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Fragility Assessment of Single Concrete Pier and Pile-Soil Interaction Impact under Near and Far-Fault Earthquakes

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Abstract

Civil engineers face a significant challenge in assessing seismic vulnerability due to the complex of soil-pile-structure interaction system. This research aims to evaluate the seismic vulnerability of individual piers under various seismic ground motions. Factors like sand type, pile diameter, pier height, and mass placed were investigated for their impact on the seismic fragility of concrete piers. Using incremental dynamic analysis with a beam on a nonlinear Winkler foundation model, the study compared the effects of near and far ground motions. Results from the dynamic analysis and fragility assessment demonstrated the effects of the parameters above-mentioned on the design of fragility curves, as well as its relationships to fundamental period of structural system.

Keywords: soil-pile-structure interaction; ground motions ; incremental dynamic analysis; seismic fragility ; Winkler model.

1. Introduction

The soil-pile interaction system involves the intricate dynamics that occur when a structure, such as a building, channels its load down through a pile (a long, thin column embedded in the ground) to the underlying soil. This interaction is crucial in civil engineering because comprehending it is essential for designing safe and stable foundations. This phenomenon illustrated by (Sextos, 2013), which carried out how earthquakes affect bridges. It focuses on two key areas; how the ground interacts with the bridge structure (soil-structure interaction) and how earthquake shaking can vary across the ground beneath the bridge (spatial variation). The research examines how these factors can considered when evaluating the earthquake safety of existing bridges and designing new ones. It indicates different modeling methods for effectively separating the movement (kinematic) and resistance (inertial) effects between the soil and a pile. It also examines the challenges of choosing and creating the right ground motions for these models.

the soil's elastic behavior has little to no impact on the seismic response of structures, as found in research (Cavalieri et al., 2020) .In contrast, for all buildings, including the inelastic behavior of the soil-foundation system resulted in more favorable fragility curves compared to the scenario where the base was fixed. The method of analysis plays an important role as discussed in research (Su et al., 2019) for understanding how earthquakes will damage wharfs. It can pinpoint the weakest piles within the entire system (piles, soil, and the wharf itself), and predict the maximum level of earthquake force a wharf can withstand before failure. However, the way the soil interacts with the piles (soil-pile interaction) can significantly affect how different parts of the wharf handle earthquake forces. This interaction can either strengthen or weaken certain parts of the wharf depending on the type of damage and the specific component. It advise that accurately assess a wharf's fragility to earthquakes, engineer needs a reliable understanding of these soil-pile interactions. Another investigation about this subject is simulated numerically by (Ghotbi, 2015) on how likely the pile was to be damaged by considering different ways to measure the fragility of the pile, it concluded that the curvature being the most sensitive. The pile was more likely to suffer minor damage than severe failure based on this analysis. Including more ground motion scenarios in the study would improve the accuracy of the results by reducing the variation in the data, and, the peak ground acceleration (PGA) emerged as the best measure of ground motion intensity. (Kwon & Elnashai, 2010) developed a new way (multiplatform approach) to create fragility curves, this method is reliable The new method also relies on fewer assumptions than the older way (foundation springs method), it said that the older method (foundation springs) might be a good starting point for designing things, but only if the values used are very precise. This is because the older method makes many assumptions that can lead to inaccurate results.

The importance of both scenarios, including kinematic and inertial interactions is found in results of research (Forcellini, 2022) where soil-structure interaction (SSI) helps reduce system fragility and the mechanisms of site amplification driven by soil-structure interaction (SSI) effects,. Specifically, the developed fragility curves illustrate the impact of the mutual interaction between soil and structure, evidenced by changes in period elongation, lateral deflections, floor drifts, and roof accelerations. In addition, ignoring the role of soil-structure interaction (SSI) has shown to increase the fragility of the entire system, encompassing the soil, foundation, and superstructure. The study (Sunil et al., 2021) pointed out that the integral bridges vibrate naturally shows they are more rigid in the longitudinal direction. This rigidity keeps their swaying period within a safe zone during earthquakes. Additionally, these bridges can withstand much stronger shaking compared to what a major earthquake might cause. This strength likely comes from the pressure exerted by the soil behind the supports and the way the entire bridge works together to resist lateral forces.

The research (Miari & Jankowski, 2022) shows that the pounding can have both negative and positive impacts, where, Buildings shaking in soft clay were most susceptible to pounding damage, and, the fragility lessened with stiffer soil, then very dense soil and soft rock, and finally was lowest on rock and hard rock.

A salient earthquake parameter so-called frequency have big connection with the damage predictions for bridges (fragility curves), as demonstrated in article (Lesgidis et al., 2017), it noted that; If the earthquake has high average frequencies and a wider range of wave strengths (Fourier amplitude), then a simple method that ignores these frequencies will be more likely to give wrong results for how likely the bridge is to be damaged. Moreover, the study (Wang et al., 2013) found that the vertical shaking (vertical ground motions) greatly affects how easily fixed bearings break. In contrast, vertical shaking has almost no effect on how easily expansion bearings break. This difference is due to how the weight is distributed on each type of bearing. Additionally, vertical shaking also has little impact on how much pile caps move (pile cap displacements), which is how pile fragility was measured here. This is because the forces pushing the piles come mainly from the rocking motion of the entire structure caused by the sideways shaking (horizontal ground motions). Similarly, the study (Ćosić et al., 2018) shows that bridge piers are more affect by changes in peak ground acceleration (PGA) compared to piles. This means that for the same level of peak ground acceleration, the pier will likely suffer more damage and have a higher chance of experiencing more severe damage. This research provides a valuable method for analyzing how earthquakes influences bridges by considering the complex interplay between the ground, foundation, and the structure itself.

This research examined how near and far earthquakes affect the fragility of a single concrete pier. We considered that the soil interacts with the pile using a software called ˵Seismostruct˝ and dynamic p-y curve analysis.

2. Material and Methods

Generally, Earthquakes close to the fault (within 15-20 km) are particularly destructive because of powerful bursts of ground movement, as indicated in research (Bhandari et al., 2019), These strong pulses are caused by the specific direction the fault ruptures and how it relates to the location of the shaking. Additionally, the way the fault itself moves (shear dislocation) creates these intense pulses in a direction perpendicular to the fault. Imagine these pulses as short, powerful bursts of shaking from both directions along the fault.

In this paper, we choose the pacific earthquake-engineering center (PEER) (*PEER Ground Motion Database - PEER Center*, n.d.) for selection the series of both near and far earthquakes to simulate seismic fragility of single concrete pier, figure 1 presents general components of p-y link element (figures 1-a and 1-b), and our model design (figure 1-c). H is the pier height, and, L is the pile length. We considered the L=30m and the diameter of both pile and pier is 1.5m, as presented in research (Gerolymos et al., 2009),(Lemsara et al., 2023) with two different soil; loose and dense. Note that the two different masses places at pier top are 1500 and 4500 KN. Specifically, the models (cases study) indicted in tables 1 and 2 with fundamental periods.

Through the dynamic numerical software ‶seismostruct” (“SeismoStruct,” n.d.), the concrete material defined by using the nonlinear ‶mander” model, and, the ‶Menegetto-Pinto” models define the steel reinforcement bars.

Table1: models with mass M=4500KN

Model		Fundamental period (s)
H=5m	Dense-4500	0.85
	Loose-4500	0.98
H=10m	Dense-4500	1.64
	Loose-4500	1.84

Table2: models with mass M=1500KN

Model		Fundamental period (s)
H=5m	Dense-1500	0.50
	Loose-1500	0.58
H=10m	Dense-1500	0.99
	Loose-1500	1.09

Based on the reference *p-y* model of research (Tombari et al., 2017), the formulation of soil resistance defined as follow:

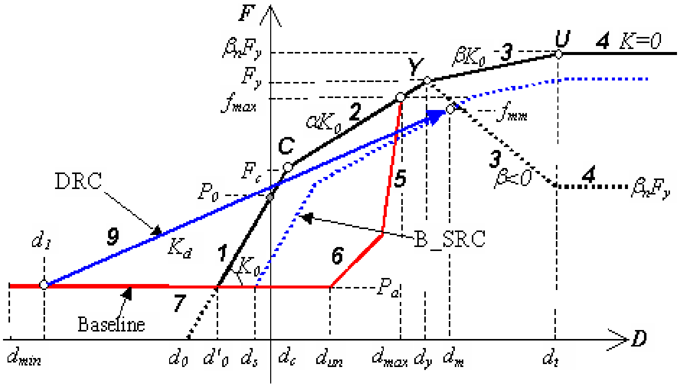
$$p = 0.9\, p_u \tanh\left(\frac{k * z}{0.9\, p_u} y\right)$$

Where k define the initial modulus of the subgrade reaction in soil and p_u is the ultimate bearing capacity.

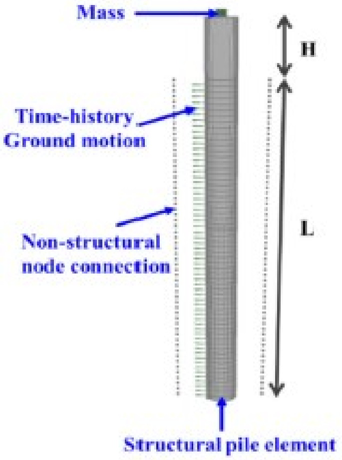
In fact, Seismic fragility refers to the susceptibility of a structure to damage caused by earthquake ground motions. It is a way of expressing how likely a structure is to suffer different levels of damage (from slight cracking to complete collapse) when exposed to earthquakes of varying intensities. The research (Miari & Jankowski, 2022) define the equation for calculation seismic fragility as:

$$P\left(\frac{D}{PGA}\right) = \Phi\left(\frac{\ln(PGA) - u}{\sigma}\right)$$

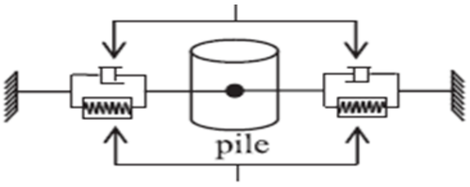
The equation considers the mean logarithmic peak ground acceleration (represented by the symbol u) and its standard deviation (σ). The standard normal cumulative distribution function (Φ) is also incorporated into the calculation.



1-a:link p-y of soil-pile system



1-c: soil-pile spring modeling



1-b: stiffness proportional damping

Figure 1 : Characteristics of soil-pile spring interaction

The design of seismic fragility curve follow these procedures:

1-by using seismostructe software, we define soil-pile spring interaction and precise the masse.

2- Throughout the pushover analysis, we assess the drift value for all different limit state.

3- Selection of near and far field ground motion records.

4- Perform an incremental dynamic analysis (IDA) on the system. Then, analyze the results to determine the median and standard deviation.

5- Plotting a seismic fragility curve.

3. Results

The outcomes of this paper is the added simulations to our research (Lemsara et al., 2023) which consider the seismic fragility of concrete pier for all models (casas studies) above-mentioned, the analysis precise for two-limit state, namely, Immediate occupancy (IO) and Collapse Prevention (CP). The figures from 2 to 5 shows the results of fragility curve for H=5m, and from 6 to for seismic fragility in case of H=10m.

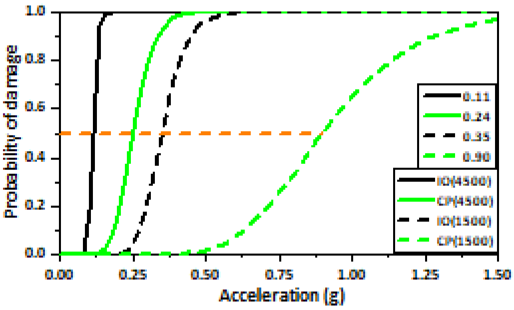


Figure 2 : seismic fragility in case dense sand with near earthquake (H=5m)

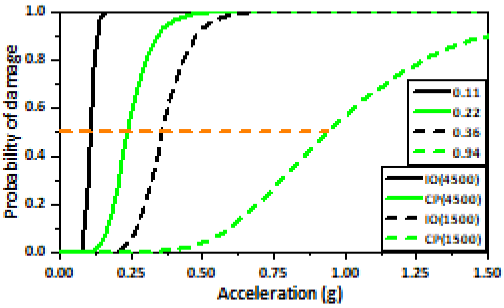


Figure 3 : seismic fragility in case loose sand with near earthquake(H=5m)

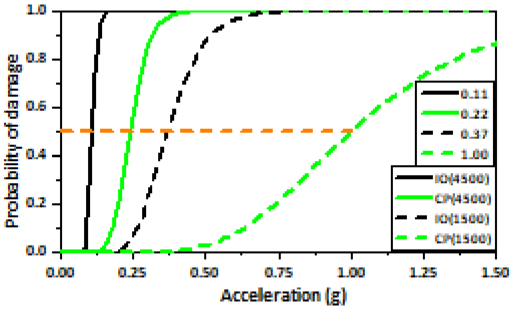


Figure 4 : seismic fragility in case dense sand with far earthquake (H=5m)

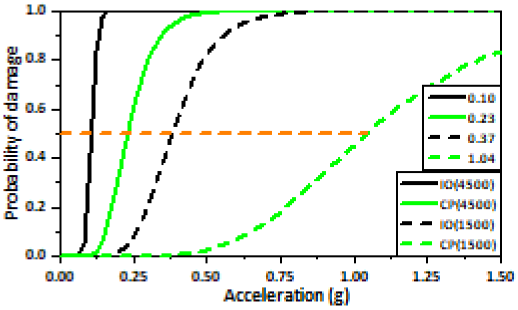


Figure 5 : seismic fragility in case loose sand with far earthquake (H=5m)

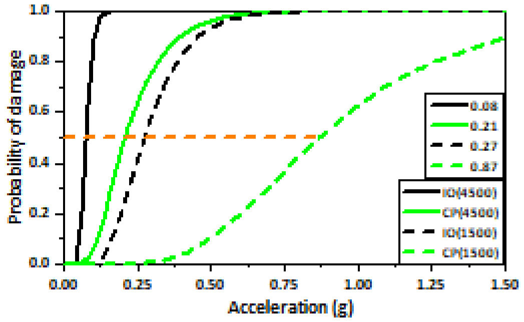


Figure 6 : seismic fragility in case dense sand with near earthquake (H=10m)

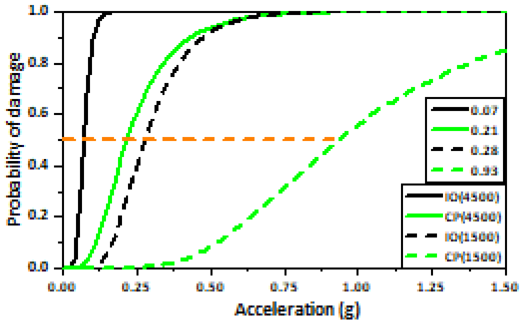


Figure 7 : seismic fragility in case loose sand with near earthquake (H=10m)

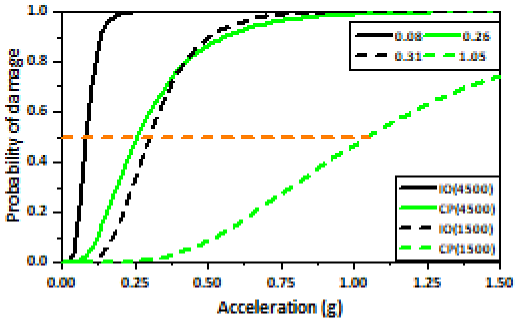


Figure 8 : seismic fragility in case dense sand with far earthquake (H=10m)

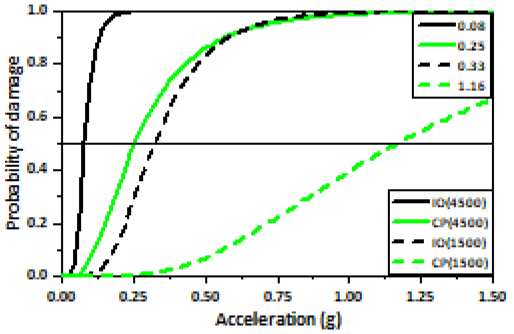


Figure 9 : seismic fragility in case loose sand with far earthquake (H=10m)

4. Discussions

The figure 2 shows that the acceleration for exceeding 50% of failure probability in case dense sand and mass of 1500KN and H=5m at limit state (IO) under near earthquake is 0.35g and 0.90 at limit state (CP). On the other hand, with same model but under far earthquake as shown in figure 4, the acceleration for exceeding 50% of damage probability at limit state (IO) is 0.37 and 1.00 at limit state (CP). We conclude that the difference between the two limit states is 0.55g under near ground motion that lower than far ground motions that is equal to 0.63g.

After look forward to all figures, we show that near earthquake have lower difference studies between limits states (IO) and (CP) for two cases of H.

Also, the figure 2 shows that the acceleration for exceeding 50% of failure probability in case dense sand and mass of 4500KN and H=5m at limit state (IO) under near earthquake is 0.11g and 0.24 for limit state (CP). On the other hand, with same model but under far earthquake as shown in figure 4, the acceleration for exceeding 50% of damage probability at limit state (IO) is 0.11 and 0.22 at limit state (CP). We conclude that the difference between the two limit states is 0.13g under near ground motion that greater than far ground motions that is equal to 0.11g.

After look forward to all results of remaining models, we show that this difference is lower in cases of near-fault earthquakes.

The comparison of the model above-mentioned with two mass 1500KN and 4500KN, we show the lower mass obtained greater difference of acceleration between limit states (IO) and (CP) for exceeding 50% of failure probability, the figures indicates the same trend for all models.

When we compare the seismic fragility of each model of H=5m and model of H=10m, we show that model of H=10m have higher difference of acceleration between limit states (IO) and (CP) to exceeding 50% of failure probability, due to its higher fundamental period.

5. Conclusions

Seismic fragility analyses are important for understanding the probability of various damage states in structures subjected to earthquakes. They are typically summarized in fragility curves, which show the probability of exceeding a particular damage level for a given earthquake intensity. These are valuable tools for earthquake assessments in the field of engineering, in this regard, the main conclusions of this study as following:

The lower mass obtained greater difference of acceleration between limit states (IO) and (CP) for exceeding 50% of failure probability

The model which have higher fundamental period obtained greater difference of acceleration between limit states (IO) and (CP) for exceeding 50% of failure probability.

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Conflict of Interests

The Authors declare that there is no conflict of interest.

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