, 0.29, 0.31, 0.36).](image)
4.5. Arias Intensity versus Horizontal Displacement of Embankment

The horizontal displacement at the top and toe of embankment give useful information about failure modes of soil and superstructure. The PSDMs for horizontal displacement at the top of embankment/slope are shown in figure 7 using IA as IM.

![Figure 7: IA-Horizontal displacement at the top of embankment: a) Structures with batter piles (σ=0.26, 0.30, 0.22); b) structures without batter piles (σ=0.30, 0.25, 0.28, 0.21).](image)

The horizontal displacements at the top of embankments were predictable regarding the placement of soil layers and their geotechnical properties. For example, the deformation in JCB01 model is more than SMS02 due to the existence of loose sand layer. In case of using $S^a$ or $S_d$ instead of IA, the dispersion will increase 30% in average. In some models, this fact causes problems in the efficiency for examining optimal PSDM. But $S_a$ is more practical than IA. However, it may be useful for the designer to consider period-independent IMs. Therefore, to eliminate $S_a$ 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 figure 8.

![Figure 8: IA-Horizontal displacement at the toe of embankment. a) The structures with batter piles (σ=0.29, 0.34, 0.25); b) The structures without batter piles (σ=0.30, 0.28, 0.32, 0.26).](image)

The toe of embankment in the models with two slopes is the toe of the lower embankment. Horizontal displacement values are slightly lower at the toe of all models in comparison with
those at the top of their embankments. On this basis, the form of embankment failure can be envisioned. For all models, the slope failure is the base failure.

### 4.6. Spectral Acceleration versus Differential Settlement at Deck

Since cranes operations is rigorously dependent on differential settlement at deck, so the last PSDM was developed for differential settlement at the deck. The optimal model was obtained using Sa as IM, figure. 9.

![Figure 10](example_image)

**Figure 10:** Sa-Differential settlement between deck and behind land: a) the structures with batter piles ($\sigma=0.35, 0.28, 0.22$); b) the structures without batter piles ($\sigma=0.30, 0.31, 0.33, 0.36$).

### 5. Determining Optimal IM-EDP Pairs

This section addresses the search for an optimal PSDM among possible combinations of IM and EDP.A PSDM describes the relation between certain EDPs and specific IMs. In previous sections, PSDM for each of several IM-EDP pairs have been developed. Based on definition in section 3, this section investigates the optimality for obtained PSDMs, For this purpose, the relationship between Sa and displacement ductility factors were selected (figure. 6) in order to investigate other demand model properties. In addition to the mean, calculated for the models, here $\mu \pm 1\sigma$ (16thand 84thpercentile) distribution stripes can be generated as well, below formula:

$$
EDP_{\pm1\sigma,j} = \sqrt{\frac{1}{N^{-1} + \frac{\sum_j (IM_j - \mu(IM))^2}{N}}} 
$$

Eq. 8

The probability distributions are studied in the above mentioned example and shown in figure 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, $\mu_d$ is used for evaluating seismic performance of pile-supported wharf structures (Seismic Design Guideline for Port Structure. 2000), (Technical Standard for Port and Harbor Facilities in Japan, 2009). A clearly one of
the practical EDPs is the displacement ductility factor. The sufficiency is needed to determine whether total probability theorem can be used for de-aggregating various components of PEER framework equation.

Figure 11: \( \mu \pm 1\sigma \) stripes (\( Sa - \mu_d \)): a) the structures with batter piles; b) the structures without batter piles.

The regression was performed on the IM-EDP pair residuals, conditioned on M, R, in order to assess the sufficiency. The resulting sufficiency plots for interested PSDM are shown in figures 12-13. Figure 12 takes Mw from the database of IMs and plots it versus the residual of the chosen IM-EDP fit for both subgroup structures. Similarly, figure 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.

\[
\ln(EDP) = A + B \ln(IM) + C(M) + D(R)
\]

Eq. 9

Figure 12: Mw dependence (\( Sa - \mu_d \)): a) The structures with batter piles (\( C = 0.26, 0.46, 0.04 \)); b) The structures without batter piles (\( C = 0.44, 0.31, 0.31, 0.20 \)).

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 and R, the
coefficients C and D are zero somewhere within the defined confidence interval. Regarding the purposes of this paper, no residual dependence on 80% confidence interval is sufficient.

In short, the spectral values \( (S_a, S_d) \) 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, however, 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 T. 2003).

**Figure 13:** R dependence \( (S_a-\mu_d) \): a) The structures with batter piles \( (D=-0.003, -0.009, -0.002) \); b) The structures without batter piles \( (D=-0.004, 0.005, 0.003, -0.014) \).

### 5.1 Conclusions

In this research, PSDM as one component of de-aggregated PERR-PBEE framework were developed for pile-supported wharf structures. Five centrifuge models tested at UC Davis were selected to determine the optimal PSDM using 2D numerical model and performing PSDA for each model under eighty different ground motion records. Firstly different EDPs describing seismic performance of pile supported wharf structure, and possible IMs, representing ground motion characteristics were proposed. Then considered EDPs were derived through non-linear time history analysis. Finally, EDPs were related to IMs according to PEER framework. After development of PSDMs for possible combination of IM-EDP pairs, optimal PSDM were determined for any classified EDPs.

- Properties of optimal model described as: *practicality, effectiveness, efficiency and sufficiency*;

1. By practicality, PSDM is realistic in an engineering sense.
2. The effectiveness describes its ability to fit a linear or piecewise linear form to the data for use in the closed-form solutions of PEER-PBEE equation.

3. The dispersion around these linear fits is described by its efficiency.

4. A sufficient model has no residual dependence on Mw and R, allowing hazard de-aggregation.

- The optimal PSDMs were determined as below

   **Table 6: Optimal IM-EDP Pairs**

   | Class of EDP | Engineering Demand Parameter (EDP)                      | Intensity Measure(IM) |
   |--------------|--------------------------------------------------------|-----------------------|
   | Local        | Moment curvature ductility factor(μΦ)                  | Spectral acceleration (Sa) |
   | Intermediate | Displacement ductility factor (μd)                     | Spectral acceleration (Sa) |
   |              | Horizontal displacement of embankment                  | Arias Intensity (IA)    |
   | Global       | Differential settlement between deck and behind land   | Spectral acceleration (Sa) |

- Among the resulted optimal IM-EDP pairs, which are practical, effective, and sufficient, dispersion is the measure for considering the PSDM as the best. The PSDMs with dispersions of 0.20-0.35 are superior. According to this point, the (Sa-μd) determined as the best IM-EDP pair.

- 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).

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