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FRAGILITY CURVES: A POWERFUL TOOL FOR SEISMIC VULNERABILITY ASSESSMENT OF PILE-SUPPORTED WHARVES

Ali.Kermani[1]* & Khosrow Bargi[2]
*[1,2]*School of civil engineering, College of Engineering, University of Tehran, Tehran, Iran*

Corresponding author:
Email: alikermani86@yahoo.com

Abstract:-
Seismic vulnerability assessment of structures is usually illustrated in the form of fragility curves. These curves show the probability that a component, element or system will be damaged to a given or more severe damage state as a function of a single predictive demand parameter. In addition, these curves are useful for seismic risk assessment and performance based design engineering, as well as prioritization of retrofitting programs. This paper reviews recent works on the seismic vulnerability analysis of pile-supported wharf structures. Different aspects for each paper are reviewed in terms of characteristic of the selected pile-supported wharf structure, institution and procedure of numerical modeling, capabilities of numerical models, analysis method for seismic response evaluation, ground motion records, damage states, intensity measure and obtained results. This paper shows that very limited studies have been performed on the seismic vulnerability of pile-supported wharves indicating a clear need to the development and application of fragility analysis of pile-supported wharf structures.

Keywords: - “*Seismic vulnerability analysis, Fragility curves, Pile-supported wharf structures***”**

1. INTRODUCTION

Recent major shaking events demonstrated that ports are susceptible to seismically induced damage which caused financial losses that were estimated in the billions of dollars. Some of them are mentioned below.

The port of Kobe faced extensive damage in both structural and non-structural components during Hyogoken-Nanbu earthquake (Kobe 1995) [1]. Widespread liquefaction at the reclaimed Port Island in Kobe [2], damage to quay walls [3], large seaward movement involving tilt and settlement in caisson walls [4] were example of these damages in Kobe port. Most of the ports and jetties in Izmit Bay sustained damages including failure of piers, mechanical equipment, piping and collapse of cranes [5]. For example, the concrete caisson type at Deince Port experienced 0.7m horizontally and 1.0 m vertically displacement due to liquefaction.

During Loma Prieta earthquake (1989), the port of Oakland severely damaged comprising of failures of connection at the tops of piles as well as lateral spreading and settlement of a pilesupported wharf [6].

The Port de Port-au-Prince was widely damaged during The Haiti earthquake [7]. These damages involve widespread soil liquefaction, the poor performance of batter piles, and the poor pre-earthquake condition of many components of the Port's waterfront structures. The North Wharf, which was a pile-supported marginal wharf structure, was severely damaged during this earthquake.

Undoubtedly wharves are a fundamental part of ports in maritime transport system. Among many types of wharf structures (includes gravity quay walls, sheet pile quay walls, caisson quay walls and so on.) pile-supported wharves are the most common type.

A pile-supported wharf is composed of a deck supported by a substructure consisting of piles and a dike/slope. The unsupported length of piles over the dike/slope surface is variable. Piles for marginal wharves may be constructed using reinforced concrete, prestressed concrete (solid or hollow sections), steel tubes (hollow or filled with concrete), or even timber. Solid prestressed concrete piles are nowadays most commonly used, because of their serviceability under the driving forces and corrosion from marine environment. Decks are made of cast in-situ reinforced or prestressed concrete and act as a diaphragm rigid in-plane, because of their large dimensions [8, 9]. Fig. 1 shows the schematic view of pilesupported wharf cross section [10].

The seismic performance of pile-supported wharves is widely affected by complex soilstructure interaction during ground motion excitation. Generally three failure modes of pilesupported wharves are characterized which depend on the magnitude of the inertia force relative to the ground displacement [9]. These failure modes are :

- Deformations due to inertia forces on deck
- Deformations due to horizontal forces from retaining wall
- Deformations due to lateral displacement of loose sub soil

Causing significant damage to pile-supported wharf structures by past earthquakes, researchers' attention has been attracted to the need for seismic vulnerability assessment of these structures. Unfortunately, despite a large number of studies on the seismic performance evaluation of pile-supported wharf structures, there are limited investigations about seismic vulnerability assessment of pile-supported wharves. These investigations will be reviewed in this paper.

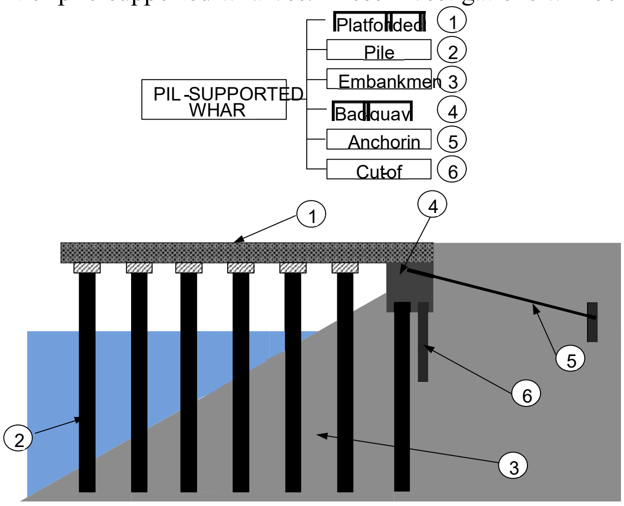


Fig. 1. Schematic view of pile-supported wharf structures [10]

2. Fragility definition

A vigorous method for seismic vulnerability assessment of structures under different levels of seismic excitations is fragility analysis.

Fragility curves are useful to seismic risk assessment and performance based design engineering in high seismic activities regions. In addition, these curves provide decision makers with essential tools for optimizing investment in retrofit of wharf structures.

Ground motion intensity measure (IM) is the input and probability of reaching or exceeding predefined damage states is the output of this analysis.

Over the last few years, fragility analysis was developed for a great variety of structures including buildings [11-13], bridges [14-16], geotechnical structures such as expressway embankments [17] and dams [18].

Fragility curves represents the probability of the response of the selected engineering demand parameter (EDP) exceeding a selected structural limit state (LS) for a specific intensity of seismic excitation (IM).

Fragility can be expressed in the form of lognormal cumulative distribution functions with a median value α and lognormal standard deviation β, as a below analytical form [19]:

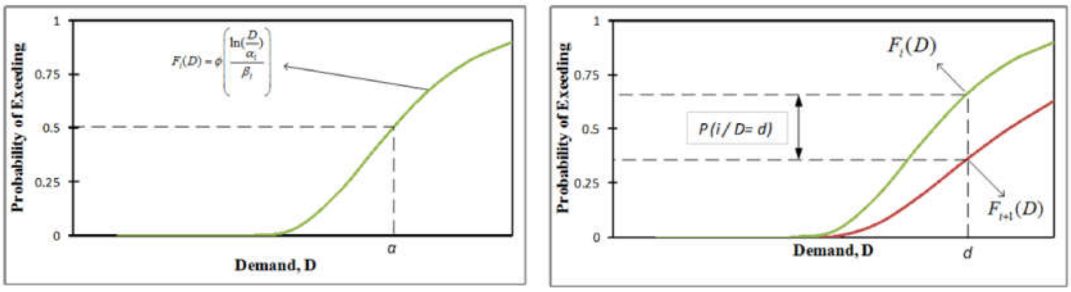
$$F_i(D) = \Phi\left(\frac{\ln(D/\alpha_i)}{\beta_i}\right) \qquad (1)$$

Where $F_i(D)$ is the conditional probability of exceeding structural damage from a predefined damage state i as a function of demand parameter, "D".

Φ (.): denotes the standard normal cumulative distribution function. α: is the median value of probability distribution.
B: is the lognormal standard deviation.The probability that a component or system will be damaged to damage state "i" and not to a more or less severe level given that it experiences demand, D is [20]:

$$P(i|D) = F_i(D) - F_{i+1}(D) \qquad (2)$$

where $F_{i+1}(D)$: is the conditional probability that the component will be damaged to damage state "i+1" or a more severe state,
$F_i(D)$: is as previously defined.
Figure 2(a) illustrates the form of a typical fragility function when plotted in the form of a cumulative distribution function; and (b), illustrates the definition of Eq. (2).



(a) (b)

Fig. 2. (a) Definition of fragility function (b) Individual damage state probabilities evaluation [20]

Finally**,** investigations about seismic fragility analysis of pile-supported wharf structures will be reviewed in the following section.

3. Fragility analysis of pile-supported wharves

3.1. Na *et al.* [21] (2009)

In this study, effect of soil parameter uncertainty on the seismic response of a typical pilesupported wharf in the west coast of United States was demonstrated in terms of seismic fragility curves.

A representative two-dimensional (2D) model of the selected pile-supported wharf was constructed using FLAC 2D. Nonlinear behavior of piles and soil-structure interaction were considered using nonlinear column elements and elasto-plastic p-y springs, respectively. In addition, elasto-plastic behavior with no stiffness degradation and strength deterioration was considered for the material model of nonlinear elements. To take into account the effects of seismically induced pore water pressure, the Finn and Byrne model [22, 23] of FLAC 2D was used to perform coupled dynamic-groundwater flow calculations.

In order to study the effect of soil parameter uncertainty (including Density, Friction angle, Shear modulus and Liquefaction parameters $(N1)_{60}$) on seismic response, random samples were generated using Latin Hypercube Sampling (LHS) and nonlinear time history analysis was conducted repeatedly for each realized sample using 3 sets of 20 earthquake motions. Each set was linearly scaled so as to have return periods of 2,500 years, 475 years, and 72 years representing the earthquakes with exceedance probabilities 2 %, 10 %, and 50 % in 50 years, respectively.

Residual horizontal displacements of a dike and a deck and Peak Ground Acceleration (PGA) were used as seismic demands of the wharf structure and intensity measure (IM), respectively.

Eventually, seismic fragility curves were developed for four damage states including serviceable, repairable, near collapse and collapse with or without consideration of uncertainty in soil parameters.

Results showed that for each damage state, a probabilistic fragility curve has lower median value than that the corresponding deterministic fragility curve, indicating that the deterministic model with mean soil parameter values underestimated the vulnerability of the considered pile-supported wharf structure considered.

3.2. Chiou *et al.* [24] (2011)

They proposed a procedure for developing seismic fragility curves for a typical pilesupported wharf in Taiwan. Three-dimensional numerical model of the wharf was constructed using the program SAP2000. Their model was able to capture the nonlinear behavior of the soil using spring elements with nonlinear p-y and t-z relations for horizontal reactions and skin friction, respectively. In addition, distributed plastic hinge model [25] was used to simulate the plasticity development in the piles.

Capacity Spectrum Method (CSM) proposed by ATC-40, which is a systematic nonlinear static procedure, was conducted for seismic demand estimation using 12 sets of earthquake record from past earthquakes that happened in Taiwan. They used wharf deck displacement as wharf performance indicator and PGA as intensity measure in their paper.

Qualitative and quantitative bounds of used damage states were based on criteria proposed by International Navigation Association (PIANC) [9] and sequence of plasticity development in the pushover analysis, respectively. Based on the damage criteria and the obtained response (from CSM), fragility curves of the wharf were constructed through simple statistical analysis.

3.3. Wang *et al.* [26] (2011)

They proposed an approach to construct fragility curves of pile-supported wharves considering different level of uncertainties without the need to perform Monte Carlo simulation. They considered uncertainties associated with ground motion, capacity spectrum and thresholds of different damage states.

The uncertainty in ground motion demands was simulated in terms of the statics of the response spectra obtained from earthquake records near the site. The uncertainty in capacity properties was related to the material properties involving Young's modules (E) and concrete compressive strength (f'_c). The uncertainty in the damage state threshold was included by the way that the threshold be defined for each capacity curve. In order to demonstrate the proposed approach, a representative wharf in the Taichung area was numerically modeled using SAP2000 program.

Nonlinear behavior of piles and pile-soil interaction were modeled using P-M2-M3 hinges and inelastic Winkler springs. The capacity spectrum method was adopted to estimate the damage state of the target pilesupported wharf structure using 18 ground acceleration time histories near the site of pilesupported wharf.

Four threshold values including slight damage, moderate damage, extensive damage and complete damage in terms of spectral displacement, associated with the state of plastic hinges in pushover analysis, were used. Finally, fragility curves as function of PGA considering three levels of uncertainties were constructed for the target pile-supported wharf.

3.4. Shafieezadeh [27] (2011)

In this study, a set of fragility curves were developed using soil deformation time-histories generated for an ensemble of synthetic and recorded ground motions for the west coast of the United States.

Two and three-dimensional models of a typical pile-supported wharf in liquefiable embankment soils on the west coast of the United States, representing the class of wharf construction in the late1960s and early1970s, were constructed using OpenSees software. Nonlinearities in the piles, pile-deck connections, and soil-structure interaction were included in the models.

Among various selection procedures of ground motions, the bin approach proposed by Shome and Cornell [28] was adopted in this study. Each bin consisted of approximately 12 ground motions selected randomly from the database used to develop the Next Generation Attenuation of Ground Motions (NGA) project [29]. Theses ground motions represented a broad range of earthquake scenarios in terms of moment magnitude and the closest distance to rupture.

The response measured included the curvature of piles and pile-deck connections, the relative displacement of the wharf with respect to the landside rail, the transverse deformation of shear keys, and the relative transverse displacement of collector trench at expansion joints.

The capacities or limit states used to construct fragility curves were obtained from numerical simulations, experimental results, and expert judgment.

Finally, seismic fragility curves for pile sections, pile-deck connections, relative movement of the wharf with respect to the landside crane rail for slight, moderate, and extensive damage states for the two-dimensional and three-dimensional models were obtained.

Fragility analysis of wharf components showed that the relative movement of the wharf with respect to the landside rail was the most susceptible component to slight and moderate damage. However, pile sections were the most vulnerable components of the wharf to extensive damage primarily due to the large deformation demands on the piles at the interface of loose and dense sand layers. In addition, fragility curves of the three-dimensional wharf model demonstrated larger probabilities of failure compared to the corresponding quantities from the two-dimensional wharf model.

3.5. Thompolous and Lai [30] (2012)

They proposed a methodology for performance-based fragility analysis of pile-supported wharves on the basis of nonlinear dynamic analysis.

A vertical pile-supported wharf similar to typical Port of Los Angeles (POLA) was two dimensionally modeled using Ruaumoko 2D. The constructed model, which accounted nonlinear response of soil and piles, was subjected to parametric analysis which variables were input motion, its intensity and soil properties.

The strength of this study is properly accounting for the kinematic interaction on the foundation as well as dynamic nonlinear structural response of pile-columns (expected inground plastic hinges).

Seven input motions selected from the NGA database, scaled to Eurocode 8 response spectra anchored to PGA= 0.15g and 0.30g, were input to soil class B and C corresponding to Eurocode leading to 28 analyses. For each analysis, the envelopes of moments and curvatures were obtained.

Based on the performance criteria taken from Port of Los Angeles (POLA) seismic design code [31, 32]., two levels of structural limit states including Serviceability Limit State (SLS) and Damage Control Limit State (DCLS) were defined in terms of strains of materials.

At the end, a two-parameter lognormal distribution was implemented for the preliminary derivation of fragility curves for the selected pile-supported wharf.

3.6. Yang *et al.* [33] (2012)

They developed seismic fragility curves for vertical-pile-supported wharves commonly found in the western United States.

Two-dimensional numerical models representing the wharf were constructed in the software Open Sees. These models were able to consider the soil-structure interaction and nonlinear behavior of the precast and prestressed concrete piles as well as pile-wharf connections and wharf deck. Furthermore, a simplified crane model was adopted in the wharf model for considering the effect of container cranes on the wharf.

Nonlinear time-history analysis was conducted in order to obtain the seismic response of the wharf models using two suites of ground motion records.

Experimental data was used to calibrate each wharf component response in order to verify the appropriateness of numerical models.

During analyses, the curvature in the piles and pile-deck connections were monitored. The seismic curvature demand was then the peak value of the representative curvatures for each ground motion record. Peak Ground Acceleration (PGA) and spectral acceleration at the fundamental period of the wharf with cranes were used as Intensity Measure (IM).

For fragility analysis, they used a set of appropriate experimentally-based limit states. The qualitative aspect of limit states were based on the limit states defined in Federal Emergency Management Agency (FEMA) loss assessment package

Package HAZUS-MH [34]. As quantitative aspect of the limit states, curvature of the pile-deck connection was selected based on the tests information of T-headed dowel connections performed by Jellin [35] and Brackmann [36].

Finally, two sets of seismic fragility curves of the wharf were developed for the wharf with container cranes in the Los Angeles area and in coastal California, respectively.

3.7. Heidary et al. [37] (2013)
The aim of this paper was to develop seismic fragility curves for a vertical typical pilesupported wharf. This model was selected from a centrifuge model (NJM01) which was conducted at the geotechnical modeling center of California University to assess the seismic performance of pile-supported wharf structures [38].

In order to simulate the seismic performance of the wharf structure, FLAC2D which is a 2D explicit finite difference computer program was used. The numerical model was able to simulate liquefaction susceptible soils.

Using eight time history records from PEER Strong Motion Data base as seismic loading, incremental dynamic analysis (IDA) was applied to evaluate the Engineering Demand Parameter (EDP) values (herein displacement ductility factor, μ_d). The IDA method includes conducting nonlinear time history analyses of a structure under a suite of ground motion records; each scaled to several intensity levels.
In order to verify the numerical model, the Loma Prieta earthquake time history was applied to the model and the results were compared with the centrifuge model measured data.

Three levels of structural damage states including serviceable, repairable and near collapse damage state were defined in terms of displacement ductility factor (μ_d) which was based on the peak responses of piles following qualitative criteria presented at PIANC [9]. Then, analytical fragility curves were developed using spectral acceleration ($S_a(T_n)$) as IM.

3.8. Heidary *et al.* [39](2014)
Heidary et al. presented seismic fragility curves and sensitivity analysis for a model (JCB01), which is an idealized pile-supported wharf with batter piles, from western United States ports [40].

They have used the same method as their previous paper for developing fragility curves, except that they have used two other EDPs including different settlement between deck and behind land (DS) and normalized residual horizontal displacement (NRHD) in addition to the previous EDP (i.e. displacement ductility factor (μ_d)).
The bounds of each damage state corresponding to NRHD and DS were defined based on the damage criteria proposed by Shinozuka [41].

3.9. Heidary et al. [42] (2014)
In this study, the seismic vulnerability of a pile-supported wharf was evaluated through analytical fragility curves using the results of the dynamic analysis of wharf subjected to the different time histories. In addition, sensitivity analysis using both the first-order secondmoment method and the tornado diagram analysis was performed to assess the impacts of geotechnical uncertainties on the seismic response of the wharf.

The 7th Street terminal at the POOAK, damaged seriously in the Loma Prieta earthquake (1989), was chosen as a target pile-supported wharf. All of the aspect of this paper including procedure of numerical modeling, analyses, ground motion records, intensity measure and EDPs were similar to their previous paper.

Results of sensitivity analysis showed that uncertainties associated with the permeability of hydraulic placed sand fill has significant effect on the variance of both NRHD and μ_d.

4. Conclusion
A great deal of research was carried out to seismic vulnerability assessment of various structures using fragility curves; however, less effort was made in the case of pile-supported wharf structures.
The methodologies available for fragility analysis of pile-supported wharves are overviewed with an emphasis on characteristic of the selected pile-supported wharf structure, institution and procedure of numerical modeling, capabilities of numerical models, analysis method for seismic response evaluation, ground motion records, damage states, intensity measure and obtained results.
In sum, this paper not only presents an review about the seismic vulnerability assessment of pile-supported wharf structures using fragility analysis, but also shows the clear need to the development and application of fragility analysis for these structures.

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