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Research Article

Probabilistic Assessment for Seismic Performance of Pile-Supported Wharves

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Abstract: The main objective of this study is to investigate the influence of uncertainties associated with the material properties on the seismic performance of pile-supported wharves. For this purpose a two-dimensional finite difference model, representing typical pile-supported wharf structures from western United States has been constructed using software FLAC2D. Incremental dynamic analysis has been applied to evaluate the response of wharf structure under different levels of seismic loading. The uncertainties at both structural and geotechnical parameters have been investigated using a tornado diagram and a First-Order Second-Moment (FOSM) analysis. It has been found that the uncertainties at the dead load of structure, friction angle of rock fill and the porosity of rock fill contribute most to the variability of the displacement ductility factor of the pile-supported wharf structures. Based on the results, design considerations have been provided.

Keywords: Incremental dynamic analysis, pile-supported wharf, tornado diagram analysis, uncertainty

INTRODUCTION

Seaport transportation systems play a significant role in the world's economy. They are important components of regional and local transportation network, since they provide a financially beneficial method for transporting a large amount of cargoes into and out of a region via water (Shinozuka, 2009). Berthing Facilities are one of the main components of seaport transportation networks and wharf structures are the main component of berthing facilities. Wharf structures play a crucial role in the transportation system in terms of evacuation of people before and after natural or man-maid disasters like earthquakes and explosions, especially when other transportation systems (like as land and air) fail to deliver. Past experience have demonstrated that seaports facilities are often vulnerable to severe damage during not only in the case of a strong earthquake but also under moderate earthquakes (Werner, 1998). During past decades, a number of pile-supported wharves have suffered extensive earthquake induced damage due to poor seismic design.

Considering above reasons, seismic performance of port facilities should be enhanced to guarantee the fact that they will be functional before and after earthquake for required services. Therefore, we need to an accurate evaluation of the seismic performance of port facilities under different levels of seismic loading. This is one of the critical issues of Performance Based Earthquake Engineering (PBEE) methodology. Recent efforts have been aimed at moving away from traditional single limit state and deterministic design techniques and developing rational methods and guidelines for the analysis and design of seaports structures. A great deal of research using numerical simulations was carried out to investigate the seismic performance of wharf structures) in deterministic way (McCullough *et al.*, 2007; Na *et al.*, 2008; Chang *et al.*, 2010); however, less effort was made in probabilistic assessment of wharves. The recent effort is the case study related to caisson type quay walls (Na *et al.*, 2008).

A pile-supported wharf consists of a deck supported by a number of piles beneath it. The embedded length of the piles is variable. To retain the hydraulic fills usually a rock dike is built. Because of the embedded portion of piles, the seismic performance of these types of wharves inherently involves a Soil-Structure Interaction (SSI). Therefore, the seismic performance pile-supported wharves are significantly governed by the properties of structural element (piles and deck) and soil layers properties. Due to the inherent uncertainties associated with the properties of soil and structural elements, realistic estimation of the seismic response of pile-supported wharves requires a probabilistic approach, which is based on an

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appropriate treatment of uncertainty of geotechnical and structural properties. These uncertainties affect the overall performance of a structure and subsequently the estimation of loss due to damage and the corresponding repair cost of the structural system. Thus, it is very prominent to identify and rank the sources of uncertainty according their relative influence on the seismic behavior of the wharf structure (Kramer and Elgamal, 2001; Jones *et al*., 2002).

In this study, sensitivity analyses have been carried out to determine the sensitivity of seismic performance of pile-supported wharves to the uncertainty in both structural and geotechnical material properties.

The displacement ductility factor (μd) has been selected as engineering demand parameter for indicating the seismic response of pile-supported wharf structures. Focus has been placed on the variance of displacement ductility factor considering uncertainties of 13 input uncertain parameters.

CLASSIFICATION OF PILE-SUPPORTED WHARVES

Pile supported wharf is classified as Open type wharves which are constructed in such a way that seawater can run below the platform. Generally a pile-supported wharf is composed of a deck supported by a sub structure consisting of piles and dike/slope beneath it. The unsupported pile length above the dike/slope surface is variable. The seismic response of the pile-supported wharves is highly influenced by the soil structure interaction during shaking (PIANC, 2001). Failure modes during earthquakes depend on the magnitude of inertia force relative to the ground displacement. This is highly associated to geotechnical aspects. Therefore, the uncertainty associated with the geotechnical parameters influence the seismic response of wharf structure. Figure 1 shows three different types of pile-supported wharves.

Large diameter pile supported wharf: It consists in a platform simply supported on large diameter piles, whose diameter vary between 1 and 2 (m), depending on the size of the wharf and the type of function (Werner, 1998). Container wharves generally require the larger diameter of piles for such typology.

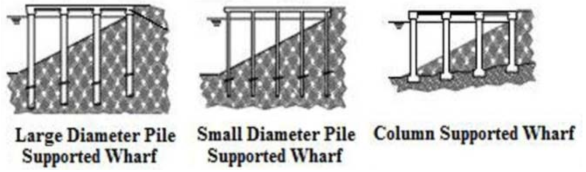

Fig. 1: Different typologies of pile-supported wharves

Small diameter pile supported wharf: It consists in a platform moment connected to small diameter piles, whose diameter vary in the range of 60 (cm). Such typologies are found in ports and are used for various functions including container wharves and cruise liner wharves (Priestley, 2003a).

Column supported wharf: It is similar to pile supported wharves, but instead of having piles, they have columns since the foundation is rock or very stiff granular material (PIANC, 2001). The columns generally have large diameters.

DESCRIPTION OF ILLUSTRATIVE EXAMPLE WHARF

A suite of centrifuge models was carried out at the geotechnical-modeling center of California University, (UC Davis), to evaluate the seismic performance of pile-supported wharf structures. There were several objectives of this test series:

Table 1: Characterization of wharf model

Parameter	Values in prototype scale
Water depth (m)	16.0
Rock dike height (m)	19.5
Wharf deck thickness (mm)	255.0
Pile diameter (mm)	636.0
Pile wall thickness (mm)	50.8
Pile moment of inertia (m^4)	3.02*10-3
Modulus of elasticity (GPa)	
Plastic moment (N.m)	7.5*106

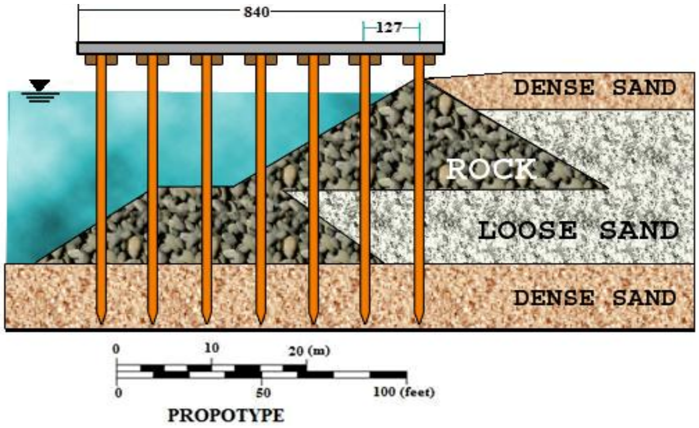

Fig. 2: Cross section profile of wharf structure showing structural elements and soil layers

- Examine the seismic behavior of piles in a sloping rock fill.
- Examine the seismic behavior of piles at soft-stiff soil interfaces.
- Examine the general pattern of seismically induced deformations for pile-supported wharf structures.
- Examine the effect of soil improvement strategies.
- Provide a database for the validation of design methods and numerical models.

In this study, the centrifuge model (NJM01) was selected as a typical pile-supported wharf structure from western United States ports (McCullough *et al*., 2000). This is classified as small diameter pile-supported wharf structures. Figure 2 shows the cross-section profile of selected wharf model. All structural properties and geotechnical parameters of different soil layers are defined according to NJM01 model provided by McCullough *et al*. (2000) and are shown in Table 1.

GROUND MOTION RECORDS FOR SEISMIC LOADING

In order to perform a nonlinear dynamic analysis of the wharf structure, a set of earthquakes is required, which represent the characteristics of the possible seismic hazards and their associated uncertainties. For this study, an ensemble of eight acceleration time histories was selected from PEER Strong Motion Database website (http://peer.berkeley.edu/peer_ground_motion_database). Details of all ground motion records used, including earthquake names, sensor location, magnitude, distance and peak ground acceleration are provided in Table 2.

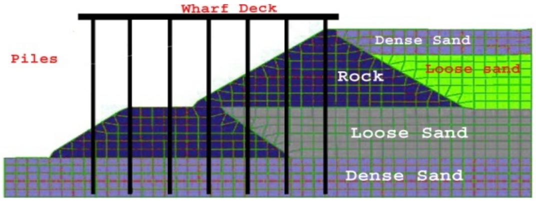

Fig. 3: Finite difference model of pile-supported wharf

NUMERICAL MODELING

The program FLAC2D was used to construct the two-Dimensional (2D) nonlinear finite difference model of the wharf, as shown in Fig. 3. FLAC2D (Fast Lagrangian Analysis of Continua) is a 2D explicit finite difference computer program for performing Soil-Structure Interaction (SSI) analysis under static and seismic loading conditions (Itasca, 2000).

DESCRIPTION OF PILE-SUPPORTED WHARF DAMAGE STATES

The International Navigation Association (PIANC) proposed qualitative criteria for judging the degree of

Table 2: Details of the ground motion records (adopted from PEER strong motion database)

No	Event	Station	Year	M	R (km)	PGA (g)
1	Imperial valley	Chihuahua	1979	6.5	28.7	0.270
2	Imperial valley	Delta	1979	6.5	43.6	0.351
3	Livermore	San Ramon-Eastman Kodak	1980	5.8	17.6	0.154
4	Loma prieta	APEEL 2E Hayward Muir Sch.	1989	6.9	57.4	0.171
5	Loma prieta	Palo Alto-SLAC Lab.	1989	6.9	36.3	0.278
6	Loma-prieta	Sunnyvale-Colton Ave.	1989	6.9	28.8	0.209
7	Morgan hill	Capitola	1984	6.2	38.1	0.142
8	Northridge	Canyon Country-W Lost Cany	1994	6.7	13.0	0.482

Table 3: Description of damage states (PIANC, 2001)

Damage state		Degree I, serviceable	Degree II, repairable	Degree III, near collapse	Degree IV, collapse
Deck	differential settlement between deck and behind land	≤0.3 m	N/A	N/A	N/A
	residual tilting	$\leq 3^0$	N/A	N/A	N/A
Dike	horizontal displacement	≤0.15 m	≤0.3 m	N/A	N/A
Piles	peak response	essentially elastic response with minor or no residual deformation	controlled limited inelastic ductile response and residual deformation intending to keep the structure repairable structure repairable structure repairable	ductile response near collapse (double plastic hinges may occur at one or limited number of piles)	beyond the state of near collapse

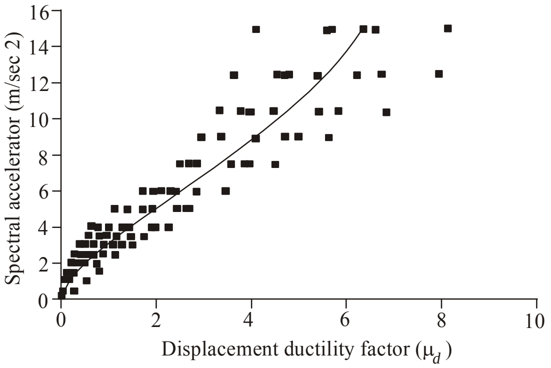

Fig. 4: Contribution of displacement ductility factor resulted from IDA

Table 4: Structural parameter uncertainties

Parameter	Mean	COV (%)
Dead load of structure (Kg/m^2)	1500	30
Elastic modulus of piles (GPa)	70	6

Table 5: Geotechnical parameter uncertainties

	Soil types			
Parameter	rock fill	dense sand	loose sand	COV values (%)
Dry mass density (kg/m^3)	1682	1662	1519	9
Shear modulus	1.15E+08	2.58E+08	5.20E+07	12
Porosity (%)	37.7	39.11	43.4	10
Permeability (%)	3.1E-07	3.10E-09	3.10E-10	50
Friction angle (deg)	45	37.91	33	9
Liquefaction factor $(N_1)_{60}$	-	-	7	30

damage to a pile-supported wharf structure as shown in Table 3. In this table, four damage states, I, II, III and IV, correspond to serviceable, repairable, near collapse and collapse levels of a wharf structure, respectively. At the serviceable level, the structure have minor or no structural damage and the structure should be functional. The repairable level denotes the state, which the structural damage is controllable and repairable. When the structural damage is extensive, damage state is called near collapse. Finally, at the collapse damage state, the structural strength is completely lost.

WHARF RESPONSE UNDER SEISMIC LOADING

Accurate evaluation of the seismic performance of port facilities under different levels of seismic loading is one of the key issues of Performance Based Earthquake Engineering (PBEE) methodology. To calculate the seismic response of wharf structure, either static or dynamic analysis methods can be used. In this study, Incremental Dynamic Analysis (IDA) was applied. IDA is a computational-based methodology to estimate structural performance under seismic loading, proposed by Vamvatsikos and Cornell (2002), Vamvatsikos and Cornell (2005) and Vamvatsikos and Cornell (2006).

The IDA approach involves performing nonlinear dynamic analyses of a structural system under a suite of ground motion records, each scaled to several intensity levels of ground motion. The Spectral Acceleration (Sa) at the natural period of wharf structure was selected as Intensity Measure (IM) used to describe ground motion characteristics. This intensity of ground motion (i.e. Sa), is incrementally increased from 0.2 to 15 (m/se^2) and displacement ductility factor, is monitored during each analysis as shown in Fig. 4.

UNCERTAINTY ASSOCIATED WITH MATERIAL PROPERTIES

As indicated by Na *et al.* (2008) consequential variation observed in maximum displacements of caisson-type quaywalls with identical configuration, similar soil condition and located at the site with similar seismic intensity during the 1995 Kobe earthquake. This observation shows that inherent uncertainties associated with material properties highly influence the seismic performance of a wharf structure. Especially, in case of port structures, where liquefaction is involved, uncertainties in soil properties results in significant variability in seismic response of wharf structure. It is therefore necessary to consider the uncertainty in material properties to guarantee a safe seismic design.

For evaluating the effect of uncertainty associated with material properties in seismic performance of pile-supported wharves, uncertainty in material properties has been represented by assigning a mean and standard deviation in terms of coefficient of variation for each parameter as shown in Table 4 and 5. These mean and standard deviation values of material properties have been chosen from the range of values suggested in literature (Jones *et al.*, 2002; Baynes, 2005; Na *et al.*, 2008).

The mean values considered herein are the same as those used in the reference model for seismic analysis, in section 7. Based on the results of previous research and engineering judgments in this study, only 13 parameters have been identified as key parameters for the uncertainty analysis (Na *et al.*, 2008).

SENSITIVITY ANALYSIS METHODOLOGY USED IN THE PRESENT STUDY

There are several methods for considering uncertain parameters according to their sensitivity to desired response parameters such as, FOSM analysis, tornado diagram analysis and Monte Carlosimulation (Porter *et al.*, 2002; Lee and Mosalam, 2006). Herein both tornado diagram analysis and FOSM analysis have been used. The reasons behind selecting these methods are their simplicity and efficiency to identify sensitivity of uncertain parameters. These analyses are described in the following sections.

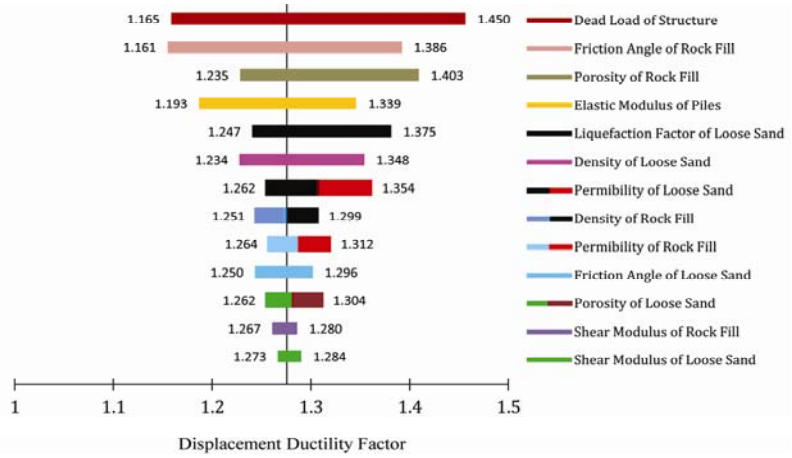

Fig. 5: Tornado diagram regarding the uncertainties in geotechnical and structural parameters

Tornado diagram analysis: For the tornado diagram analysis, all uncertain parameters are assumed as random variables, which follow the normal distribution. For each of these random variables the 84th percentile and 16th percentile are assumed as the upper and lower bounds, respectively. For a specific random variable (i.e. uncertain parameter), using both of these bounds (i.e. 84th percentile and 16th percentile) the seismic response of the wharf structure has been evaluated under certain ground motion record and performing nonlinear time history analysis, while all other random variables have been assumed deterministic parameter with values equal to their mean value.

The difference between seismic response quantities of wharf structure (here displacement ductility factor) corresponding to the two bounds of that random variable is calculated. This calculation procedure has then been repeated for all random variables presented in Table 4 and 5. Finally, these results have been plotted in a figure from the top to the bottom in a descending order according to their size to demonstrate the relative contribution of each variable to the seismic response of wharf structure, Fig. 5.

In this figure, the length horizontal bar represents the variation in the displacement ductility factor (μd) due to the variation in the respective random variable. The longer difference (i.e., longer horizontal bar) shows that the corresponding variable has larger effect on the seismic response of wharf structure than those with shorter difference. As seen in this figure, the dead load of structure, friction angle of rock fill and the porosity of rock fill are the three largest contributors of the seismic response variability.

FOSM analysis: For the FOSM analysis, the displacement ductility factor has been considered as the function of uncertain parameters, following below equation:

$$Y = f(\mathrm{X1}, \mathrm{X2}, \ldots, \mathrm{XN}) \qquad (1)$$

In which, Y is denoting the seismic response of wharf structure in term of displacement ductility factor. Xi is denoting the uncertain parameters (Table 4 and 5).

Expanding Eq. (1) in Taylor series with only the first order terms and ignoring higher

Order terms, Y can be approximated as follows:

$$Y \approx f\left(\mu_{X_1}, \mu_{X_2}, \cdots, \mu_{X_N}\right) + \frac{1}{1!}\sum_{i=1}^{N}\left(X_i - \mu_{X_i}\right)\frac{\partial f}{\partial X_i} \qquad (2)$$

where $\mu_{X_i}$is denoting the mean of random variable Xi. Taking expectation of both sides, the mean of Y, μY can be expressed as:

$$\mu_Y \approx f\left(\mu_{X_1}, \mu_{X_2}, \cdots, \mu_{X_N}\right) \qquad (3)$$

Utilizing the second moment of Y as expressed in Eq. (4) and simplifying, the variance of Y, σ_{Y2} can be expressed as:

$$\sigma_Y{}^2 \approx \sum_{i=1}^{N}\sum_{j=1}^{N} COV\left(X_i, X_j\right)\frac{\delta f(X_1, X_2, \cdots, X_N)}{\delta X_i}\frac{\delta f(X_1, X_2, \cdots, X_N)}{\delta X_j} \approx \sum_{i=1}^{N}\sigma_{X_i}{}^2\left(\frac{\delta f(X_1, X_2, \cdots, X_N)}{\delta X_i}\right)^2 + \sum_{i=1}^{N}\sum_{j\neq i}^{N}\rho_{X_i X_j}\frac{\delta f(X_1, X_2, \cdots, X_N)}{\delta X_i}\frac{\delta f(X_1, X_2, \cdots, X_N)}{\delta X_j} \qquad (4)$$

where $\rho_{X_i X_j}$denotes correlation coefficient for random values Xi and X j. The partial derivative of $f(X_1, X_2, \cdots, X_N)$ with respect to Xi has been calculated numerically using the finite difference equation given below:

$$\frac{\delta f(X_1, X_2, \cdots, X_N)}{\delta X_i} = \frac{f(X_1, X_2, \cdots, \mu_i + \Delta X_i, X_N) - f(X_1, X_2, \cdots, \mu_i - \Delta X_i, X_N)}{2\Delta X_i} \qquad (5)$$

In this case, a large number of simulations were performed varying each input parameter individually to approximate the partial derivatives as given in Eq. (5).

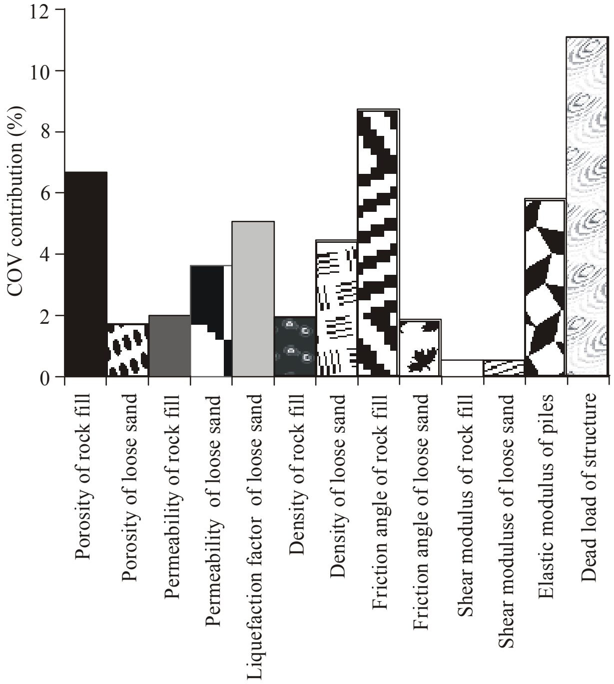

Fig. 6: Relative variance contribution

For these sensitivity analyses, at first, the reference model with mean parameters of each 13 random variable considered in this study has been analyzed with the selected time history. Then the analyses have been carried out using their lower and then upper bounds. Figure 6 shows relative variance contributions of each parameter to the displacement ductility factor as the seismic performance indicator of pile-supported wharf when the correlation, as given in the second term of Eq. (4), is neglected.

RESULTS AND DISCUSSION

In tornado diagram analysis, the length of horizontal bars (i.e. the difference of seismic response corresponding to the upper bound and lower bound) represents the variation in the seismic response due to the variation in the respective uncertain parameter. As seen from Fig. 5 the horizontal bars representing the dead load of structure, friction angle of rock fill and the porosity of rock fill are the three largest. The FOSM analyses results in the same trend. As seen in Fig. 6 the dead load of structure, friction angle of rock fill and the porosity of rock fill have the three largest COV.

In summary, regarding to the objective of this study, both tornado diagram analysis and FOSM analysis shows that, the uncertainties in the dead load of structure, friction angle of rock fill and the porosity of rock fill are the three largest contributors of the seismic response variability. While, as indicated by Na *et al.* (2008) for the case of caisson-type quay walls, the friction angle and the shear modulus of reclaimed soil contribute most to the variability of the Residual Horizontal Displacement (RHD) response.

In present study, displacement ductility factor (μd) has been selected as the parameter, which indicates the seismic response of pile-supported wharves. It is informative to consider other engineering demand parameters such as moment curvature ductility factor, differential settlement between deck and behind land. In addition the accuracy of the results may be enhanced by using a fully-3 dimensional model of wharf structure.

CONCLUSION

In this study, using 2D finite difference model, the effect of uncertainties of geotechnical and structural parameters in seismic performance of a typical pile-supported wharf have been investigated. To investigate the sensitivity of the performance of port structures with respect to uncertainties of geotechnical parameters, tornado diagram and FOSM analyses have been conducted with 13 geotechnical and structural uncertain parameters and choosing their values from related literature. The model has then been subjected to a set of eight ground motion records. After that, seismic response of wharf structure has been evaluated sing Incremental Dynamic Analysis (IDA). Accurate evaluation of the seismic performance of port facilities under different levels of seismic loading is one of the key issues of Performance Based Earthquake Engineering (PBEE) methodology. The proposed procedure in this study can be used for considering uncertainties of the structural components and geotechnical parameters for the accurate evaluation of the seismic performance of pile-supported wharves.

As an important consideration for design, it can be suggested that the dead load of structure should be determined more accurately. In addition, properties of soil-structure interaction system should be characterized well with emphasis on the friction angle of rock fill and the porosity of rock fill.

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