SEISMIC FRAGILITY ANALYSIS OF AXIALLY LOADED SINGLE PILE

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ABSTRACT :

Performance-based seismic design is the latest trend to earthquake resistant design for Sub structure and Super structures. Many parameters involved in seismic design have uncertainty associated with them. Characterizing the probabilistic nature of these parameters can be done through the use of 'Fragility Curves'. A fragility analysis assesses the probability that the seismic demand placed on the structure exceeds the capacity conditioned on a chosen IM representative of the seismic loading. Demand (D) and capacity (C) are assumed to follow a lognormal distribution, and the probability of exceeding a specific damage state for a particular component can be estimated with the standard normal cumulative distribution function as per Cornell et. al. [9]. This paper presents the performance of axially loaded single pile subjected to different earthquakes of varying PGAs. FEM software called openseesPL is used for Times history analysis. Floating pile is modelled by beam-column elements, and rigid beam-column elements are used to model the pile diameter. A nonlinearity of soil is introduced using pressure dependent multiplied model and the pile is modelled as elastic. Proper boundary conditions, simulating radiation effects are used. To conduct nonlinear dynamic analysis, forty four natural time history data are selected, and modified to match with Indian response spectrum (IS 1983-2002) using WavGen (Mukharjee and Gupta, 2002). Uncertainty in soil properties is included. A Latin hypercube sampling technique is adopted for generation of random variables which follows a normal distribution with mean and standard deviation. The numerical modelling was done from the generated random values which then subjected to different PGA for performance evaluation.

KEYWORDS: Fragility, axially loaded pile, openseesPL, Response spectrum

1. INTRODUCTION

Significant number of studies has been reported in the past for dynamic analysis of pile and pile groups in liquified and non liquified soils. Based on FE analysis, Maheshwari et.al (2004) reported that the soil nonlinearity increases the pile head's structural responses at low frequencies and at higher frequencies its effect is insignificant under for both harmonic and transient excitation. Adak et.al. (2004) reported that the failure due to buckling instability of the axially loaded pile is the predominant failure mechanism during liquefaction and also explained the failure mechanism of pile in layered soils. Some researchers like Shahrour et al. (2001) conducted a 3-D FEM analysis of micro piles using a finite element program, PECPLAS. The soil-micro pile structure system was assumed to be elastic with Rayleigh material damping. Juran et al. (2001) etc. studied the behaviour of micro piles under different modelling techniques including numerical modelling. Juran et al. (2001) used finite difference software namely LPILE and GROUP to study the structure-soil-micro pile behaviour and also to investigate the response of the micro pile systems subject to earthquake loading. However a limited number of studies over the past years are reported for the performance evaluation of pile under different limit states condition under earthquake. In this study, we conduct a finite element simulation of Pile No. 2 of the Arkansas test series (Alizadeh and Davisson, 1970) using the OpenSeesPL interface. This pipe pile is subjected to earthquakes of different PGAs. The pile is subjected to axial compressive load of 750 kN. The present work is to assess the performance of typical axially loaded single pile under earthquakes in probabilistic approach. Uncertainties in the soil properties are also considered.

2. METHODOLOGY

2.1. Development of Fragility curves

A fragility function represents the probability of exceedance of the selected Engineering Demand Parameter (*EDP*) for a selected structural limit state (*DS*) for a specific ground motion intensity measure (*IM*). These curves are cumulative probability distributions that indicate the probability that a component/system will be damaged to a given damage state or a more severe one, as a function of a particular demand.Fragility curve damaged to a given damage state or a more severe one, as a function of a particular demand.Fragility curve can be obtained for each damage state and can be expressed in closed form as using Eq. 1

$$P\,(C\text{-}D \leq 0|IM) = \Phi\left(\frac{\ln\frac{S_d}{S_c}}{\sqrt{\beta_{d|IM}^2+\beta_c^2}}\right) \tag{1}$$

where, C is the drift capacity, D is the drift demand, S_d is the median of the demand and S_c is the median of the chosen damage state (*DS*). $\beta_{d/IM}$ and β_c are dispersion in the intensity measure and capacities respectively. Eq. 1 can be rewritten as Eq. 2 for component fragilities (Nielson, 2005) as,

$$P\,(DS|IM) = \Phi\left(\frac{\ln IM - \ln IM_m}{\beta_{comp}}\right) \tag{2}$$

Where, $IM_m = exp\left(\frac{\ln S_c - \ln a}{b}\right)$, a and b are the regression coefficients of the probabilistic Seismic Demand Model (PSDM) and the dispersion component, β_{comp} is given as,

$$\beta_{comp} = \sqrt{\frac{\beta_{d|IM}^2+\beta_c^2}{b}} \tag{3}$$

The dispersion in capacity, β_c is dependent on the building type and construction quality. For βc, ATC 58 50% draft suggests 0.10, 0.25 and 0.40 depending on the quality of construction. In this study, dispersion in capacity has been assumed as 0.25.
It has been suggested by Cornell et. al (2002) that the estimate of the median engineering demand parameter (*EDP*) can be represented by a power law model as given in Eq. 4.

$$\widehat{EDP} = a(IM)^b \tag{4}$$

In this study, threshold displacement (δ) at the pile top is taken as the engineering damage parameter (EDP) and peak ground acceleration (PGA) as the intensity measure (IM).

2.2. Ground motion data

The number of ground motions normally required for an unbiased estimate of the structural response is 3 or 7. However, ATC 58 50% draft recommends a suite of 11 pairs of ground motions for a reliable estimate of the response quantities. ASCE/SEI 41(2005) suggests 30 recorded ground motions to meet the spectral matching criteria for NPP infrastructures. A set of forty four Far-Field natural Ground Motions are collected from Haselton and Deierlein (2007). These are converted to match with IS 1893 (2002) spectrum using a program, WavGen developed by Mukherjee and Gupta (2002). Figure 2 shows the Response spectrum for converted ground motions along with Indian spectrum.

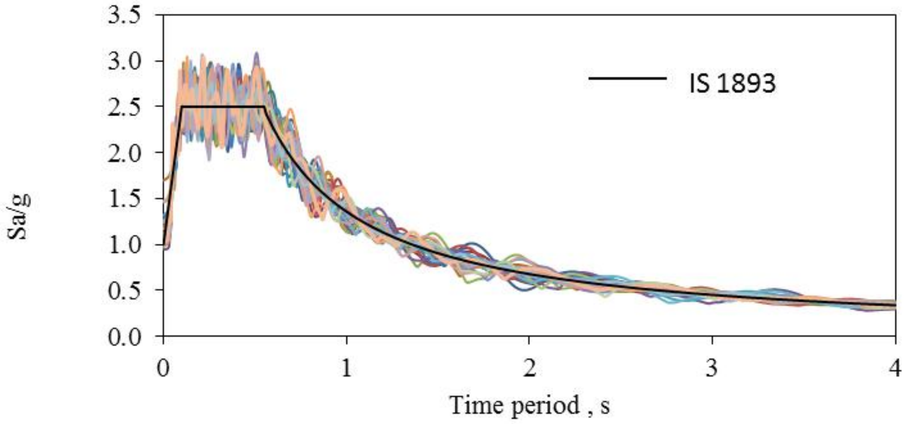

Figure 2 Response Spectra for 44 converted ground motions along with IS 1893 (2002) design spectrum axial strain curves

3. NUMERICAL STUDY

3.1 Pile data employed in the OpenSees simulation

The pile considered in the present study is circular in section with a diameter of 0.406m and a wall thickness, t= 7.925 mm, Table 3.1 Shows the details of pile properties taken from Bowles (1988).

Table 3.1 Properties of Pile

Sl. no	Description	Value
1	Pile diameter	0.406 m
2	Pile length	16.5 m
3	Moment of inertia	834.2 in^2
4	Youngs modulus of pile, (E)	29000 ksi

3. 2 Soil data

The pile is embedded in a uniform soil layer and its properties are shown in the Table 3.2. Projection of pile length above ground surface is 0.3048 m and below the ground surface is 16.195 m. Uncertainty in soil parameters are taken from Phoon and Kulhawy (1999). Forty four statistical models are developed according to Latin Hyper cube sampling.

Table 3.2 Properties of soil

Sl no	Description	Mean Value	Cov (%)	Reference
1	Reference confinement	80KPa	-	Lu et al. (2006)
2	Shear modulus, Gs	10.88Ksi	-	Lu et al. (2006)
3	Bulk modulus, B	29Ksi	-	Lu et al. (2006)
4	Poisson’s ratio	0.33	-	Bowles. (1988)
5	Unit weight, (γ')	62.8pcf	14	Bowles. (1988)
6	Friction angle, φ	320	10	Bowles. (1988)
7	Shear strain, γmax	10%	-	Bowles. (1988)

3.3 Modelling

In view of symmetry, a half-mesh (2,900 8-node brick elements, 23 beam-column elements and 207 rigid beam-column elements in total) is studied as shown in Figure 2. Length of the mesh in the longitudinal direction is 520 ft, with 260 ft transversally (in this half-mesh configuration, resulting in a 520 ft x 520 soil domain in plan view). Layer thickness is 80 ft (the bottom of the soil domain is 27.2 ft below the pile tip, so as to mimic the analytical half-space solution). The floating pile is modelled by beam-column elements, and rigid beam-column elements are used to model the pile size (diameter). The following boundary conditions are enforced:

i) The bottom of the domain is fixed in the longitudinal (x), transverse (y), and vertical (z) directions.
ii) Left, right and back planes of the mesh are fixed in x and y directions (the lateral directions) and free in z direction.
iii) Plane of symmetry is fixed in y direction and free in z and x direction (to model the full-mesh 3D solution). The lateral load is applied at the pile head (ground level) in x (longitudinal) direction. The above simulations were performed using OpenSeesPL (Lu et al. 2006).

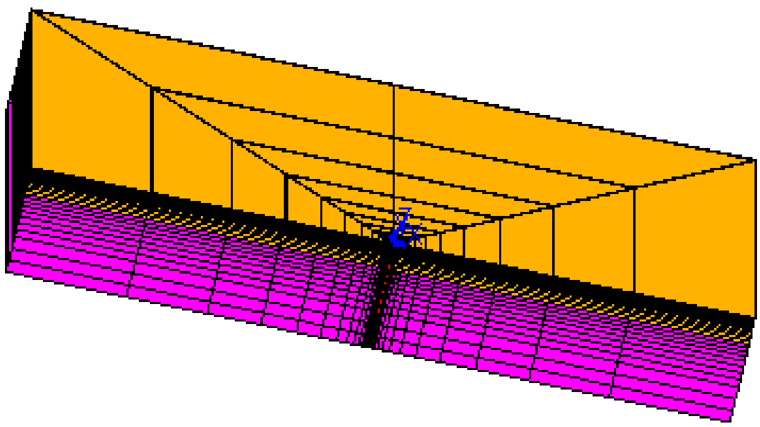

Figure 2 FEM Modelling of axially loaded pile in OpenseesPL

4. PERFORMANCE LEVEL

The design threshold displacements at the ground level can be set to approximately 2%, 3% and 4% of the pile diameter for the serviceability limit state in the Normal Situation and the Frequent Earthquake Situation (Masahiro Shirato et.al, 2003). These values are generally larger than the past values of 0.01B and 15 mm for a typical range of pile diameters in highway bridge foundations. Hence the fragility curves for different design threshold displacement at the ground level are calculated.

5. ANALYSIS

Forty Four Time history analyses are performed for the developed statistical models using openseesPL. Selected forty four earthquakes are scaled from 0.065g to 0.72g. Displacement at each node is recorded throughout the analysis. Maximum Displacement in Pile is considered as an Engineering Damage parameter. It is found that Pile top always shows the maximum response.

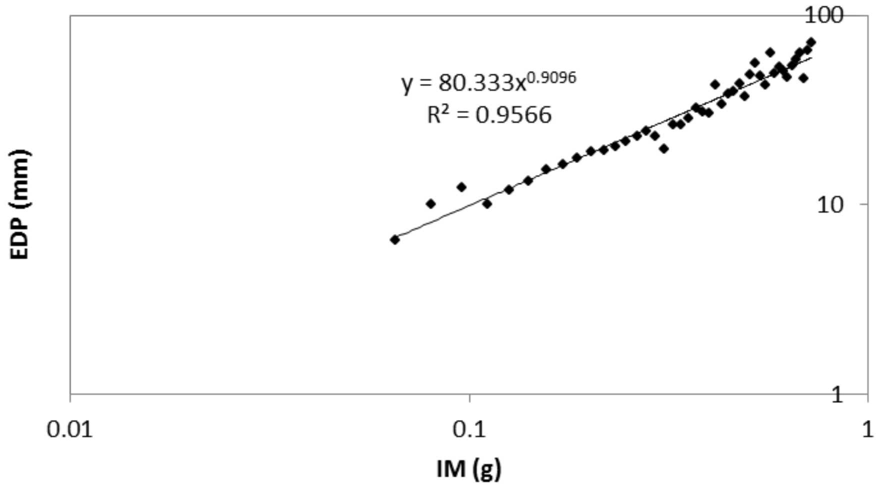

Figure 3 PSDM for Pile

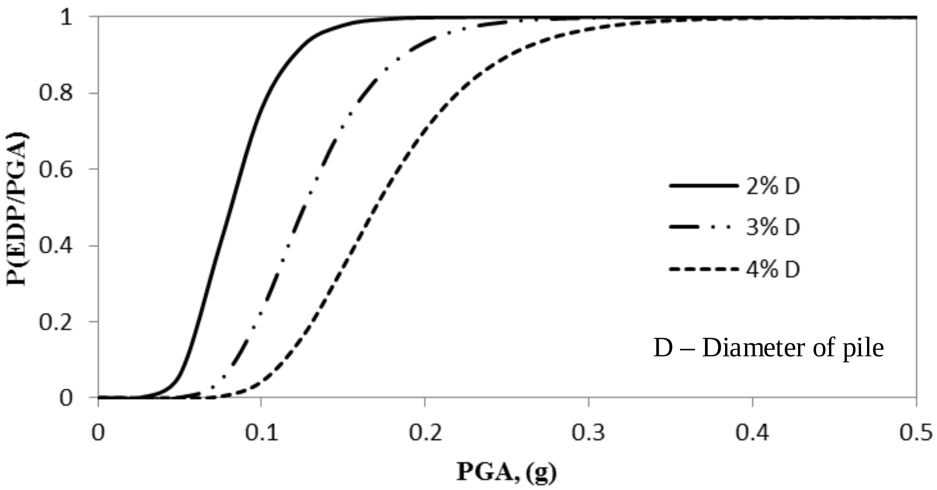

Figure 4 Fragility curves for design lateral deformation

DISCUSSIONS AND CONCLUSIONS

The response of axially loaded pile under earthquake loading has been studied in probabilistic manner and the corresponding fragility curve has been formulated for different limit state of serviceability condition 2%, 3% and 4% diameter of pile as reported in the literatures. Figure 3, shows the Probabilistic Demand model between Intensity Measure and Engineering Demand parameter. It is fitted through the power law equation having R^2 value as 0.9566 and corresponding uncertainty is calculated ($\beta_{d/IM}$ =0.125). Figure 4, shows the exceedance probability of pile for various serviceability limit states. It is seen that for a 50 % probability of exceedance for 2%, 3% and 4% limit state condition of serviceability is 0.079g, 0.124g and 0.17g, respectively. It is observed that the relative displacement at the top of the pile increases as the PGA increases. Pile considered for the present study is not designed for seismic loading,, it shows the probability of exceedance as high for small PGA.

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