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Modelling of raked pile foundations in liquefiable ground

Shengzhe Wang [a,1], Rolando P. Orense [b,*]

[a] Beca Consultants, Wellington, New Zealand
[b] Department of Civil and Environmental Engineering, University of Auckland, Auckland, New Zealand

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ABSTRACT

Raked piles are believed to behave better than vertical piles in a laterally flowing liquefied ground. This paper aims at numerically simulating the response of raked pile foundations in liquefying ground through nonlinear finite element analysis. For this purpose, the OpenSees computer package was used. A range of sources have been adopted in the definition of model components whose validity is assessed against case studies presented in literature. Experimental and analytical data confirmed that the backbone force density–displacement (p–y) curve simulating lateral pile response is of acceptable credibility for both vertical and raked piles. A parametric investigation on fixed-head piles subject to lateral spreading concluded that piles exhibiting positive inclination impart lower moment demands at the head while those inclined negatively perform better at liquefaction boundaries (relative to vertical piles). Further studies reveal substantial axial demand imposed upon negatively inclined members due to the transfer of gravity and ground-induced lateral forces axially down the pile. Extra care must be taken in the design of such members in soils susceptible to lateral spreading such that compressive failure (i.e. pile buckling) is avoided.

1. Introduction

In order to increase the seismic resistance of engineering structures, pile foundations are commonly used. Past disastrous earthquakes have shown evidence that structures supported by pile foundations performed well even when the adjacent ground liquefied. On the other hand, a number of pile foundations have been found to be damaged during major earthquakes due to the effects of lateral forces caused by soil movement associated with liquefaction.

Currently, methods to analyse pile foundations in liquefied soils range from simplified methods using an equivalent static approach to the more rigorous time history analysis based on the effective stress principle. The former has been the most common approach, where a relatively simple beam–spring model is used for the soil–pile system to conduct a nonlinear equivalent static analysis. Several researchers have proposed various methods of analysing piles in liquefying soils making used of this pseudostatic approach, also referred to as the *Beam on Winkler Foundation* or *Static Pushover Analysis* (e.g. [24,8,10,11,5,3]). These methods are similar in concept, but differ in the modelling details and analysis procedures. However, in all the works presented to date, all the piles considered were vertical and methods to analyse inclined or raked piles have not been fully presented.

In this paper, a pseudo-static analysis procedure based on a beam on a nonlinear Winkler foundation (BNWF) concept implemented through the open source finite element (FE) analysis package OpenSees (Open System for Earthquake Engineering Simulation) is discussed. OpenSees is operated by the University of California, Berkeley, and developed with sponsorship from the Pacific Earthquake Engineering Research Center. The package, which is a fully nonlinear object orientated computer code [17], has been utilised in the simulation of pile foundations.

The FE model is first validated via case studies present throughout literature to confirm that the definitions are of acceptable reliability for the modelling of vertical and inclined piles. A parametric study then follows in investigating the response of raked piles in liquefiable and laterally spreading soil. A case history involving such members subject to liquefaction is also considered.

The finalised model exhibits the ability to capture a range of ground conditions accounting for soil properties and positioning of the liquefied layer. Subsequently, loading conditions arising from static or inertial pile loads along with ground displacements in the form of lateral spreading can be simulated. Pile properties and boundary conditions can also be easily incorporated.

2. Model definition

The FE model implemented within OpenSees adopts a series of nodes adjoining pile and soil elements to represent pile behaviour.

* Corresponding author. Tel.: +64 9 3737599; fax: +64 9 3737462.
E-mail address: r.orense@auckland.ac.nz (R.P. Orense).
[1] Formerly at: University of Auckland, New Zealand.

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Displacement-based beam elements (DBE) have been adopted for representation of the physical pile while nonlinear horizontal and vertical springs act in the simulation of soil behaviour. Being less computationally intensive, displacement-based beam element was chosen for simplicity over the force-based beam element (FBE). Although the relative accuracy may be slightly reduced when using DBE, increasing the number of elements provides an easy fix.

Zero-length spring components form the basis of p–y, t–z and q–z springs permitting translation of the pile in x and z degrees of freedom. Horizontal responses are governed by p–y springs while t–z springs act in simulating shaft friction controlling vertical loading characteristics. Additionally, responses of the pile tip are represented via the q–z spring. The springs link fixed to slave nodes which are subsequently constrained to pile nodes via equal constraints. The use of constraints was necessary in addressing modelling technicalities arising from differing degrees of freedom (DOF) between pile and soil nodes.

Forces or displacements can be imposed upon either the pile or fixed soil nodes emulating a range of loading scenarios. The response of the pile can therefore be captured via considering the interaction between the springs and pile elements. The model makeup is based on the work by McGann et al. [18] whose various components are outlined in Fig. 1.

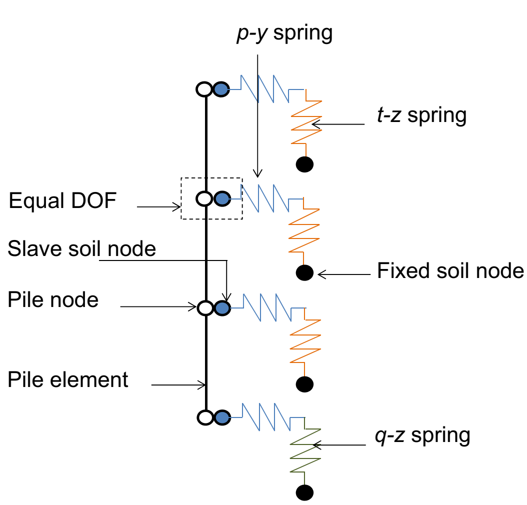

Fig. 1. Definition of FE model implemented within OpenSees.

2.1. Modelling of p–y springs

p–y curves form the basis in simulating the horizontal response of the soil. OpenSees requires definition of both the ultimate lateral resistance (p_u) and the displacement at which 50% of the ultimate lateral resistance is mobilised in monotonic loading (y_{50}) for creation of the p–y relationship. A backbone definition is first established for conditions without liquefaction. This is subsequently modified to account for liquefaction effects.

2.1.1. Definition of backbone resistance curve

The backbone curve for distribution of the ultimate lateral resistance (p_u) as a function of depth is modelled on formulae established by Hansen and Christensen [13]. The resultant pressure (passive minus active pressure) per front area of the pile, e^D, governing the ultimate lateral resistance in terms of depth is generalised as

$$e^D = \overline{q}K_q^D + cK_c^D \tag{1}$$

where $\overline{q}$ is the effective overburden pressure and c the cohesion. K_q^D and K_c^D are parameters relating to pressure at an arbitrary depth governed by pressure at the ground surface and at great depth.

2.1.1.1. Pressure at ground surface. Coefficients relating to the pressure at ground surface (K_q^o and K_c^o) are dependent solely upon the angle of internal friction (ϕ). The K_q^o term is given as the difference between passive and active pressure coefficients:

$$K_q^o = e^{(\frac{1}{2}\pi+\phi)\tan\phi}\cos\phi\tan\left(45^\circ+\frac{1}{2}\phi\right) - e^{-(\frac{1}{2}\pi-\phi)\tan\phi}\cos\phi\tan\left(45^\circ-\frac{1}{2}\phi\right) \tag{2}$$

where ϕ is the angle of internal friction. However, the K_c^o term considers only passive pressure (i.e. discarding the active term) in order to avoid potentially negative pressure values.

$$K_c^o = \cot\phi\left[e^{(\frac{1}{2}\pi+\phi)\tan\phi}\cos\phi\tan\left(45^\circ+\frac{1}{2}\phi\right)-1\right] \tag{3}$$

2.1.1.2. Pressure at great depth. Pressure coefficients at great depth have been computed adopting horizontal plane cases of failure. Evaluation of passive pressure on a deep strip foundation is presented in terms of the friction angle ϕ as

$$d_c^\infty = 1.58+4.09\tan^4\phi \tag{4}$$

Likewise, the bearing capacity factor is given as

$$N_c = \cot\phi\left[e^{\pi\tan\phi}\tan^2\left(45^\circ+\frac{1}{2}\phi\right)-1\right] \tag{5}$$

Pressure constants at great depth are subsequently calculated as follows:

$$K_c^\infty = N_c d_c^\infty \tag{6}$$

$$K_q^\infty = K_c^\infty K_o \tan\phi \tag{7}$$

where K_o is the lateral earth pressure at rest given as

$$K_o = 1-\sin\phi \tag{8}$$

2.1.1.3. Pressure at arbitrary depth. Evaluating the pressure coefficients at an arbitrary depth (K_q^D and K_c^D) required for the computation of ultimate lateral resistance follows empirical formulae dependent upon the angle of internal friction (ϕ), depth to pile diameter ratio (D/B) and pressure coefficients corresponding to the ground surface and at great depth. The series of equations are presented below:

$$a_q = \frac{K_q^o}{K_q^\infty - K_q^o}\frac{K_o\sin\phi}{\sin(45^\circ+1/2\phi)} \tag{9}$$

$$a_c = \frac{K_c^o}{K_c^\infty - K_c^o}\times 2\sin(45^\circ+1/2\phi) \tag{10}$$

$$K_q^D = \frac{K_q^o + K_q^\infty a_q(D/B)}{1+a_q(D/B)} \tag{11}$$

$$K_c^D = \frac{K_c^o + K_c^\infty a_c(D/B)}{1+a_c(D/B)} \tag{12}$$

After substitution into Eq. (1), the pressure per unit length of the pile, p_u, (required by OpenSees as the ultimate capacity of the p–y material) is determined via

$$p_u = Be^D \tag{13}$$