Coupled behavior of pile foundations in liquefied and non-liquefied soils during earthquakes including case study

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**ABSTRACT**

Design of pile foundations coupled with vertical and lateral loads under earthquake conditions in both liquefied and non-liquefied soils have been addressed in the present study with inclusion of recent advancement in research. Starting with pseudo-static analysis of a pile embedded in non-liquefied and liquefied soil, an analytical procedure based on finite element approach to determine the bending moment and lateral deflection of piles at various depths and normalized moment amplification factor for different $l/d$ ratios have been evaluated. Dynamic analysis of the pile is implemented by using finite difference based FLAC3D program and different ground motions are applied at model base to obtain the complete couple behavior of piles subjected to vertical and lateral loads. Necessary steps for modern design of piles in seismic areas with a case study of pile foundation for oil tanks in Iraq have been presented to highlight the significance of dynamic soil properties, site-specific ground response, liquefaction analysis in addition to behavior of piles as stable foundation system.

**Keywords:** pile, finite element, pseudo-static, dynamic, liquefaction, soil amplification, ground response.

**1 INTRODUCTION**

The choices of a suitable foundation for various structures like high-rise buildings, factories, hospitals are primarily governed by the in-situ subsoil condition and topography existing at the particular site. In the recent past, there has been a substantial growth in infrastructure in urban cities having high population. This has necessitated the construction of several high-rise building and structures and has created a challenging task to civil engineers for their safe and economical design under both static and seismic conditions. Although Indian seismic design code IS 1983: Part 1 (2002) highlights the various criteria that should be considered for seismic design of structures in earthquake prone areas; however the selection and use of seismicity parameters for analysis and design of deep foundation like single pile and pile groups for various structures has not gained considerable attention in the seismic design code [Choudhury et al. (2014)]. Hence a detailed study of the response of underlying soil to seismic ground motions and liquefaction vulnerability at a particular site is required for stable and safe design of deep foundations in seismically active areas.

The behaviour of pile foundations under static lateral and vertical loadings have been studied by Poulos (1971a, b), Randolph and Wroth (1978, 1979), Mylonakis and Gazetas (1998) and bending moment, deflection and settlement were computed. Failure of pile foundation due to earthquake induced lateral spreading in liquefaction prone areas with absence or presence of vertical loading have been studied by various researchers like Ishihara (1997), Tokimatsu et al. (1998), Abdoun et al. (2003), Liyanapathirana and Poulos (2005a), Motamed et al. (2009, 2010), Motamed and Towhata (2009), Dash et al. (2010), Knappett and Madabhushi (2012), Phanikant et al. (2013) among others.

Adequate analysis and design of oil tank foundation storing highly inflammable materials are critical because of their vulnerability to strong seismic motion. The failure of such tank in past earthquakes in Japan, US caused heavy loss of lives and properties forced geotechnical earthquake engineers to incorporate seismic analysis into design.

In the present study, pseudo-static analysis of single pile has been implemented using a coupled analytical approach based on finite element method. It is followed by dynamic analysis by using FLAC3D, wherein different seismic motions having a wide range of ground motion parameters are applied at the base of the soil model and variations in deflection and bending responses are observed. Finally, the case study of seismic design of pile foundation for oil tank at a

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seismically active site in Iraq has been conducted by mentioning the steps and critically of the problem.

2 SEISMIC ANALYSIS OF PILE FOUNDATIONS

The coupled behaviour of pile foundations subjected to vertical and lateral loads in both liquefying and non-liquefying soils subjected to seismic forces is a complex soil-structure interaction phenomenon and can be analyzed by pseudo-static and dynamic approaches. Pseudo-static analysis [Kramer (2005)] is a two stage approach which involves a free field site response analysis for obtaining maximum ground displacement and maximum horizontal acceleration at various depths along the soil deposit in the first step and then a static load analysis is implemented by subjecting the pile to maximum horizontal ground displacement profile, as obtained in step 1 [Liyanapathirana and Poulos (2005b), Chatterjee et al. (2015)]. Chatterjee et al. (2015) implemented pseudo-static analysis of free headed single pile with floating tip boundary condition and embedded in liquefying soil using a finite element approach. A force based procedure was adopted by the authors and a vertical circular friction pile of diameter \(d\), length \(l\) and flexural stiffness \(EI\) subjected to a compressive vertical load having magnitude \(P\) were considered. The governing differential for a vertically and laterally loaded pile, according to Hetenyi (1955) is given as:

\[
EI \frac{d^4 y}{dx^4} + P \frac{d^2 y}{dx^2} + k_h y = 0
\]  

(1)

where, \(k_h = \eta_h \eta \) is the coefficient of horizontal subgrade reaction in kN/m³ and \(y\) being the lateral deflection of the pile at depth \(x\) below ground level [Chatterjee and Choudhury (2015)]. The above equation is solved analytically using finite element approach and non-linear pile-soil interaction analysis is carried out by writing a mathematical code in MATLAB (2012).

Figure 1 shows the variation of normalized moment with normalized depth for a pile having \(l/d\) ratio 40 and 26.7 and embedded in both liquefying and non-liquefying soil and subjected to 1995 Kobe earthquake motion. It is observed that for a pile having \(l/d\) ratio 26.7, the moment generated at the pile top varies from 143kNm to 580kNm under non-liquefied and liquefied soil conditions, respectively showing a normalized moment amplification of 4 while for a \(l/d\) ratio 40, the normalized moment amplification factor increases to 5 [Chatterjee et al. (2015)].

Dynamic analysis is conducted by using finite difference based FLAC3D(2009) by considering a 8m long (\(l\)) and 600mm diameter (\(d\)) free headed single pile embedded in liquefying soil strata underlain by a non-liquefying soil. Soil model (8m x 8m x 15m, (L x B x H)) is subjected to 1989 Loma Gilroy, 1995 Kobe, 2001 Bhuj and 2011 Sikkim earthquake motions at its base. The depth of the liquefying soil layer is also varied to analyze its influence on the bending moment and pile head displacement, as shown in Figure 2.

Fig. 1. Variation of normalized moment with normalized depth for a pile embedded in non-liquefied and liquefied soil and subjected to 1995 Kobe earthquake motion for \(l/d\) ratio 40 and 26.7.

Fig. 2. Variation of (a) bending moment (kNm) and (b) deflection (cm) of pile with depth (m) for different combinations of \(L_{liq}/l\) ratio and subjected to 1995 Kobe earthquake motion.

It is observed from Figure 2 that maximum bending moment of 170kNm and maximum pile head displacement of 47cm occurs when depth of the liquefying soil layer (\(L_{liq}\)) is 5m and \(L_{liq}/l\) ratio is 0.6,
and 1995 Kobe motion is the input ground motion. Figure 3 illustrates the variation of bending moment and deflection along pile depth for different input motions considered in the present study. The maximum deflection of 24cm and bending moment of 138kNm is observed at a depth of 4m for 1995 Kobe motion, while for the others it is comparatively lower.

![Bending Moment and Pile Deflection](image)

3 CASE STUDY ON PILE FOUNDATION FOR OIL TANK

Seismic analysis and design of pile foundation for soft soil strata to support oil tank in Iraq were carried out by Kumar et al. (2015). The oil tank site is located within Arabian tectonic plate having crustal thickness of about 45km in the region [Agard et al. (2011)]. Site investigation revealed 2.5m of medium dense sand layer followed by soft to stiff clay (Plastic limit> 20%) layer up to 24m then dense sand extending to greater depth. An oil tank of height 15m and radius 11.75m is proposed having empty weight is 1400kN. The weight of tank under full operating condition is 62000kN, whereas shear and moment loads induced due to wind are 1600kN and 1200kNm respectively. The M35 concrete was chosen for design of the foundation components.

A finite element based program PLAXIS3D is used to simulate in-situ condition. Mohr-Coulomb model is adopted for modeling zone of soil with 100m length, 100m breadth and 70m deep. Size of the soil model is chosen through iterative procedure with minimal boundary effect. Table 1 provides the details of properties of soil adopted for modeling. End bearing piles and pile cap were modeled as 10 noded tetrahedral pile elements and 6 noded plate elements, respectively.

| Layer No. | Depth (m) | Unit wt. (kN/m³) | Cohesion cₑ (kPa) | Soil friction angle (ϕ) |
|-----------|-----------|------------------|------------------|------------------------|
| 1         | 0-2.5     | 18               | -                | 30                     |
| 2         | 2.5-20    | 7                | 15               | -                      |
| 3         | 20-24     | 9                | 250              | -                      |
| 4         | 24-70     | 9                | -                | 35                     |

The numerical model is first validated with in-situ pile load test. Loading test in PLAXIS3D gave settlement of 16.37mm which is in close agreement with field recorded value of 15.79mm. The obtained result and measured results are comparable and can be considered as good validation of the present model. A total of 89 piles having 400mm radius and 26m length is finalized as shown in Figure 4 considering allowable capacity of single pile as 1300kN for the oil tank foundation for above mentioned loading condition.

![Pile Foundation System](image)

Maximum vertical settlement of 37mm at the center and 34mm at the foundation periphery is observed under static loading condition as illustrated in Figure 5. The axial load carried by pile varies from 510kN to 697kN from center to periphery pile.

Seismic analysis is carried out after the completion of static analysis by applying synthetically generated input motion having PGA of 0.15g at the base of the soil model obtained through Probabilistic Seismic Hazard Analysis (PSHA). Rayleigh damping is chosen as 5%, which is typical value for geologic material.

Maximum vertical settlement of 39mm at the center and 35mm at around the periphery of the pile is obtained after complete dynamic analysis, as shown in Figure 5. The maximum acceleration obtained at the top of pile cap is 0.2g which shows amplification of the
base applied motion. The maximum bending moment at the point of maximum bending moment is 107 kNm at the outer periphery pile and 85 kNm at the central pile. The maximum axial load of 1284 kN is obtained at the outer periphery pile which gradually reduces to 772 kN at central pile showing the safe design of pile.

Fig. 5. Settlement contour (in m) for pile foundation of oil tank as obtained for static case in PLAXIS3D (Kumar et al. 2015).

5 CONCLUSIONS

The major conclusions that can be drawn from the present study are:

• Normalized moment amplification factor increases with an increase in l/d ratio of the pile.
• Maximum bending moment was observed to occur at the interface of the liquefying and non-liquefying soil layer and when $L_{u}\over L_{c}$ ratio is about 0.6.
• Case study of pile foundation design for oil tank shows the importance of dynamic soil properties with ground response and liquefaction studies. The differential settlements found to be within permissible limits of 1/300.

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