DEM analysis of ultimate lateral resistance to rigid short piles in sand

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ABSTRACT

A DEM numerical model is constructed for analysis of ultimate lateral resistance to piles in sand. The pile was modeled as a rigid body with two kinds of pile movements: rotational and translational movement, simulating free head and fixed head condition, respectively. In the numerical experiments, the lateral resistance, lateral pressure distribution along the pile and the displacement of pile at different depths can be measured and used to construct p-y curve. In addition, the soil-pile interaction can be examined in detail to reveal the extent of influence due to the movement of the pile. In general, the results of the numerical simulation were compared favorably with other semi-empirical solutions.

Keywords: DEM, ultimate lateral resistance, rigid short pile, sand.

1. INTRODUCTION

For a rigid short pile in sand subjected to laterally load, different response will be observed for different boundary conditions of pile as shown in Fig.1. A pile with free head will rotate with respect to a point usually below the ground surface. The other one is a pile restrained by a pile cap from rotation, and a short pile will translate as a rigid body with the pile cap. The p-y method is widely used as a tool for analysis of laterally loaded pile. In the p-y method, the lateral resistance \( p \) is a nonlinear function of the lateral displacement \( y \) of the pile segment. Numerous investigations were perform this subject using continuum approach, such as finite element method. However, complex soil-structure interaction behavior around the pile cannot be modeled easily with continuum approach. In this paper, the DEM is used as an alternative tool to investigate soil-structure interaction problems. The laterally loaded pile will be systematically studied by comparing the conventional p-y curve and other semi-empirical solutions with the DEM analyses.

2. REVIEW OF THE PROPOSED METHODS FOR LATERALLY LOADED PILE

Several methods are available for determining the ultimate lateral resistance to piles in sands (Broms 1964; Reese et al.1974; Fleming et al.1992; Prasad and Chari 1999). Some of them are briefly reviewed in this paper.

Reese et al. (1974) proposed the method with p-y curve, it is based on the Mustang Island tests, Reese et al. (1974) suggested , for near the ground ultimate resistance

\[
P_u = \gamma z \left[ K_o z \tan \phi \sin \beta \cos \alpha \right. \\
- \tan \beta \left( B + z \tan \beta \tan \alpha \right) \\
+ K_o z \tan \beta (\tan \phi \sin \beta + \tan \alpha) K_o B \right]
\]

where \( \gamma = \) effective unit weight of soil; \( z = \) depth from the ground surface; and \( B = \) diameter or width of the pile; \( \phi = \) friction angle of sand; \( K_o = \) coefficient of earth pressure at rest; \( K_o = \) minimum coefficient of active earth pressure; \( \alpha = \phi / 3 - \phi / 2 \) for loose sands, and up to \( \phi \) for dense sand, \( \beta = 45 + \phi / 2 \).

Fleming et al. (1992) assumed \( \rho \) proportional to the square of the passive earth pressure coefficient.
\[ p_u = K_p g_z B \]  \hspace{1cm} (2)

where \( K_p = \tan^2(45 + \phi/2) \) = passive earth pressure

Prasad and Chari (1999) proposed the ultimate soil resistance and provided a semi-empirical to determine the rotation center of pile, \( x \), as follows.

\[ p_u = s f(\phi) g_z \]  \hspace{1cm} (3)

\[ x = \frac{-(0.567L + 2.7e)}{(5.307L^2 + 7.29e^2 + 10.541L e L^{0.5})^{0.5}} / 2.1996 \]  \hspace{1cm} (4)

where coefficient \( s \) = shape factor, and \( s \) is a function of \( \phi \) and embedment ratio (embedded length/diameter). \( L \) = embedded length of pile; \( e \) = eccentricity of loading; \( x \) = point of rotation.

3 MODEL CONFIGURATION

In this study, the particles are modeled as uniform spheres with diameter of 2.0mm, which was chosen based on an estimate of the reasonable number of particles for the DEM models to be analyzed. Only mono-size particles were used to facilitate the analysis although more realistic particle shapes and size distributions were used in other simulations which will not be discussed here. The other physical parameters are shown in Table 1.

Table 1. Physical parameters in DEM model

| Particle | Wall |
|----------|------|
| Friction coefficient | 0.5  | Friction coefficient | 0 (smooth) |
| Normal stiffness | 1x10^4 kN/m | Normal stiffness | 1x10^4 kN/m |
| Normal stiffness | 1x10^4 kN/m | Normal stiffness | 1x10^4 kN/m |
| Density | 2.65 Mg/m^3 |

The assembly of the particles has an initial void ratio of 0.68, the peak friction angle of the granular assemblies is 24.39°. The basic dimension and geometry of pile and container size were designed based on the pot test performed by Matlock (1962) and is shown in Figure 2. The DEM model was subjected to 100 times gravity to simulate a prototype test. As shown later, the DEM results are reasonable compare with the p-y curves method which is based on field-scale load tests.

4 TEST RESULT AND DISCUSSION

The DEM results will be converted into prototype test results according to the scale factors which are proposed by David wood (2004), so the 0.01m depth in DEM model will be converted to 1m of prototype test and the unit of force, force/unit length should be converted by the scale factors accordingly

4.1 Result of translational movement

After the soil sample had been placed into the container, the pile slowly moves in translation in quasi-static manner. The displacement and force are recorded during the process of movement. The p-y curves of different depths are plotted in Figure 3-4. As the pile started to move against the soil mass, the lateral resistance increased, and eventually ultimate state was reached. The ultimate state was reached at different depths nearly simultaneously except at 2m depth, which seems to have higher capacity at larger movement. The initial stiffness of p-y curves of DEM is a little bit smaller than the results of Reese et al. (1974). DEM results are apparently smaller than the results of Reese et al. (1974) at 1-2m depth, but the gap between DEM result and Reese et al. (1974) result at 3-5depth is closing and the range of difference is 8% - 22%. The distribution of lateral pressure is shown in Figure 5, the distribution of lateral resistance is linear increasing with depth in the results of Fleming et al. (1992). There are two different parts of linear increasing lines from result of Reese and DEM, the slope for 3-5m depth is smaller than that of 0-2m. From the results of translational movement, it can be observed that the ultimate lateral resistance from DEM is in good agreement at 3-5m depth compared with the result of Reese et al. (1974)

![Fig. 2. Schematic diagram of numerical model](image)

![Fig. 3. P-y curves of DEM and Reese (1974) at 1-2m depth.](image)
4.2 Results of Rotational Movement

The simulation of pile with rotational movement in DEM is based on the lab test of Prasad and Chari (1999). The position of center of rotation is 3.8m when the lateral load was applied at an eccentricity of 1m above the ground surface. The displacements of pile at different depth are different under the rotational movement of pile and their relations are shown in Fig.6.

The basic condition of the soil resistance to the pile during the pile rotation is shown in Fig.7-10. As the pile started to rotate in the soil mass, the lateral resistance increased, but not all depths of soil reached ultimate state. According to the analysis by Zhang (2009), the soil reaction in a laterally loaded rigid pile can be divided into two processes, the first process is only soil in a region above the rotation point reaches ultimate state, and then the second process is that all of soil reaches ultimate state in the failure state. It is believed that the lateral resistance for the soil above rotation reached ultimate state and the soil below has not reached ultimate state based for the results of DEM. At the depth of 1-3m, the p-y curves of DEM indicated that the soil has reached ultimate state and the result compared with Reese (1974) is almost the same as the translational movement. As shown in Figure 9-10, the p-y curves of DEM at 4m indicated that the soil has not reached ultimate state, and the soil at 5m is close to the ultimate state. It can be observed that the lateral resistance of rotational movement is a little smaller than the case of translational movement at 3-5m depth. The comparison of lateral pressure distribution is shown in Fig.11, the lateral resistance at 3-5m depth is a little bit smaller than results of Reese et al. (1974) and Fleming et al. (1974) due to the ultimate state not fully activated.
5 CONCLUSIONS

In this study, a DEM model was constructed to simulate responses for different boundary conditions of pile with translational and rotational movements. The lateral resistance of pile is affected by the different movements of pile with translational and rotational movements. Comparisons of the p-y curves of DEM with conventional p-y curve of Reese et al. (1974) show that the initial stiffness and of p-y curves of DEM is a little bit smaller than the results of Reese et al. (1974), and the lateral pressure at different depths are smaller than the result of Reese et al. (1974) and Fleming et al. (1992).

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