# Vulnerability assessment of pile foundation in soft clay incorporating SPSI

SwagataDebRoy[1]and RajibSaha[2]

[1,2]NIT Agartala, Agartala799046, Tripura
swagatadevroy@gmail.com; rajib.iitbbsr@gmail.com

**Abstract.** Past failures of pile foundation supported structures during moderate to severe earthquake had lead earthquake professionals to develop sustainable design guideline. Dynamic soil structure interaction (DSSI) is considered as an important phenomenon in seismic design as it leads to increased or decreased response that of conventional fixed base design. On the other hand, variability of subsoil properties and ground motion influence the dynamic response of structure. In this context, present study attempts to assess the seismic vulnerability of pile foundation embedded in soft clayey layer by developing fragility curves incorporating both material and ground motion uncertainity. Finite element model of soil-pile-foundation-structure-system is modeled using OPENSees software. Total 0.36 million nonlinear dynamic analysis of the whole system are performed to obtain the probabilistic response of pile foundation. Monte Carlo simulation is performed to calculate the probability of failure and finally multiple strip analysis technique is used to construct fragility function. Results indicate that probability of failure is higher pertaining to serviceability limit state as compared to collapse criteria.

**Keywords:** DSSI, Fragility, OPENSees, pile foundation, vulnerability.

## 1 Introduction

Fragility analysis is a generalized theory of structural reliability to estimate vulnerability of foundation or structure subjected to earthquake forces. The assessment of seismic vulnerability of buildings or bridges is a prerequisite for seismic loss estimation and risk management. Pile foundation is considered as highly engineered and robust foundation system to support heavy structural load in soft as well as loose soil deposit. Currently available seismic fragility codes are developed for fixed-based structures ignoring SSI effects. Failures of several pile supported structures, such as, bridge, buildings, flyovers etc. during past earthquake events (e.g. Niigata (1964), Loma Prieta (1989), Kobe earthquake (1995)) has given a strong lesson and insisted engineers and researchers to modify the existing seismic design guidelines of foundation and structures. Post-facto analysis of failure of such structures indicated that the behaviour of pile supported structure embedded in soft soil during seismic excitation is a dynamic soil-structure interaction (DSSI) problem. In recent studies (Pitilakis et al., 2014) it is shown that SSI effect plays a crucial role modifying considerably the seismic performance and fragility of structures. SSI affects the seismic performance of structures depending on the type of foundation. Veletsos and Meek (1974) stated SSI consideration in analytical models can be performed by kinematic interaction simulation techniques which results in natural time period elongation of the system and increased damping due to energy dissipation. Considering DSSI in study may result in either increased or decreased forces in superstructure and foundation than in fixed base condition. In fact, vulnerability assessment of structure needs to address uncertainty factors associated with the system. Material and load are the main sources of uncertainty. It has been shown that uncertainity in soil properties and SSI may modify response and fragility of structures and indicates the effect of soil and foundation parameter uncertainities to be relatively small compared to uncertainity from ground motion (Rajeev *et al.* 2012). Inherent variability is described as one of the major sources of soil uncertainty (Phoon and Kulhway 1999). Previous studies emphasized on different reliability based approaches for probabilistic seismic design of pile (e.g. Tandjiria *et al.* 2000, Haldar and Babu 2008, Pula and Rozanski 2012). Present study is focused on to study the effect of earthquake ground motion uncertainty and material uncertainity (shear strength) on seismic response of pile foundation embedded in soft clayey deposit. It is seen that input motion characteristics have a most significant effect on vulnerability curves (Kwon *et al*. 2005). Zentner *et al.* (2016) has discussed about different fragility analysis methods and their advantages and disadvantages too.

Present study attempts to calculate vulnerability of pile foundation in soft clayey deposit incorporating the effect of variability of ground motion as well as variation in shear strength of soil considering soil-pile foundation-structure interaction in the form of fragility curves. Beams on nonlinear Winkler foundation (BNWF) is used to model soil-pile foundation-structure interaction (SPSI). Response statistics is obtained for an idealized structural system having fundamental period of 0.6 sec supported on piled foundation embedded in soft clay. Probabilistic analysis is performed based on randomly generated IS code spectrum consistent synthetic ground motions. Fragility curves are generated based on the ‘failure’ and ‘success’ information gathered from comparisons using maximum likelihood method. Serviceability limit state as well as collapse is considered in present study. Hence, the present study helps to give some useful insight in the design of pile foundation in soft clayey deposit.

## 2 Modelling of structural system

A representative short period structure with fundamental period ($T_{fixed}$) of 0.6 sec, resembling a 6-story RCC building is designed to be supported by pile foundation embedded in very soft homogenous clay. The pile tips are assumed to be resting on a hard soil deposit. The pile groups are decided based on live load of 7.2 KN/m$^2$ acting at each floor, for a total bay size of 22.5 m × 15 m along with the dead load of the structure. Centrally loaded $2 \times 2$ pile group is modeled herein. The spacing (s) between the piles is kept 5 times the diameter (*d*) of the pile and the length (*L*) of the pile is 45 times the diameter of the pile. Table 1 presents the properties of pile used. Superstructure is modeled as a lumped mass stick SDOF system in OPENSees. Column is modeled as beam column element whose stiffness is adjusted for $T_{fixed}$= 0.6 sec. Pile cap is modeled as a four-noded shell element, each node having six degrees of freedom. Dimension of pile cap is considered as 4m × 4m, discretized into 0.5m × 0.5m small elements. Pile is designed as displacement based beam column element, each node having six degrees of freedom. Each of the pile is discretized into 0.9m interval. Pile head is attached to the pile cap by a rigid link to maintain the same degrees of freedom of pile cap element. Plate on Winkler foundation and Beams on Winkler foundation (BWF) model is used to model the pile-soil interaction. Pile-soil interaction is modeled considering non-linear idealization of load-deformation behavior of soil. Nonlinear pile-soil modelling in clayey soil is carried out using cyclic *p*-*y*, *t*-z and *q*-z springs as suggested by Boulanger *et al.* (1999) and Curras *et al.* (2001) based on benchmark stiffness curve proposed by Matlock (1970).However, present study proposes a modification in the backbone *p*-*y* curve for soft clay suggested by Matlock (1970) to incorporate the effect of spatial variability in $£_{50}$. The curve in Matlock (1970), the critical displacement $y_c$ is a function of strain parameter $£_{50}$ and this value was given on the basis of triaxial laboratory test. Present study proposes $£_{50}$ as a function of undrained cohesion ($C_u$) based on Evans and Dunkans (1982) which seems to be more rational from the point of view on predicting the accurate response of soil-pile foundation-structure system. The relationship between mean values of $£_{50}$ and $C_u$ is found to be best fitted with power based equation. The modified expression used is presented below.

$$£_{50} = \left( \frac{0.1796}{\log_{10} C_u} \right)^{\frac{1}{1.1841}} \quad y_c = 2.5 \times d \times \left( \frac{0.1796}{\log_{10} C_u} \right)^{\frac{1}{1.1841}}$$

Soil damping is idealized as linear dashpots connected parallel to the soil springs for pile. This study considers 5% of critical damping in each mode regardless of structural support condition. Plan and elevation of the building and finite element model of the soil-pile-structure system is shown in Fig. 1.

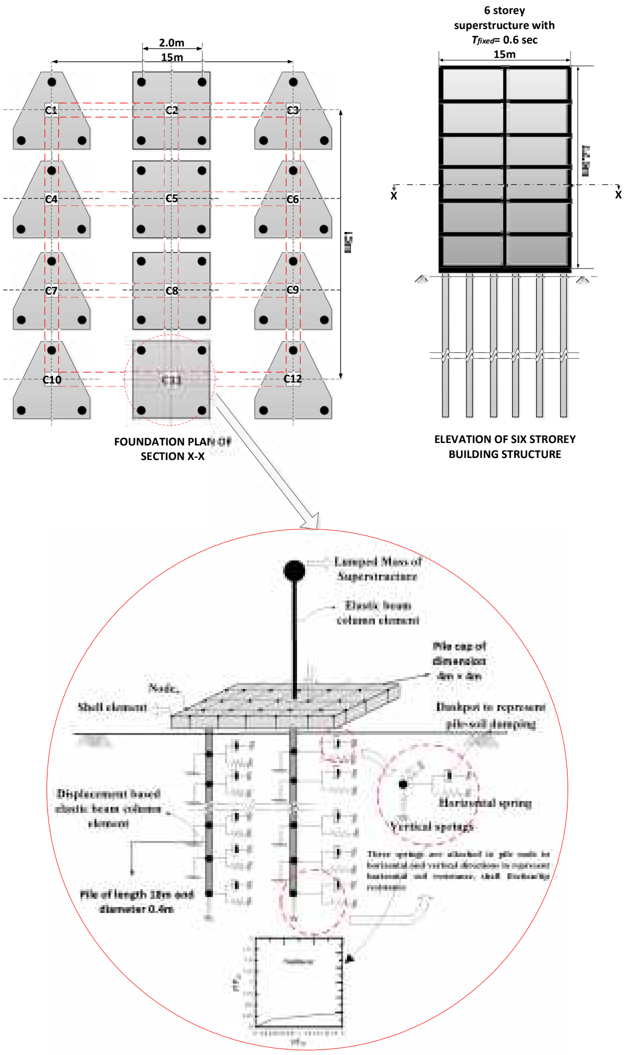


**Fig. 1** Plan and elevation of a 6-storey pile foundation supported building and finite element model of the central pile foundation lumped mass system in OPENSees.

# 3 Uncertainities in modelling

Uncertainities arise either from lack of knowledge known as epistemic uncertainity or from factors that are inherently random known as aleatoryuncertainity. In the present study, aleatory uncertainities in both ground motion as well as uncertainity in soil parameter (material uncertainity) i.e. undrained shear strength are considered.

## 3.1 Uncertainities in input motion and generation of artificial ground motion

In generating artificial ground motions, spectral ordinates are considered as random variables, as suggested by Halder and Babu (2009). Halder (2009) pointed that the variability associated with elastic response spectrum can be classified into three main categories; like as seismic source and attenuation variability $(\pm_{SE})$, variability due to local geology and site condition $(\pm_{GS})$ and variability associated with seismic force determination $(\pm_{RS})$. The value of $\pm_{SE}$ is taken from Bea (1999), which suggested the value based on peak ground acceleration divided by gravitational constant for different seismo tectonic characteristics of a location. The value considered in this study is 0.001g. The variability due to $\pm_{GS}$ is taken as 0.004g taking in to account the soil class A (IS 1893 Part I 2016). The variability due to $\pm_{RS}$ is considered 0.003g based on modelling uncertainity. The resultant variability $\pm_{R}$ of the spectrum ordinate is the combination of these three variabilities used for the determination of variability in ground motion. The resultant variability ($\sigma_R$) is presented as follows,

$$\pm_{R} = \sqrt{\pm_{SE}^{2} + \pm_{GS}^{2} + \pm_{RS}^{2}}$$

The ordinates of ground motion are considered as lognormally distributed random variables which are valid for non-negativity of the response spectrum and its simple relation with normal distribution. The mean spectra considered here is the IS spectra for soft soil considering 5% damping and COV 10%. Monte Carlo Simulations (MCS) are conducted for generating random spectrum ordinates considering the mean spectra.

For this study, artificial earthquake motions matched to a specified target response spectrum are generated using Seismoartiff 2016 software for carrying out nonlinear dynamic analyses. This software uses different calculation methods and varied assumptions to generate target response spectrum. Here 15 numbers of response spectrums are randomly generated using the software and for each spectrum eight numbers of ground motions are developed. Therefore a total of 120 numbers of artificial ground motions are generated for carrying out this study.

### 3.2 Uncertainities in soil parameter

The spatial variability of undrained soil shear strength ($C_u$) and Young's modulus ($E_S$) of soil is modeled by random field for uncertainities in soil. Random field generation is done following Halder and Babu (2008) within the finite element grids by assigning $C_u$ or $E_S$ at each grid location which is not presented herein due to brevity. These two parameters are considered as log normally distributed random variables are depicted by mean «$C_u$ , standard deviation ±$C_u$ and spatial correlation distance a$_z$ =1.5. Deterministic soil parameters presented in Table 1 are assumed as mean values for probabilistic analysis. The probability analysis is conducted for a range of variability and a correlation parameter of soil. The range of values is selected based on the typical range for coefficient of variation (COV) of shear strength (10%-50%) as suggested by Phoon and Kulhway (1999). Monte Carlo simulation (MCS) is adopted in present study for probabilistic analysis. Based on a convergence study (Das *et al*. 2016**)**, the number of sample realizations for MCS analysis is considered as 200. The range of co-efficient of variation (COV $C_u$ or COV $E_S$ %), is considered as 10, 30 and 50.

**Table 1** Pile and soil properties

| Pile data | Value | Soil data | Value |
|---|---|---|---|
| Diameter of pile, *d* (m) | 0.3 | Consistency | Very soft |
| Length of pile, L(m) | 18 | Undrained cohesion $C_u$ (KN/m$^2$) | 9.80 |
| Young's modulus $E_p$(KN/m$^2$) | 2.178×10$^6$ | *SPT N* value | 1 |
| Poisson's ratio of concrete | 0.17 | Young's Modulus | 2500 |
| Section Modulus *Z* (m$^3$) | 0.0063 | Poisson's ratio | 0.4 |
| Flexural moment, $M_y$(KN/m) | 251.2 | Undrained cohesion at tip, $C_d$ (KN/m$^2$) | 100 |

## 4 Dynamic Analysis

Non-linear dynamic analyses are performed to obtain the dynamic response of the 3D finite element model of soil-pile system. A total of 0.36 million cases are carried out to obtain the probabilistic response of pile foundation. Newmark's β-γ time stepping method with time integration parameters $\gamma$=0.25 and $\beta$=0.5 is used to solve the equation of motion. Modified Newton algorithm is considered to carry out the analyses.

# 5 Fragility curves derivation

Vulnerability of a system can be expressed in many ways; development of fragility curves is one of them. The fragility curves represent relationships yielding the probability of reaching or exceeding a certain level of damage under an excitation of certain intensity. Multiple strip analysis (Baker 2011) approach is chosen here as it is the most common approach while using conditional spectrum method. It is, therefore, of a great importance to select an indicator of the earthquake intensity that describes it as well as possible. Similarly, in analyzing the seismic vulnerability of any part of structures, definition of limit state is of particular importance.

## 5.1 Intensity Measures (IMs)

With multiple strip analysis approach, the analyses are done till the IM amplitude where all the ground motion causes collapse. Common IMs generally used to indicate the damage intensity are peak ground velocity (PGV), peak ground acceleration (PGA), spectral acceleration ($S_a$). $S_a$ is considered here as the IM to describe the damage intensity. $S_a$ values corresponding to each spectra by MCS as mentioned in the earlier section are used.

## 5.2 Limit state definition

In this study, two limit states are defined based on displacement and moment carrying capacity of the pile foundation which are serviceability limit state and collapse limit state respectively. The maximum displacement for the pile to be serviceable is considered 30 mm as per Das *et.al* (2016) and the maximum moment capacity is the yield capacity of the pile i.e. 251.2 KN-m for the pile diameter considered.

## 5.3 Fitting of curves

The statistical procedure for fitting data when conditional spectrum method is used, as used herein is slightly different when IDA is used. In such cases, Maximum likelihood estimation (MSE) is adopted for fitting of vulnerability curves as per Baker (2011). It is the probability of observing collapses out of total suite of ground motions.

$$P(C \mid Sa = x_j)_{observed} = \frac{numberofcollapseswhenS_a = x_j}{numberofgroundmotions}$$

A lognormal cumulative distribution function is often fit to this data, to provide a continuous estimate of the probability of collapse as a function of $S_a$. The equation for this function is

$$P(C \mid Sa = x) = ¤(\ln x - «)/$$

where, $P(C \mid Sa = x)$ is the probability of collapse of a given ground motion $Sa = x$, ¤() is the normal cumulative distribution, « and   are the mean and standard deviation of $\ln Sa$ respectively. Therefore, « and   can be calculated as

$$« = \frac{1}{n}\sum_{i-1}^{n} \ln Sa_i$$

$$= \sqrt{\frac{1}{n-1}\sum_{i-1}^{n} (\ln Sa_i - «)^2}$$

## 6 Results and Discussion

The vulnerability curves are developed considering both ground motion uncertainity and material uncertainity and checked for both serviceability limit state criteria and collapse limit state criteria. Figure 2 presents the vulnerability curves for pile foundation under serviceability criteria. It is seen when only ground motion uncertainity is considered (i.e. COV 0%), failure starts around 0.7g and 100% failure occurs at 1.12g. When material uncertainity is considered along with ground motion uncertainity, the failure starts early as seen in Fig. 2. For COV 10%, there is a slight difference of failure from COV 0%. For COV 30% and 50%, failure starts much earlier around 0.2g and 0.1g respectively and 100% failure occurs around 0.8g for both the cases.

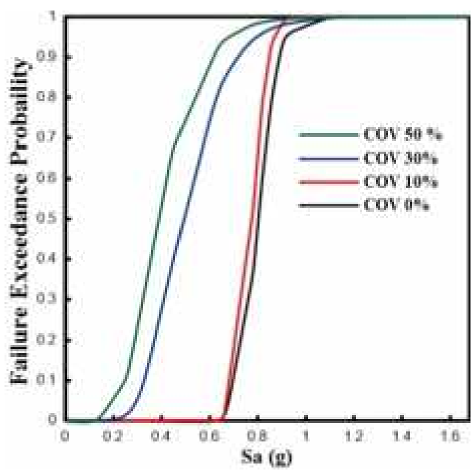


**Fig. 2** Fragility curves of pile foundation for serviceability criteria.

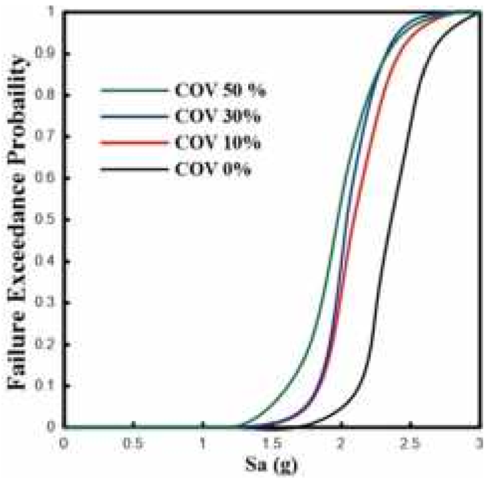


**Fig. 3** Fragility curves of pile foundation for collapse criteria.

Fig. 3 presents the fragility curves of pile foundation for collapse criteria. It is seen that under ground motion uncertainity alone, failure starts occurring at higher $S_a$ i.e above 1.5g. In cases of COV 10%, 30%, 50%, failure starts occurring earlier than COV 0%. But all the failures are at higher levels of $S_a$ i.e. above 1g.

## 7 Conclusion

This present study highlights vulnerability of pile foundation of a six-storey building embedded in soft clayey deposit considering two limit states, namely serviceability and collapse criteria incorporating input ground motion uncertainity and material uncertainity. Fragility curves are constructed to present the vulnerability of pile foundation. Ground motion uncertainity is modeled by the incorporation of variability in IS proposed spectrum acceleration curves. Material uncertainity in undrained soil shear strength ($C_u$) and Young's modulus ($E_S$) of soil is modeled by random field. It is seen that the fragility curves developed for serviceability limit state has higher failure exceedance probability as compared to collapse criteria. For instance, in case of COV 10%, failure exceedance probability reaches 100% at $S_a$ 0.86g and 2.5g respectively considering serviceability and collapse criteria respectively. This trend is similar for all the other cases. The results are quite in accordance with earlier studies. Thus the results of this study might be helpful to the vulnerability assessment of pile foundation.

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