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Research Paper

Seismic analysis of laterally loaded pile under influence of vertical loading using finite element method

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ABSTRACT

An efficient analytical approach using the finite element (FE) method, is proposed to calculate the bending moment and deflection response of a single pile under the combined influence of lateral and axial compressive loading during an earthquake, in both saturated and dry homogenous soil, and in a typical layered soil. Applying a pseudo-static method, seismic loads are calculated using the maximum horizontal acceleration (*MHA*) obtained from a seismic ground response analysis and a lateral load coefficient (a) for both liquefying and non-liquefying soils. It is observed that for a pile having l/d ratio 40 and embedded in dry dense sand, the normalized moment and displacement increase when the input motion becomes more severe, as expected. Further increasing of a from 0.1 to 0.3 leads to increase in the normalized moment and displacement from 0.033 to 0.042, and 0.009 to 0.035, respectively. The validity of the proposed FE based solution for estimating seismic response of pile is also assessed through dynamic centrifuge test results.

1. Introduction

The behavior of piles under seismic loading is a complex soil–structure interaction phenomenon that can affect the integrity of pile-supported structures in earthquake-prone areas. Pile foundations may be significantly damaged during and immediately after the occurrence of an earthquake. As earthquake motions propagate through stiffer to softer near-surface soil layers, the motions tend to amplify and transfer, through the piles, to the superstructure. As a result, structural vibrations are set up in the superstructure which in turn impose inertial loadings on the pile cap and the piles. Piles can suffer significant lateral displacement and bending moment if the inertial load is of a large magnitude. Hence appropriate geotechnical and structural design procedures for pile foundations are required in seismically active areas.

During the past years, various boundary element, finite element and finite difference techniques, based on analytical approaches [1–15] and numerical approaches [16–18] have been used to obtain the displacement and bending response of single piles and pile groups in liquefied and non-liquefied soil, subjected to lateral loading, axial loading and dynamic loading or a combination of all. Although one-dimensional Winkler models have been developed for linear analysis [19–21] and non-linear analysis [22–24] of soil–pile interaction in non-liquefying soil, the ability to accurately predict pile behavior is considerably reduced when the soil around the pile starts liquefying.

As a result pseudo-static approaches for seismic analyses of pile foundation have emerged which are relatively simple to implement when compared to more complex dynamic analyses, and hence are preferred by design engineers. Pseudo-static analyses are used for calculating the maximum pile bending moment, shear force and deflection by performing a static load analysis for the pile and involve two main stages [12]:

1. A free field site response analysis is conducted for obtaining the maximum ground displacement and minimum effective vertical stress at various depths of the soil deposit. The maximum ground surface acceleration generated during the earthquake loading is also computed [12].
2. A static load analyses is next implemented for the pile subjected to the maximum computed free field ground displacement profile along the pile and the static loading at the pile head. The inertial loading at the pile head is given by the product of the maximum ground surface acceleration and the cap-mass,

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where, for example, the cap-mass is calculated based on the ultimate load carrying capacity of the piles in sand with a factor of safety of 2.5 [12].

Pseudo-static analyses of pile foundations have been previously implemented by Abghari and Chai [25], Ishihara and Cubrinovski [26], Tabesh and Poulos [27], Liyanapathirana and Poulos [12], Cubrinovski et al. [28], Dash et al. [29] and Elahi et al. [30], amongst others.

In the present study, an efficient pseudo-static analysis, based on the finite element approach, is proposed to compute the bending moment and lateral deflection of a free-headed pile with a floating tip boundary condition, embedded in both dry and saturated homogenous soil, and in a typical layered soil profile. The ultimate capacity of the pile in the various soil profiles is computed as per the Indian design code IS 2911 Part 1: Section 4 [31] and divided by a factor of safety of 2.5 to obtain the allowable load carrying capacity of the pile. Free-field ground response analyses are conducted using the computer program SHAKE2000 [32] and selecting 5 different seismic ground motions, i.e., 1989 Loma Gilroy, 1994 Northridge, 1995 Kobe, 2001 Bhuj and 2011 Sikkim, having a wide variation in bedrock level acceleration, frequency content and duration of shaking, as tabulated in Table 1. The lateral load acting at various depths along the pile is obtained by multiplying the allowable capacity of the pile located in a particular soil by the lateral load coefficient (a), which is defined as the fraction of vertical load assumed to act at different depths along the pile length. In the present study the lateral load coefficient (a) is considered to remain constant along pile depth and parametric variation is done by varying it between 10% and 30% [33–35]. This is further multiplied with the maximum horizontal acceleration obtained at various depths of the soil deposit under the influence of different earthquake motions to obtain the net lateral loading acting at different depths on the pile, which is similar to the approach followed by Liyanapathirana and Poulos [12] and Phanikanth et al. [13]. If P_{all} is the vertical load acting at the pile top and p_1 is the maximum horizontal acceleration (MHA) at the ground surface which is also referred as the peak ground acceleration (PGA), then lateral load acting on the pile at the ground surface (L_1) is given as:

$$L_1 = (a \times P_{all}) \times p_1 \tag{1a}$$

However, with an increase in depth below the ground surface the distribution of vertical load for a fully embedded pile has been taken into consideration according to the relation proposed by Reddy and Valsangkar [36]. At any depth x below the ground surface, the vertical load P is given as:

$$P = P_{all}\left(1 - \psi\frac{x^2}{l^2}\right) \tag{1b}$$

where P_{all} is the vertical load at the pile head, l is the pile length and ψ = parameter ($0 \leqslant \psi \leqslant 1$) and taken here as 1.0. Thus Eq. (1b) modifies to

$$P = P_{all}\left(1 - \frac{x^2}{l^2}\right) \tag{1c}$$

So the lateral load (L_2) acting on the pile at a certain depth x below the ground surface can be approximated conveniently as:

$$L_2 = (a \times P) \times p_2 \tag{1d}$$

where p_2 is the maximum horizontal acceleration, as a proportion of the gravitational acceleration (g), at that particular depth x. In a similar manner, the lateral loads acting at various depths along the pile length is computed for different values of lateral load coefficient (a). Hence, in the present study authors have extended the JRA [33,34] approach to compute the equivalent lateral loads acting at different depths of the pile. This can be considered as a useful contribution of the present study wherein the influence of lateral loads at different depths along the pile length is considered for the pseudo-static analysis using a force-based approach. This issue has not been considered in analytical methodologies presented by previous researchers, where only the effects of lateral load at the ground surface were accounted for in seismic design of piles (using a force-based approach), or a maximum soil displacement profile (displacement-based approach) was applied to the pile using non-linear springs [12]. However, it should be recognized that for a displacement-based analysis in which vertical loads are incorporated, it would be necessary to estimate the vertical ground movements during the earthquake as well as the lateral ground movements. Analysis of vertical pile–soil interaction would then be necessary. It may be noted that for all practical purposes of design, even today, worldwide, a force-based method is in common use because of its simplicity and the fact that it can be adopted in design by using manual calculations while a displacement-based analysis is usually more complicated and needs to be implemented using a rigorous numerical approach e.g., by use of a finite element program. Hence the design charts proposed in the present study simulate the actual field conditions and are therefore more relevant for design of piles in seismically active areas. Moreover the present methodology also takes into effect the influence of non-linearity associated with the presence of vertical loads on the pile top. Non-linear pile–soil interaction analysis is implemented using a code written in the mathematical program MATLAB [37]. The results obtained from the present pseudo-static analyses are compared with the available results in the literature and good agreement is found.

2. Present analytical methodology

A flexible, vertical, circular friction pile of diameter d, length l and flexural stiffness EI embedded in soil medium is subjected to a compressive vertical load of magnitude P applied at the center of the pile section at ground surface, as shown in Fig. 1a. Soil pile interaction is modeled as a beam on non-linear Winkler foundation and the pile is modeled as a beam element. The lateral pressure

Table 1
Strong motion parameters of the various earthquake motions considered in the present study (modified after Phanikanth et al. [13]).

Earthquake strong motion parameters	1989 Loma Gilroy earthquake	1994 Northridge earthquake	1995 Kobe earthquake	2001 Bhuj earthquake	2011 Sikkim earthquake
Date of occurrence	18/10/1989	17/01/1994	17/01/1995	26/01/2001	18/09/2011
Moment magnitude (M_w)	7.0	6.7	6.9	7.7	6.9
Recording station	Gilroy Array Station 1, CA	Castatic Old Ridge Route	KJMA Station	Passport office building, Ahmedabad	Gangtok station
Distance from source (km)	21.8	22.6	0.6	230	68
Epicenter	37.040°N 121.877°W	34.213°N 118.537°W	34.895°N 135.035°E	23.419°N 70.232°E	22.723°N 88.064°E
Bedrock level acceleration (g)	0.372	0.568	0.834	0.106	0.202
Mean period (s)	0.391	0.268	0.641	0.603	0.529
Bracketed duration (s)	16.22	11.54	21.92	69.80	47.65