6ICEGE
6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch. New Zealand

Effect of Uncertainties in Soil properties on Probabilistic Seismic Performance of Pile-supported Wharves

Seyed A. Mirfattah[1], Carlo G. Lai[2, 3]

ABSTRACT

Pile-supported wharves are soil-structure systems that characteristics of soil directly influence their seismic performance. In order to have a realistic estimate of uncertainties in soil, experimental data from 5 Italian seaports including samples from 400 boreholes on port sites, have been closely investigated and associated uncertainties in soil properties were evaluated. Sensitivity analysis is performed and influential characteristics are determined. Using FLAC 2D a fully stochastic framework is set up for the target wharf. The model captures uncertainties in geotechnical properties of the soil, their spatial variation, layering patterns and the surcharge loads acting on the wharf. The approach integrates an advanced finite difference model and random field theory into a probabilistic framework to perform fully nonlinear analysis. The work yielded considerable sensitivity of response to uncertainty of geotechnical properties and also reveals its slight influence on final probabilistic performance of wharf presented by fragility curves.

Introduction

Marginal pile-supported wharves are common typology of wharves serving as major facilities in seaports worldwide. Any disruption in their serviceability will directly and adversely affect the function of the entire seaport causing significant potential losses. Therefore probabilistic performance of wharves is often considered within the frame work of seismic risk assessment. The particular configuration of these soil-structural systems as labeled by the seismic design guidelines for port structures (PIANC), their seismic response is strongly influenced by soil-structure interaction as well as characteristics of the underling soil deposit. In fact, the influence of soil on seismic response is twofold, since it not only alters the input motion through site effects and kinematic interaction, but it also affects the response via inertial interaction between soil and piles. In this regard, uncertainties in geotechnical properties of the system is expected to have significant effect on response of the system. This fact needs to be taken into account in performance-based probabilistic seismic vulnerability assessment of pile-supported wharves. It has been found important in previous studies [Priestley, M. J. N. et al. 2007b]. However, limitations in numerical simulation of seismic response of saturated soil hosting structural elements and also modeling liquefaction induced damage mechanisms, have greatly hampered achieving a robust numerical model of these vital structures.

In this study, using a geotechnical code FLAC an advanced numerical model of a pile-supported wharf is developed in which both structural and geotechnical components have been properly

[1]Post-doc, UME School, University Institute for Advanced Studies (IUSS), Pavia, Italy mirfattah@gmail.com
[2]Associate Professor, Department of Civil Engineering and Architecture, University of Pavia, Italy
[3] Head of Geotechnical Earthquake Engineering Section, EUCENTRE, Pavia, Italy carlo.lai@eucentre.it

idealized. Additionally, using the geotechnical capabilities of FLAC in performing effective stress analysis, seismic excitation is applied in form of wave propagation in saturated soil deposit. Liquefaction is modeled and effect of soil properties in site effect and kinematic interaction are well captured. Soil conditions and realistic geotechnical data at 5 Italian seaports have been carefully analyzed and their associated uncertainties are considered. The spatial variation of soil properties was modeled through appropriate cross-correlated random fields. The influence of horizontal and vertical auto correlation distance and cross correlation coefficient were thoroughly investigated. Finally Monte Carlo analysis is performed in both stochastic and deterministic models and fragility curves are used to reflect the results of probabilistic evaluation of seismic response of wharves.

Target wharf system and modeling

Large-diameter pile-supported wharves are common throughout Europe and parts of Middle East. Comparing to the wharves with small diameter that are common along the west coast of the United States, in this class of marginal wharves, the deck load and seismic actions are carried via smaller number of large diameter piles providing larger spans between the rows of the piles. Due to large diameter of piles, the interaction between piles and soil is more dominant in this typology. The marginal wharf facility in Gioia Tauro seaport located in southern Italy is an example of this typology. Figure 1 illustrates configuration and geometry of this wharf. The structural configuration of this wharf with typical properties was chosen as a representative target wharf system for the purpose of this study.

Deck is modelled in ten segments using beam elements. The structural nodes at the ends of each beam element are constrained to each other in horizontal direction. Vertical piles are defined as pile elements in FLAC. According to the results of moment-curvature analysis plastic moment of the section is 10 MN-m which corresponds to yield curvature of 0.0035 1/m. Table 1 lists major properties of the structural components of the target wharf structure. Coupling elements consisting of shear springs and sliders available in FLAC are used to simulate the soil-pile interaction in the direction parallel to the pile, while a set of springs, sliders and gap elements are calibrated to simulate the soil-pile interaction in the direction perpendicular to the piles. Figure 2 shows a schematic representation of piles interface between the soil elements (shown in blue) and the structural nodes on piles (shown in red). It should be noted that the nodes of soil elements are rigidly connected to the end of the coupling elements.

Table 1. Specifications of structural components of target wharf system.

Property	Deck thickness (m)	Pile diameter (m)	Pile moment of inertia (m4)	Modulus of Elasticity (GPa)	Plastic Moment of Pile (kN.m)	Transverse spacing of pile (m)
Value	0.3	1.5	0.111	30	10000	6

In order to select representative characteristic for soil in target wharf model, geotechnical date collected from site investigation of 5 Italian seaports were studied. Although the layering patterns were limited to a few, but soil properties were found quite variable. Table 2 shows the dominant layering pattern and mean values of soil properties in each layer.

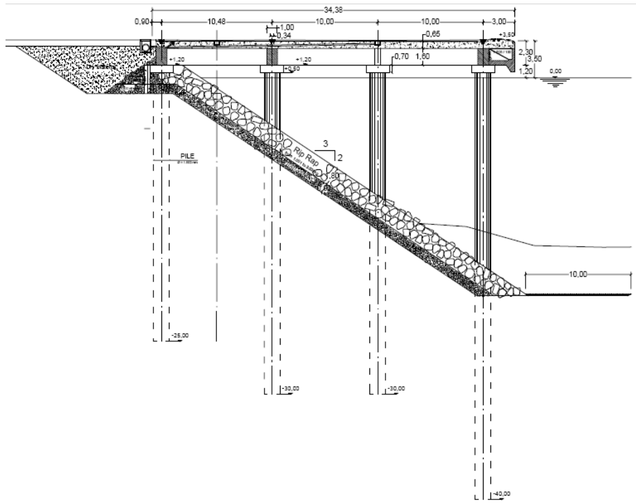

Figure 1. A typical large diameter pile-supported wharf in Gioia Tauro seaport, Italy.

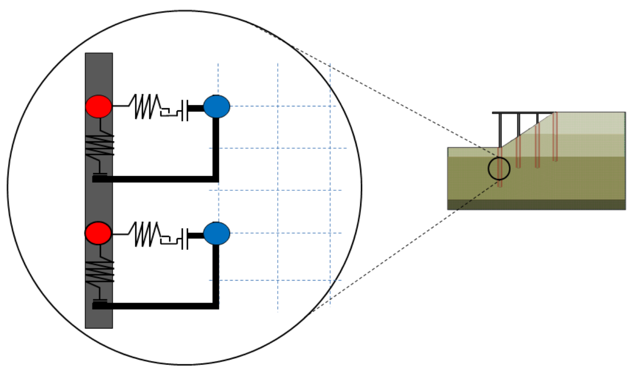

Figure 2. Schematic illustration of coupling spring, gap and slider elements along the piles.

Table 2. Dominant stratigraphy and mean properties of soil observed at port sites.

Soil type	Dry density (kg/m3)	Drained Friction angle (deg)	Drained Cohesion (Pa)	Porosity (%)	Hydraulic conductivity (cm/s)	Shear wave velocity (m/s)
Loose sand	1640	35.73	1000	27	1.0E-4	217
Silty sand	1760	32.44	5636	42	1.0E-6	230
Silty clay-clay	1890	23	462625	47	1.0E-8	318
Bedrock	2800	-	-	-	-	1017

For the purpose of numerical modelling, considering that response of geomaterials is highly dependent on their initial stress state and also their stress path, a realistic stress state simulation is performed in several stages. In first stage, dry embankment of soil with drained properties shown in Table 2 is modelled. Due to the irregular geometry of the model the distribution of shear stress is not uniform through the depth of the model. In the next stage the steady state of water flow is initiated by applying pore pressure gradient along the vertical boundaries of the model. Therefore in accordance with permeability and porosity of the soil layers the soil elements get saturated and the water table is raised gradually until the phereatic surface is achieved. Later, hydrostatic pressure of the sea water is exerted along the slope and on the seabed. Having these conditions simulated, stress state of submerged embankment is obtained. In the last stage, structural members of wharf including piles and deck are added to the model and static analysis is performed. Therefore, the updated stress state distribution affected by the existence of piles and deck is obtained.

The interaction between water and submerged portion of piles are simulated using Morison equation [Morison 1950]. Mohr Coulomb constitutive model combined with Finn Byrne et al. [2004] liquefaction model of soil available in FLAC 2D [Itasca 2000] are used to represent liquefiable soil layers. As schematically demonstrated in Figure 3, the ground motion acceleration is converted to shear stress wave propagating into the soil embankment. Non-reflective quiet boundary and also free field motion are applied around the model using specific modelling facilities available in FLAC. Residual seaward displacement of wharves in Kobe port has been reported after Kobe earthquake 1995. That has been mostly result of flow failure of dike over liquefiable sand layer. [PIANC 2001]. This residual displacement has been used as engineering seismic demand parameter by similar studies such as the ones conducted by Calabrese [2012] and Shinozuka [2009]. Therefore, it is used as the main response measure of the wharf in this study.

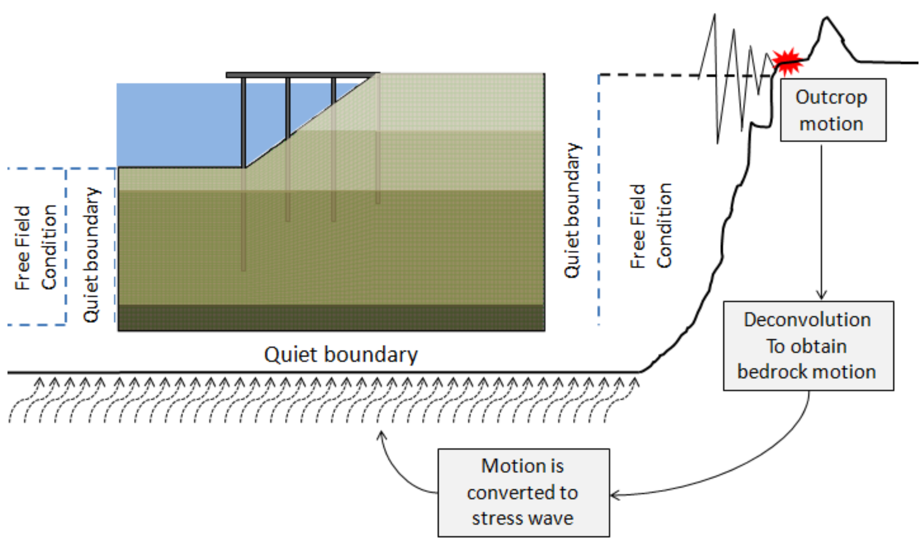

Figure 3. Schematic representation of wharf model, boundary conditions and seismic wave propagation implemented in FLAC.

Stochastic model of soil properties

In order to have a representative stochastic model of soil deposit, sources of uncertainty should be well recognized. These sources are namely, layering pattern, temporal and spatial variation in geotechnical properties, loads and also error in measurement. Spatial variability of soil properties is taken into account by means of random field theory. In this regard, with the intention of enhancing credibility of the representative stochastic model of soil deposit, it is calibrated with real geotechnical data obtained from five seaports located in southern Italy. The investigated database included results of around 400 borehole tests. Variation of soil properties during the lifetime of the wharf system is usually not considerable. Similarly, error in measurement is small comparing to spatial variation.

Layering pattern

The dominant stratigraphy of the soil observed in the seaports were as following: saturated loose to medium dense sand right below the surface, silty sand in the middle layer and a layer of silty clay and clay on top of bedrock. The pattern is shown in Figure 4 as a typical stratigraphy in seaports. It should be noted that this assumed pattern is only for sequence of layers, however, thickness of each layer changes even in a single port site along marginal wharf. It means increase in thickness of one layer is associated with decrease of thickness in adjacent layers, in other words, depth of boundary between them changes. This would be considered in stochastic model of soil.

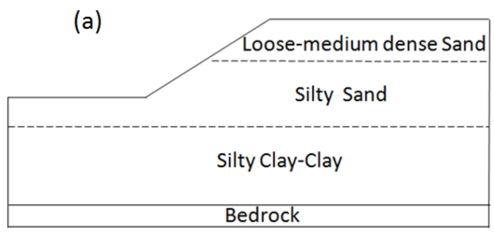

Figure 4. Dominant stratigraphy pattern obtained from real experimental data from seaports.

Table 3. Variation of geotechnical properties observed in Italian port sites.

Sequence of soil types Presented in Pattern-1				Geotechnical properties of each soil type observed in different port sites				
			SPT	Poisson Ratio	γ_{dry} (T/m3)	G_0 (kPa)	C' (kPa)	φ' (deg)
Layer1	Medium to coarse sand	Mean	40	0.308	1.64	235870	0.066	35.73
		Std	13.2	0.064	0.08	144616	0.258	1.88
Layer2	Silty sand	Mean	36	0.303	1.76	164525	5.636	32.44
		Std	10	0.034	0.10	71202	11.065	4.00
Layer3	Silty clay-clay	Mean	33	0.413	1.89	201029	462.62	23.00
		Std	12	0.048	0.05	252350	693.71	2.51

Geotechnical properties of soil

Geotechnical properties of each soil type were studied and based on their associated variation probabilistic distributions are fit to represent their variation. Geotechnical property range, observed in each specific soil type is merged with those of similar type observed in different locations of port sites to cover a wider range of variation. Table 3 illustrates mean and standard deviation of geotechnical properties of each soil type in each stratum.

Sensitivity analysis to specify the most influential parameters

Tornado sensitivity analysis is performed to evaluate the sensitivity of response to characteristics of the wharf including geotechnical specifications of soil deposit. Nonlinear finite difference effective stress analysis of the wharf model is the deterministic function between input parameters and response of an Engineering Demand Parameter (EDPs). Based on probability distribution of each property of soil, two values of 10% and 90% percentiles are selected and their corresponding responses are calculated.

As it is observed from Figure 5 that illustrates the results of sensitivity analyses, geotechnical properties and stratigraphy of the soil profile are among the major influential parameters on final seismic response of the system. The depth of second boundary which is the thickness of liquefiable sand layers is the most influencing parameter. Softening of liquefiable layers control the horizontal stiffness and strength of the wharf as well as final residual seaward displacement. After that, cohesion and shear modulus in surface layers together with loads on the wharf are nearly equally influencing the response the most. This has been observed also in previous studies that involved simulation of soil as a continuum within a probabilistic framework [Lizarraga 2010].

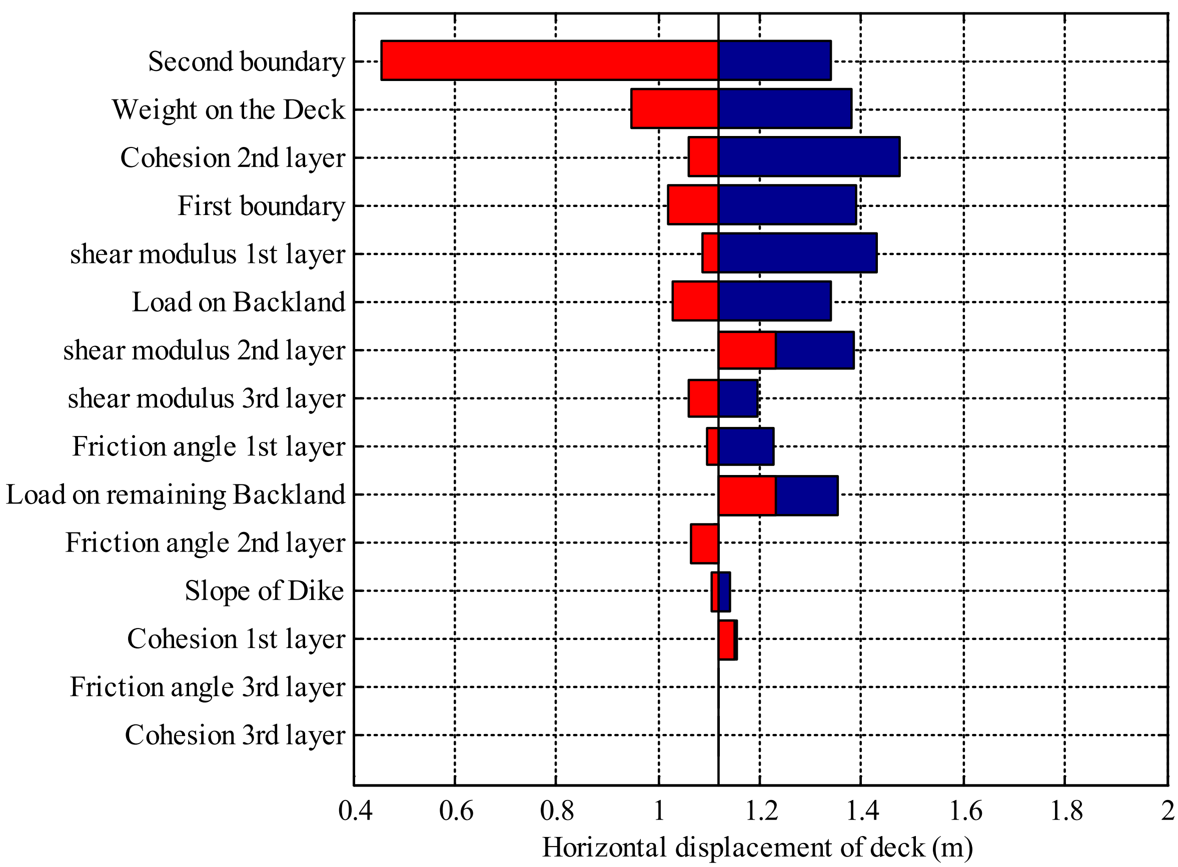

Figure 5. Results of Tornado sensitivity analysis, showing sensitivity of residual displacement of the deck to different variable specifications of the wharf.

Spatial variation in soil properties

Spatial variation of soil properties within each specific layer (soil type) is captured by means of random field. The applied random fields are anisotropic (different auto correlation distances in vertical and horizontal direction) defined according to spatial variation observed in experimental data and also common values in the literature. Autocorrelation distance reflects the correlation between an individual property of the soil within each layer of the soil deposit, while cross correlation reflects the correlation and mutual affection between two different properties of the soil such as cohesion and friction angle in each layer containing a specific soil type. In order to recognize the cross correlation between cohesion and friction angle, the procedure suggested by Vořechovský [2008] was adopted to generate Gaussian and non-Gaussian random fields. Figure 6 shows sensitivity of the horizontal displacement of the deck to autocorrelation factor in vertical direction. It is observed that accounting for spatial variation considerably changes the response of the system depending on selected vertical correlation distance for representative random field. For the purpose of this study, vertical correlation distance of 5m and horizontal correlation distance of 40m with cross correlation coefficient of 0.5 between the friction angle and cohesion are selected to generate random fields in each layer.

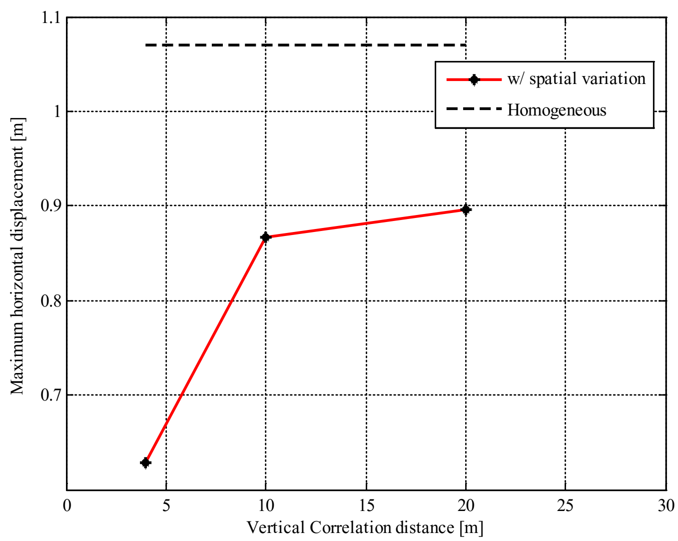

Figure 6. Comparison of displacement of deck with homogenous and spatial variation in vertical direction with random fields assuming vertical correlation distances of 4, 10 and 20m.

Fragility analysis considering uncertainties

Based on the results of sensitivity analyses a stochastic model of target wharf is produced. In this model influential system properties and loads are represented by random variables and random fields. Table 1 briefly demonstrates different elements of stochastic model and their probabilistic distributions. Other variable parameters are assumed constant value of their best estimates. Figure 7 shows a schematic view of the stochastic model of target wharf system. In order to perform Monte Carlo analysis with stochastic model, a set of 60 ground motions corresponding to six hazard levels are selected by assuming spectral displacement at fundamental period of the system as the optimum intensity measure [Mirfattah 2013]. Then corresponding to each intensity level 50 realizations from stochastic model are randomly combined with 10 records of the same intensity levels. The procedure is performed by a MATLAB code to generate input data bank for the Monte Carlo analysis. Total number of 300 finite difference analyses are carried out. The results showed high discrepancy in horizontal displacement of the deck as the EDP for seismic response of the system. Although as represented by solid line in Figure 8 a fragility curve was fit to data but it should be noted that the response in each case could be significantly different than that of deterministic model with mean values and homogenous distribution for soil properties in each layer. For the sake of comparison a deterministic model of target wharf system is also produced. Similar Monte Carlo analysis is performed on deterministic model too. In this case the only input variable is the ground motion. Appropriate limit states for wharves are used based on the study carried out by Mirfattah [2013]. Finally fragility curves of both stochastic and deterministic systems are derived and compared as shown in Figure 8. The stochastic and deterministic fragility curves are close. That implies that the uncertainty in response due to ground motion characteristics is dominant comparing to that of system properties. This was observed in Lizarraga [2010] study.

Table 4. Components of the stochastic model of wharf with their statistical distributions

Num	Variable Parameter of the system	Statistical distribution
1	G_o, c', φ' in 1st layer + Spatial variation	Log-normal + Random Field
2	G_o, c', φ' in 2nd layer + Spatial variation	Log-normal + Random Field
3	G_o, c', φ' in 3rd layer + Spatial variation	Log-normal + Random Field
4	Surcharge load on Deck	Normal
5	Surcharge load on Backland	Normal
6	Surcharge load on Remaining land	Normal
7	1st Boundary	Uniform
8	2nd Boundary	Uniform

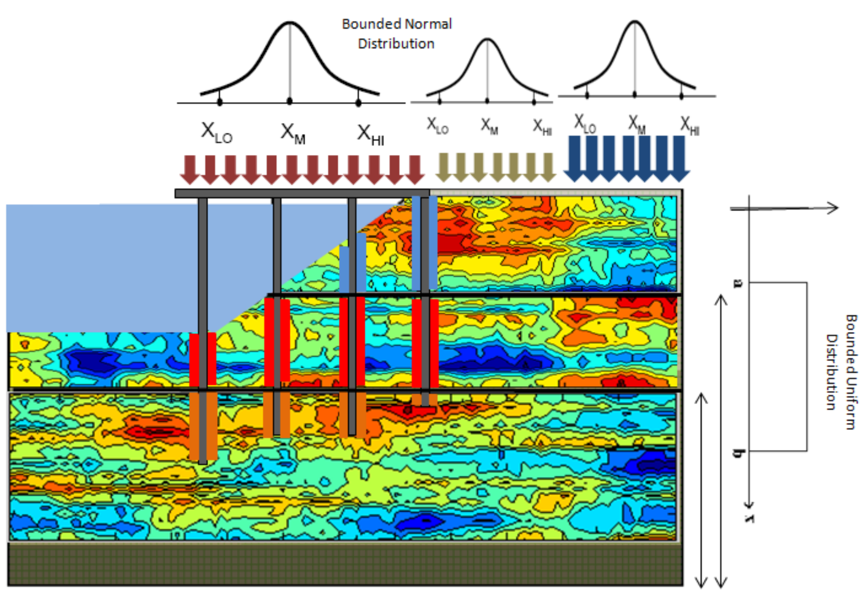

Figure 7. Stochastic representation of soil properties, layering pattern and loads on deck and backland.

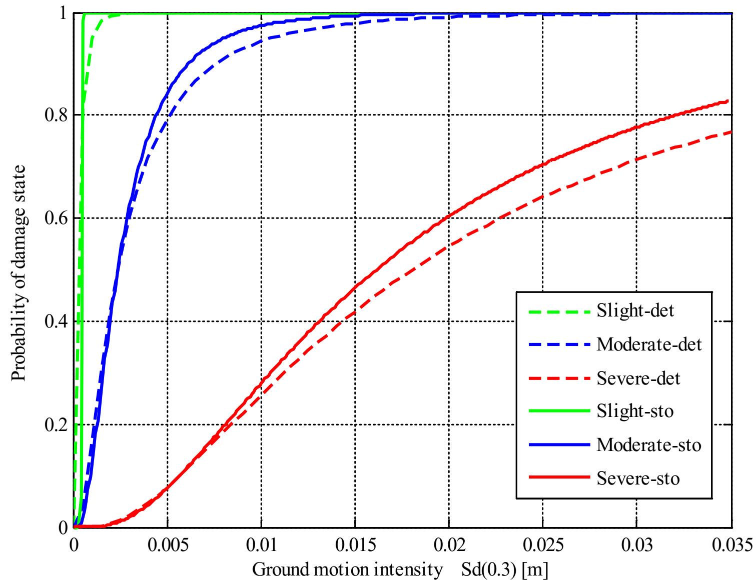

Figure 8. Comparison of fragility curves obtained from deterministic and stochastic model of the target wharf

Conclusion

Uncertainties in geotechnical properties substantially affects the seismic response of wharf structures. Thickness of liquefiable layer, shear modulus and cohesion of the soil in near surface layers, are among the most influential geotechnical parameters affecting the seismic response of pile-supported wharves.

Seismic response of pile-supported wharves is influenced by spatial variation of soil properties. Parameters that characterize this variation are namely: horizontal and vertical correlation distances and cross-correlated coefficient of the representative random fields. These parameters should be accurately calibrated with realistic data since the final seismic response is highly sensitive to them.

Variation in characteristics of ground motions with the same intensity is more influential to the response of pile-supported wharves than of variation in system properties.

In probabilistic performance assessment of wharves, accounting for variation in properties of soil deposit seem to reveal slightly more vulnerability of the system than when assuming constant properties for soil.

Acknowledgments

This study has been carried out with the financial contribution of the European Commission within the framework of the FP7 REAKT ("Strategies and tools for Real Time Earthquake Risk Reduction") Project, Working Package 5, Task 5.2.4 (“Time dependent fragility curves for critical transportation system components”) and the Department of Civil Protection of Italian Government entitled “Seismic Risk of Harbor facilities” (Project DPC-EUCENTRE S.3.5 – 2014). Both these supports are gratefully acknowledged by the authors.

References

Byrne, P.M., Park, S.-S., Beaty, M., Sharp, M., Gonzalez, L., Abdoun, T. Numerical modeling of liquefaction and comparison with centrifuge tests *Canadian Geotechnical Journal*, 2004 Vol. **41**, No. 2, pp. 193-211.

Calabrese, A. Seismic Vulnerability Analysis of Wharf Structures using Artificial Neural Networks Proceeding of *15 WCEE* Lisbon 2012.

Itasca *FLAC 7: Fast Lagrangian Analysis of Continua*. 2000

Lizarraga, H.S. *Performance-Based Seismic Analysis and Design of Earth Dams* PhD Thesis, ROSE Programme, UME School, IUSS Pavia, Italy [2010]

Mirfattah, S.A. *Assessment of seismic vulnerability and risk of Pile-supported wharves*. PhD Thesis, ROSE Programme, UME School, IUSS Pavia, Italy 2013

Morison, J. The force exerted by surface waves on piles, *Petroleum Transactions*, American Institute of Mining Engineers, [1950] Vol. **189**, pp. 149-154

Priestley, J.N., Calvi, G.M., Kowalsky, M.J. *Displacement-based Seismic Design of Structures*, IUSS Press 2007.

PIANC, I.N.A. *Seismic design guidelines for port structures*. A.A. Balkema Publishers, Lisse,Abingdon,Exton (PA),Tokyo. 2001

Shinozuka, M. Analysis of Seismic Performance of Port Facilities. *Workshop on Seismic Risk and Management of Transportation Networks Purpose*. Berkeley, PEER. 2009

Vořechovský, M. [2008] “Simulation of simply cross correlated random fields by series expansion methods,” *Structural Safety*, Vol. **30**, No. 4, pp. 337-363.