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Effect of in-situ variability of soil on seismic design of piled raft supported structure incorporating dynamic soil-structure-interaction

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A B S T R A C T

Inherent variability of soil considerably affects the seismic design of piled raft supported structures. Conventional design of such structure adopts fixity at base level of superstructure and pile head. However, soil–pile–superstructure interaction largely affects the fundamental frequency and design forces in columns and piles. In contrast, fixed base assumption cannot capture soil structure interaction (SSI) effect. In addition, uncertainty in soil may further leads to a change in the dynamic behavior of the system. This study examines the effect of inherent variability of undrained shear strength of soil in seismic design of structures supported by piled raft foundation embedded in soft clay. Superstructure is modeled as lumped mass stick model and piled raft slab is modeled as rigid plate. Pile is modeled as Euler–Bernoulli beam element and soil resistance is modeled using linear Winkler springs attached to the pile. Dynamic analysis is carried out in time domain to estimate the responses. Monte Carlo simulation technique is used for probabilistic assessment of the fundamental frequency and forces at column and pile attributing a wide range of parametric variation of a representative soil–piled raft–superstructure system. The study shows that the fundamental frequency and forces in column and pile changes significantly due to soil variability.

1. Introduction

Sustainable design of structure is a prime issue to ensure safe, economic and environmental friendly structure during any disastrous event, especially during strong earthquake. Probabilistic analysis of structural response incorporating different uncertain parameters may help to arrive at a sustainable design solution. Piled raft foundation is commonly used to support such heavy as well as important structures such as tall towers, bridges, nuclear structures etc. in soft to medium soil. Seismic design of structures supported by piled raft foundation is a challenging and complex problem as the mechanism of transfer of lateral loads to the column and soil from pile is essentially dependent on soil type and pile, which is attributed by soil structure interaction (SSI) problem. Traditionally, seismic design of such structure is performed assuming fixed base condition. As a result, the complex soil–piled raft–structure interaction is ignored which may have a serious implication on the dynamic response of structure [1–4]. However, the failure of pile foundation supported structure in various seismic events (e.g.1985 Mexico City earthquake, 1989 Loma Prieta earthquake, 1995 Kobe earthquake) indicated the importance of SSI in seismic design. On the other hand, a perception of beneficial implication of SSI generally prevails in designer's mind based on few codal guidelines [5,6] and ignored in seismic design. Several other studies have pointed out the importance of soil–pile foundation–structure interaction to obtain the design response of the structure [7,8,3,9–11].

It is observed that previous studies mostly focused on intricacy of pile-soil modeling and method of analysis, whereas, a limited effort has been rendered to see the effect of such interaction on overall seismic behavior of structure [12,13,8,10,14]. A recent study by Saha et al. [15] indicated that relative acceleration of heavy raft and upper part of the pile with respect to the neighboring soil attracts additional lateral force. They pointed that this additional force may leads to considerable increase in pile head shear, which results in unsafe design of pile and over-safe design of column and contrary to the general notion of SSI that intuitively assume reduction in shear forces in column and pile owing to the period lengthening of structure and increased damping due to soil media [6,2]. In reality in-situ properties of soil in a distinct geological layer are highly uncertain [16]. Inherent variability of soil may lead

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to uncertainty in the responses of such system which results in change in column and pile shear forces as compared to fixed base response. In order to address the uncertainty in soil properties along with SSI, probabilistic assessment is required in the context of current design paradigm.

Probabilistic assessment of piled raft supported structure incorporating SSI addressing the seismic design implication is rather limited [17]. In some studies, the effect of dynamic soil structure interaction on structural response considering system variability and uncertainty in ground motions were studied for shallow foundation supported structure through comprehensive numerical simulation [18,19]. Tandjiria et al. [20], Pula and Rozanski [21] and Chan and Low [22] outlined probabilistic seismic design of pile with an emphasis on different methods of probabilistic analysis. Further, Pula and Rozanski [21] presented a complete solution to the problem of random lateral bearing capacity of rigid piles embedded into non-stratified homogeneous soil. Haldar and Babu [23] presented the effect of in-situ variability of soil and forces on seismic design of pile considering pseudo-static analysis.

In this study, the effect of inherent variability of soil shear strength and Young's modulus parameters on dynamic response of soil–piled raft–structure system using probabilistic analysis is addressed. Beam on linear Winkler foundation (BWF) model is used to model the soil-piled raft foundation system for the sake of simplicity. Finite element analysis is performed using acceleration time history of seismic loading to obtain the dynamic response of representative soil–piled raft–structure system. Stiffness of soil springs is modeled as random variable. Variability in soil stiffness is defined by a coefficient of variation (COV) with respect to an assumed mean value from literature. The variation of stiffness at any depth is defined by Log Normally distributed function as soil properties resemble non-negative values. Based on the previous studies, it is observed that variability of density of soil does not exceed 10% [24–26], hence it is considered as deterministic parameter. Monte Carlo (MC) simulation technique is adopted for obtaining the probabilistic response of the system. The effect of inherent variability on dynamic characteristics and elastic response of the system is studied for various soil, pile and structural parameters, namely relative stiffness of pile with respect to soil (E_p/E_s), length to diameter ratio of pile (L/d), spacing to diameter ratio of pile (S/d) and different period of superstructure under fixed base case (T_{fixed}). In order to investigate the sole effect of variability of soil properties, the dynamic response of structure is obtained for three different cases, such as (a) fixed base condition, (b) deterministic SSI condition and (c) probabilistic SSI condition. Further, the probability of failure of pile foundation is calculated considering ultimate limit state and displacement criteria in the present study. Finally design implications are also suggested. This study may give a valuable input to modify the conventional seismic design approach for piled raft supported structure.

2. System modeling

The piled-raft supported structure is modeled using finite element approach which is described in the following sections.

2.1. Superstructure modeling

Superstructure is idealized as a lumped mass stick model having single degree of freedom (SDOF). The lumped mass model is used to represent a three dimensional space frame superstructure supported on soil–piled raft foundation. The elastic beam column element is used to represent column of the stick model. Two different periods of superstructure under fixed based condition (T_{fixed}), namely 0.4 s and 2.0 s, representing typical short and long period structure are considered. The periods are determined by adjusting the lumped mass and lateral stiffness of the column. Column stiffness is attributed by assigning appropriate sectional properties.

2.2. Foundation modeling

Foundation primarily consists of two major components, namely raft and pile–soil system which are discussed as follows:

2.2.1. Raft-soil modeling

A 10 m × 10 m raft is modeled as a four noded shell element, each node having six degrees of freedom (3-rotations and 3-translations) and discretized into (40 × 40) small elements based on a convergence study. Total mass of the raft is calculated and assigned as a distributed mass to all nodes. Soil beneath the raft is idealized as equivalent linear springs (Winkler soil spring idealization) connected with each node of raft in all translational degrees of freedom. Dashpots are also attached in parallel with these springs to incorporate the effect of soil damping. Stiffness of distributed lateral springs in two mutually perpendicular horizontal directions (lateral (K_{x1}) and longitudinal (K_{x2})) are assigned following Dutta et al. [27] as presented below,

$$K_{x1} = K_{xG1}/n^2 \tag{1a}$$

$$K_{x2} = K_{xG2}/n^2 \tag{1b}$$

where K_{xG1} and K_{xG2} are the overall lateral stiffness of soil spring [28] attached beneath the raft in lateral and longitudinal directions, respectively and n is number of elements. Vertical stiffness formulation suggested by Gazetas [28] takes care for the coupled lateral-rocking mode of vibration. Hence, vertical spring stiffness (K_y) values are compared with the values provided by Gazetas [28] and are adapted in a distributed form by Dutta et al. [27],

$$K_y = \frac{5.4}{(n^2+2)} \cdot \frac{E_s L_R}{2(1-\nu)(1+\nu)} \tag{2}$$

where E_s is Young's modulus of soil, L_R is the length of raft and ν is the Poisson's ratio of soil. Stiffness of all springs connected at intermediate nodes of the raft assumed to be same. However, at the corner and peripheral nodes, spring stiffness one-fourth or half of the stiffness of the springs at intermediate depending on their influence area. The expressions for K_{xG1} and K_{xG2} are presented in Table 1.

2.2.2. Pile–soil modeling

Pile is modeled using an elastic beam column element having 6 degrees of freedom at each node (3-rotations and 3-translations) which is further discretised into 20 divisions in vertical direction. Beam on Winkler foundation (BWF) modeling approach is used to model the pile-soil interaction due to horizontally applied dynamic loading. Two horizontal springs are attached to each pile in two mutually perpendicular horizontal directions (i.e. lateral

Table 1
Stiffness of equivalent springs along various degree of freedom [28].

Degrees of freedom	Stiffness of equivalent soil spring
Horizontal (K_{xG1}) (lateral direction)	$\frac{E_s l(2+2.54\chi^{0.85})}{(1+\nu)(2-\nu)}$
Horizontal (K_{xG2}) (longitudinal direction)	$\frac{E_s l(0.73+1.54\chi^{0.75})}{(1+\nu)(1-\nu)} - \frac{0.1E_s l[1-(B/l)]}{(0.75-\nu)(1+\nu)}$

where $\chi = A_b/4l^2$, A_b is the area of the foundation considered, B and l are half width and half length of a rectangular foundation, respectively, E_s and ν are Young's modulus and Poisson's ratio of soil respectively.