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Fragility estimation and sensitivity analysis of an idealized pile-supported wharf with batter piles

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ABSTRACT

The main objective of the present study is to develop seismic fragility curves of an idealized pile-supported wharf with batter piles through a practical framework. Proposing quantitative limit states, analytical fragility curves are developed considering three engineering demand parameters (EDPs), including displacement ductility factor (μ_d), differential settlement between deck and behind land (DS) and normalized residual horizontal displacement (NRHD). Analytical fragility curves are generated using the results of a numerical model. So, the accuracy and reliability of resulted fragility curves directly depend on how accurate the seismic demand quantities are estimated. In addition, the seismic performance of pile-supported wharves is highly influenced by geotechnical properties of the soil structure system. Hence, a sensitivity analysis using the first-order second-moment (FOSM) method is performed to evaluate the effects of geotechnical parameters uncertainties in the seismic performance of the wharf.

Herein, the seismic performance of the wharf structure is simulated using the representative FLAC2D model and performing nonlinear time history analyses under a suit of eight ground motion records. Incremental dynamic analysis (IDA) is used to estimate the seismic demand quantities. As a prevailing tool, adopted fragility curves are useful to seismic risk assessment. They can also be used to optimize wharf-retrofit methods. The results of sensitivity analysis demonstrate that uncertainties associated with the porosity of loose sand contribute most to the variance of both NRHD and μ_d. While in the case of differential settlement, the friction angle of loose sand contributes most to the variance.

1. Introduction

Past and recent earthquakes have demonstrated that port facilities are prone to seismically induced damage in moderate-to-strong earthquakes. During past two decades, a large number of pile-supported wharves suffered extensive earthquake induced damage due to poor seismic design, showing the necessity of reconsideration in the seismic design philosophy of these types of structures to enhance their seismic performance [1–4].

The port of Oakland damaged severely during the Loma Prieta earthquake (1989), comprising of connection failures at the tops of piles in addition to settlement and lateral spreading of a pile-supported wharf [5].The port of Kobe faced severe damage in both non-structural and structural components during the Hygoken Nanbu earthquake (Kobe 1995) [6]. Several ports at Izmit Bay faced substantial damage during the Kocaeli earthquake [7]. Recently, the Haiti earthquake (2010) caused failure to a pile-supported wharf and partial collapse to a pile-supported pier at Port-au-Prince [8].

Seismic performance of wharves has been investigated experimentally in a large number of previous studies, some of them are mentioned below.

The behavior of piles in sloping rock fill was investigated by McCullough et al. (2004) using centrifuge and numerical models, as well as field data, to better understand the performance of piles at marginal wharves [9]. Five pile-supported wharf models were dynamically tested in a large-scale geotechnical centrifuge at UC Davis, California by McCullough et al. (2007) [10]. Models representing pile-supported wharf configurations common in the United States were subjected to recorded acceleration time histories. Takahashi and Takemura (2005) carried out centrifuge model tests to investigate the dynamic behavior of a pile-supported wharf in front of backfilled gravity type caissons, focusing on the failure mechanism of the piles, the effects of liquefaction in the backfill and underlying sand layer on the permanent deformation of the

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wharf during earthquakes, and the dynamic interaction between the piled deck and caisson through the approach bridge [11].

Kawamata (2009) conducted a series of full-scale lateral load tests on piles in the rock fill in order to obtain a better understanding of the performance of the wharf deck pile-soil system against lateral loading, and reaction mechanism in rock fill [12]. More recently, in situ large-scale physical modeling using surface wave generator was performed by Chang et al. (2010) to study the dynamic soil–structure interactions in pile-supported wharves and to verify configuration of an in situ monitoring station [13].

Despite a large number of studies on the assessment of seismic performance of pile-supported wharf structures, using either numerical simulations or experimental tests, much less efforts are seen on the seismic vulnerability assessment of pile-supported wharf structures. In a recent study, Yang et al. (2012) developed analytical fragility curves for pile-supported wharves with vertical piles by constructing a 2D numerical model using the OpenSees software [14]. Some other related studies are mentioned below.

Ichii (2004) developed analytical fragility curves for the gravity-type quay walls using simplified dynamic finite element analysis, considering the liquefaction occurrence [15]. Kadkeri and Pitilakis (2010) proposed fragility curves for retaining structures without the presence of liquefaction [16]. The seismic fragility analysis was performed by Ko et al. (2010) for the sheet pile wharves of the Hualien Harbor in Taiwan using 2D finite element nonlinear dynamic analysis. They used maximum residual displacement at the top of sheet pile wall as seismic performance indicator [17].

Chiou et al. (2011) developed fragility curves for a typical pile-supported wharf in Taiwan using Spectrum Capacity Method (SCM). They developed a set of fragility curves using wharf deck displacement as wharf performance indicator and PGA as intensity measure [18]. Shaieezadeh et al. (2012) investigated the modal properties and vulnerability of pile-supported marginal wharves by using two-dimensional nonlinear plane-strain seismic analyses, using time histories of ground displacement and excess pore water pressures within the underlying soil embankment [19].

The goal of modern seismic risk assessment methods is to provide the probability of loss at different levels of hazard. The evaluation of seismic vulnerability of existing wharves has become a crucial issue in the last decades due to the frequent occurrence of destructive earthquakes, which have revealed that the number of victims and the amount of economic losses/down time of a sea port transportation system depend considerably on the seismic performance of wharf structures [2,20].

Seismic risk assessment at a port necessitates a comprehensive evaluation of the vulnerability of wharf structures, which can be most effectively done using fragility curves. Fragility curves provide decision makers with essential tools for optimizing investment in wharf retrofit and fill a major gap in seismic risk assessment of seaports [20,21]. Based on probabilistic risk analysis framework developed by the Pacific Earthquake Engineering Research (PEER) [22], as shown in the Eq. (1), the fragility analysis is the one or the prominent part of loss estimation framework in sea port transportation system.

$$P[\mathrm{Loss}>c]=\sum\sum\sum P[\mathrm{loss}>c|\mathrm{DM}=\mathrm{dm}]P\left[\mathrm{DM}\geq\mathrm{dm}|\mathrm{EDP}\geq\mathrm{edp}\right]\overbrace{P[\mathrm{EDP}\geq\mathrm{edp}|\mathrm{IM}=\mathrm{im}]}^{\text{Fragility}}P[\mathrm{IM}=\mathrm{im}] \tag{1}$$

where $P[\mathrm{Loss}>c]$ denotes the probability of total loss exceeding a predefined value "c" and IM denotes the earthquake intensity measure (e.g. S_a or PGA).

$P\left[\mathrm{EDP}\geq\mathrm{edp}|\mathrm{IM}=\mathrm{im}\right]$ is the probability of exceeding a limit state. This component is determined by comparing the EDP from structural response with predefined values (i.e. edp) representing the capacity of the structure in different limit states. The procedure to estimate this term is called "*Fragility Analysis*" of the structure, which is focused on this paper.

$P[\mathrm{DM}\geq\mathrm{dm}|\mathrm{EDP}=\mathrm{edp}]$ is called out as damage model and predicts the physical damage to a structure from the response of the structure, based on defined structural limit states. The last component in the equation gives the probability of loss exceeding a predefined value "c" given the damage state DM = dm.

Considering the prominent role of fragility analysis in earthquake induced loss estimation and scarcity of research specifically addressed to the derivation of analytical fragility curves for pile-supported wharves using detailed models and rigorous analysis techniques, present paper aims to assess the seismic vulnerability of wharf structures through developing analytical seismic fragility curves for a typical pile-supported wharf with batter piles. Seismic fragility analysis is an emerging tool for evaluating the seismic vulnerability of a structural system under different levels of earthquake hazards. The input to the analysis is the ground motion intensity measure (IM) and the output is the probability of reaching or exceeding predefined damage states.

Analytical fragility curves are produced using seismic demands values resulted from numerical simulations under a suite of earthquakes records. Hence, the accurate estimation of the wharf fragility directly depends on the accuracy of seismic response evaluation. As well, the accurate estimation of seismic response of a structure entails the accurate modeling of the geotechnical components of soil–structure system, especially in the case of pile-supported wharves in which there is inherently a complex soil–structure interaction problem. In other words, the accuracy and reliability of wharf fragility estimations intensely depend on the properties of soil layers adjacent and beneath to the wharf structure.

As a common practice, soil properties can be defined using both probabilistic and deterministic models. Deterministic models use a discrete indicator for a desired geotechnical parameter, while probabilistic models consider the uncertainties in geotechnical properties by describing them using probability distribution functions or statistical indices [23]. As indicated by many researchers, due to uncertainties associated with material properties and ground motion records, an accurate evaluation of the seismic performance of a structure is feasible if a probabilistic approach is used [24,25].

A great deal of efforts has been undertaken to identify relative significance of different sources of uncertainty in seismic performance of structural systems (e.g. RC building). However, in this regard, less attention has been paid to port structures. Based on the field damage data from the 1995 Kobe earthquake, Na et al. (2008) [24] accomplished a probabilistic assessment of the seismic performance of caisson-type quay walls at the Kobe port by developing a two-dimensional (2D) model. Also, they studied the influence of uncertainties associated with soil parameters on fragility estimates of pile-supported wharves [26]. In this regard, herein a sensitivity analysis is carried out considering uncertainties associated with soil parameters by assigning a mean and standard deviation as the coefficient of variation (COV) to each parameter. There are various methods offered for undertaking sensitivity analysis, such as Monte Carlo simulation and the first-order second-moment (FOSM) method. Due to the simplicity and efficiency of the FOSM method, this method is used for the purpose of sensitivity analysis in this study.

Considering the above, the seismic performance of an idealized pile-supported wharf with batter piles (Fig. 1), representing commonly found configurations in western US, is studied. A two-dimensional numerical model representing the wharf of interest is developed using the finite difference software FLACD2D. This software is able to take into account the soil–structure interaction and nonlinear behavior of the piles into account.