Theoretical study on the load carrying capacity of concrete drilled and expanded piles with different stiffness under horizontal load

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Abstract. Concrete drilling and expanding pile is a new type of pile in the field of foundation engineering, which has been improved compared with the traditional straight-hole pile. The expansion technology improves the bearing capacity of the pile and it has great prospect for development as it changes the overall bearing capacity of the pile. Although the performance of expanded piles under vertical loads has been studied, the performance of expanded piles when subjected to horizontal loads is not fully understood. In order to study the performance of concrete expansion piles against horizontal loads, especially the overturning resistance of the overturned piles and bent piles, a numerical simulation study is conducted in this paper.

1. Introduction

Variable section piles first appeared in the 1950s when the UK, as well as India and the USSR, began exploring multi-section expansion piles to carry loads in soft soil formations[1]. In China the developed of variable section piles was initiated in the late 1970's. Although variable section piles are used worldwide, their use of technology is fairly new and there has been little research in this area[2]. A catalytic development of variable-section piles in China occurred when the Beijing Institute of Construction Mechanization first developed a reaming machine with three distinct functions: squeezing and expanding, drilling and expanding, and soil clearing[3]. In 1998, DX concluded its experience in the development of pile foundations at home and overseas and patented the squeezing and expanding supported cast-in-place pile, referred to as "DX pile"[4]. As a direct extension of this technology, Baocheng of Beijing Rongchuang Geotechnical Engineering Co., Ltd. is the inventor of drilling and expanding machinery and tools such as "Drilling and Expanding Integrated Machine", as shown in Figure 1, and it significantly facilitates the construction of variable section piles.
Concrete drilled and expanded pile (as shown in Figure 2) has a high bearing capacity and overturning resistance, as well as excellent anti-settlement properties, and has a vast application prospect[5]. Scholars have investigated the influence of various parameters of load-bearing expansion plates by conducting preliminary theoretical and laboratory investigations on concrete expansion piles under horizontal loading, basically[6]. In an effort to improve the analysis of the damage state of the soil around the pile, this paper concentrated on model piles with both overturned and bent properties, and demonstrated the stability of the reliability of the pile-soil failure mechanism through the finite element numerical simulation of ANSYS.

2. Finite element simulation analysis of overturned concrete drilled and expanded piles and bent concrete drilled and expanded piles.
Effects of horizontal bearing capacity of different types of concrete expansion piles were simulated using the finite element software ANSYS. An important factor affecting the interaction between piles and soil is the overturned and bent of the expansion piles and the location of the bearing plate, and the state of pile interaction and its subsequent failure are associated with the bearing capacity of each individual pile directly[7].

2.1 Finite element analysis model
In order to avoid the influence of boundary constraints on the soil as far as possible, the extent of the installed perimeter soil cannot be too small[8], and a half cylinder with a diameter of 12 m and a height of 10.8 m was taken as the simulation model test soil[9]. The design compares three sets of bearing plates for overturned and bent piles at the same location. Three typical locations from the bearing plate to the top of the pile were selected for the study, with the spacing between the bearing plate and the top of the pile being 1200 mm, 2400 mm and 4800 mm respectively[10]. The overturned concrete bored expansion piles were named GM1, GM2 and GM3 and the bent concrete bored expansion piles were named RM1, RM2 and RM3. The detailed model parameters of the piles were: concrete bored expansion pile length L = 6800 (mm), slab diameter D = 1500 (mm), slab height H = 800 (mm) concrete bored expansion pile diameter d = 500 (mm), borehole expansion angle α =39°, overhang length R=500( mm), distance between slab and pile top L1=1200(mm). As shown in Table 1, concrete G was taken as the design parameter for overturned concrete expansion piles, concrete R was taken as the design parameter for bent concrete expansion piles and silty clay was chosen for the soil[11]. Accordingly, the specific parameters of the materials were derived.
With the soil as an ideal elastomer and the pile body made of linear elastomeric material\cite{12,13}, horizontal and vertical loads were being simultaneously imposed, and a separation of 1 mm between the bearing plate and the surrounding soil was designed to ensure the interplay effect in order to make the failure mode similar to that of the actual site. Horizontal and vertical loads were applied simultaneously, and a 1 mm spacing between the bearing plate and the surrounding soil was designed to ensure the interaction effect in order to make the failure mode similar to that of the actual site. SOLID65 solid element was applied to the concrete expansion pile and SOLID45 solid element was applied to the soil. The surface-surface contact pairs in the model were initiated when the pile surface was in contact with the soil interface\cite{1,14}.

2.2 Displacement-load curves of the models
The displacement and load data of three sets of expanded piles in the x-direction were assembled, and the displacement-load curves of the pile tops of the three models were plotted, as shown in Figure 3.

![Figure 3. Displacement load curves simulated for concrete drilled and expanded bent piles and concrete drilled and expanded overturned piles.](image)

On the basis of the curve trends in Figure 3 and the analytical pile top displacement-load curves of both the overturned concrete drilled and expanded bent piles and concrete drilled and expanded overturned piles models, we have concluded the following results:

(1) Comparison of the load-displacement curves of the three groups of piles, GM1 and RM1, GM2 and RM2, and GM3 and RM3, reveals that the displacements produced from the overturned and bent concrete expansion piles are significantly different even if the load-bearing plate positions are the same. The more rigid the concrete expansion pile is, the less displacement it produces and the greater the overturning resistance is. This means that the stiffness of concrete expansion pile is an influential figure in the horizontal bearing strength.

(2) Through an elaborate analysis of the load-displacement curve, it is found that when the load is bigger than 30KN, an obvious difference appears in the displacement of the pile top corresponding to various plate positions. This demonstrates that the load bearing plate rotates only when the displacement at the top of the pile reaches a certain value and the advantages of the expanded pile can be given full play. For a defined charge, as the distance between the bearing plate position and the pile
top is shorter, the displacement of the pile top is smaller.

(3) By comparing the displacement-load curves of different expansion plate pile types, it can be observed that the changing trend of displacement-load curves of each type of pile top is almost the same, i.e., with the increase of horizontal load, the gradual growth of horizontal displacement of pile top of concrete expansion pile.

2.3 Shear stress analysis of overturned and bent piles

The shear stress values of the selected nodes in the XY plane are calculated by selecting uniform points on the contact surface between the overall pile and the soil in the three sets of piles, under a specified horizontal load, and summarizing them.

![Figure 4. Diagram of shear stress curve of pile body](image)

From the analysis in Figure 4, the following conclusions can be drawn:

(1) There are significant differences in the XY plane as the maximum shear stress value of GM1 pile is 2.88 MPa and the max shear stress value of GM3 pile is 0.59 MPa, and hence shows significant differences. The position of the bearing expanded plate influences to a large extent the variation of the shear stress values in the bearing plate. Under the condition of a given stiffness, the less distance between the position of the expanded plate and the tip of the concrete drilled and expanded pile, the higher the shear stress in the pile. By this it means that as the distance between the bearing plate and the top of the pile is shorter, the better the pile resists the horizontally imposed load.

(2) A comparison of the shear stress curves of GM1 with RM1, GM2 with RM2 and GM3 with RM3 for the model piles shows that the maximum shear stress values for overturned piles are significantly larger than those for bent model piles when the support plates are placed in certain positions. Therefore, the resistance to horizontal loads is the enhanced when the stiffness of the concrete expansion pile is relatively large.

3. Conclusions

The conclusion on the failure mode and bearing mechanism of the soil around the overturned and bent expanded concrete piles under horizontal loading is as follows.

(1) The displacements of overturned and bent piles at the pile tip differ greatly for a given bearing plate position. The more rigidity, the lower the displacement of the tip of the pile and the greater the resistance to overturning. Regardless of whether the pile is overturned or bent, as the pile tip is closer to the supporting extension plate (1200mm or 2400mm), the load of the soil around the plate end is well transferred, enabling the pile to withstand a relatively large horizontal load.

(2) By analysing the displacement, stress and strain results, it can be concluded that it is possible for the stiffness of the pile to affect the horizontal load carrying capacity of the lengthened pile. On the same position, it is clear that the more the stiffness of the pile frame and the supporting plate is, the stronger and more advantageous the horizontal anti-rotation load carrying capacity of the plate lengthened pile will be.

This paper proposes a finite element analysis model to investigate the effect of horizontal forces on the damage behaviour of overturned and bent concrete pile soils. During the study, it was found that the load carrying capacity of the extension pile was increased by the horizontal loading of the extension plate. An analysis of overturned and bent piles was carried out in detail. Further studies are
planned to investigate the influences of various parameters of bent precast concrete piles, such as the geometry and location of the bearing platform and the number of bearing plates, on the load carrying capacity of the piles.

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References
[1] F.M. Abdrabbo, A.Z. El Wakil. Laterally loaded helical piles in sand[J]. Alexandria Engineering Journal, 2016,(55):3239-3245.
[2] Wei Tian, Yongmei Qian, Ruozhu Wang. A Comparative Study of Concrete Expanded Plates Pile and Common Pile Uplift Bearing Capacity, International Journal of Simulation System, Science & Technology, Vol.17(44), pp26.1-26.5
[3] Qimin Li, Manchu He, Yueqing Tan, Experimental study on Extruded Branch Plate supporting pile [J]. Geotechnical mechanics, 2005, (10): 146 - 149.
[4] G. Xiaoyuan, W. Jinchang, Z. Xiong, Static load test and load transfer mechanism Study of squeezed branch and plate pile in collapsible loess foundation[J]. Journal of Zhejiang University SCIENCEA.2007,8(7):1110-1117
[5] Liping Zhao, Li Xiang, Chen Lu, Shilin Han, analysis of stress characteristics of squeezed branch pile group under horizontal load [J]. Industrial Building, 2009, 39 (10): 52-56.
[6] S. Kumar, S. Prakash. Estimation of Fundamental Period for Structures Supported on Pile Foundations[J]. Geo technical and Geological Engineering, 2004, 22: 375-389
[7] Yongmei Qian, Jie Wang, Ruozhu Wang, Jian Zhai. Research status and working mechanism of concrete expanded pile under horizontal load [J]. Shanxi Architecture, 2016, 42 (13): 62-63
[8] ZhiXian Zhao, Finite element analysis of extruded branch and disk pile under horizontal load [D]. Taiyuan: master thesis, Taiyuan University of Technology, 2007-5.
[9] JingZhong Xing, Jun Li, The modeling method and the mesh division of the ANSYS[J]. China Water Transport (Academic), 2006, (9):116-118
[10] Wei Tian, Xuedong Guo, Yongmei Qian. “Analysis of computing theory on the uplift bearing capacity of the concrete pile with expand-reamed disc”, Energy Education Science and Technology (EESTA) PartA, Volume (Issue) 32 (4) 2493-2498, July 2014.
[11] Q. Yongmei, Z. Rongzheng, W. Ruozhu, Research on the Calculating Mode of the Uplift Bearing Capacity of the Concrete Expanded-Plates Pile, Architectural Engineering and New Materials, 2015.2, pp240-247.
[12] Yongmei Qian, Dehao Ren, Ruozhu Wang. Analysis of Soil Characteristics Affecting Failure Behavior and Bearing Capacity of the Concrete Expanded-Plates Pile, The Open Construction and Building Technology Journal, Vols.9, 2015.9, pp188-191
[13] Yongmei Qian, Jie Wang, Ruozhu Wang. The Analysis of the Vertical uplift bearing capacity of Single the CEP Pile, The Open Civil Engineering Journal, Vols.9, 2015.9, pp598-601
[14] D. Jihui, C. Yanliang, W. Weiyu, Z. Tuo. Experimental Study of Dynamic Characteristics on Composite Foundation with CFG Long Pile and Rammed Cement-Soil Short Pile[J]. Open Journal of Civil Engineering, 2014, 4: 1-12