

Case analysis of piled raft socketed in weak rock

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Abstract: Piles socketed in soft rock were traditionally regarded as end-bearing piles, and the loads transferred from superstructure were assumed in design to be shouldered totally by the piles. This paper was designated to deal with the interaction between the piles socketed in weak rock and surrounding soil through field measurement. The pile head reaction and ground pressure under piled-raft foundation were monitored, respectively. The analysis of the data measured in-situ shows the characteristics of the pile embedded in weak rock are similar to that of friction pile to some extent. The rock-socketed pile, together with the surrounding soil, shoulders the weight of the superstructure. It is suggested that soil bearing should be considered in designing the soft rock-socketed piles, which can make the design more economical.

Key words: piled raft; weak rock; rock-socketed pile

Until relatively recently, the attention from foundation experts has been concentrated on the methods of calculating or analyzing the settlement and the interaction of floating piles or pile groups. At the very beginning, based on the arbitrary assumption of the stress distribution along the pile and on the field pile loading tests, approximate methods of calculating the settlement of piles were presented by Meyerhof^[1]. Utilizing the curve of pile top deformation versus shear stress, which was first developed by Seed and Reese, Coyle and Reese proposed the load transfer method. Then the approximate closed form solution of load transfer method was presented by Randolph and Wroth^[2], and the results were extended directly to study the settlement of pile groups^[3,4]. Meanwhile, relying on the elastic theory and Mindlin solution, the elastic-based approaches were employed by several experts^[5-8]. Coupled with the commonplace availability of powerful computers, the numerical methods, such as finite element method and boundary element method, were developed rapidly^[7-9]. To simplify the calculation, based on the theory above, the hybrid approach was presented and developed^[4,10-13].

All the literature mentioned above mainly deals with the behavior of friction pile or pile groups. Little attention has been drawn to the behavior of piles embedded in weak rock. In design, the loads

transferred from the superstructure are assumed to be shouldered totally by the pile, which is a conservative assumption. For its large capacity and small pile head settlement, socketed piles are widely used in China and other countries. This paper, based on the data collected from field monitoring, discusses the interaction between the soil and the piles socketed in weak rocks.

1 Monitoring of a Case

The piled raft foundation has been used under a tall building, with 28-storey superstructure and 2-storey basement, constructed on the mucky soil zone in Nanjing, China. The excavation of the basement is 11.02 m in depth. The bored cast-in-situ piles, approximately 40 m in length and 0.8 m in dia., with a 3.0 m pile spacing, penetrate through soil strata and embed into the middle weathered bedrock. The socket depth is about $2d$ of the pile. The design load of the pile is 4.5 MN. The soil properties are shown in Tab.1.

To monitor and analyze the interaction behavior between piles and surrounding soil, 26 concrete strain transducers and 37 earth pressure cells are installed on the top of piles and in the soil beneath the raft, respectively, just before the cast of the raft. The distribution of the cells can be seen from Fig.1. The monitor work began in Jan. 2002, and ended in Dec. 2002. And the data was measured throughout the construction period.

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Tab.1 The physical and mechanical properties of the different subsoil strata

Soil name	Thickness/m	w/%	$\gamma/(\text{kN} \cdot \text{m}^{-3})$	e	c/kPa	$\varphi/(^{\circ})$	a_{1-2}/MPa^{-1}	f_k/kPa	q_{sk}/kPa	f_{rk}/kPa
Backfill	0.4 – 1.9	28	18.0	0.78	10	20	0.23			
Pond soil	2.1		16.0		5	5		50	10	
Clay	0.4 – 0.9	31	19.4	0.80	31	12	0.41	160	70	
Clayey silt	1.4 – 2.8	32	19.4	0.88	10	27	0.25	110	40	
Mucky silty soil	9.0 – 13.6	38	18.3	1.06	14	18	0.57	85	20	
Silty clay	3.8 – 10.6	25	20.1	0.70	33	17	0.26	170	60	
Clayey silt	5.9 – 11.0	26	19.8	0.73	18	24	0.27	150	50	
Intense-weathered rock								600	110	
Mid-weathered rock								4 500	500	9 000

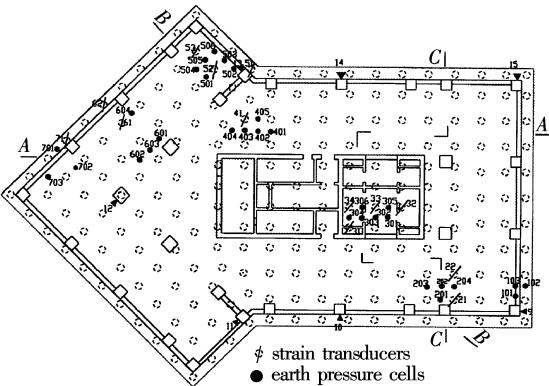


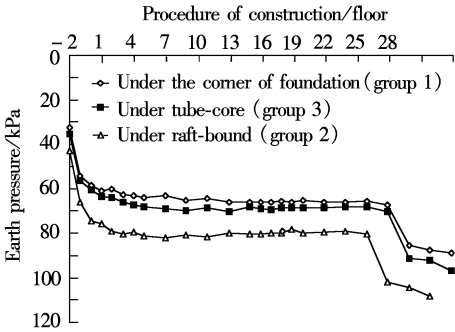
Fig.1 Distribution of the measurement point

2 Analysis of the Results

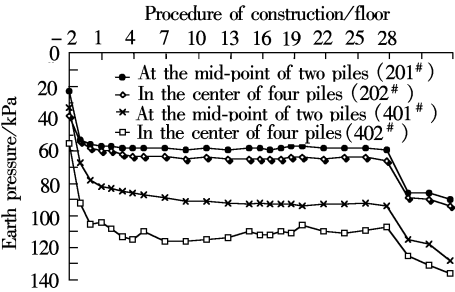
2.1 Ground reaction

The soil reaction increases with the construction of the superstructure. Fig.2 (a) shows the change curve of ground reaction, under different positions of foundation, versus the construction of the superstructure. The measured mean force under the raft bound is larger than in any other places. The soil force difference between the bound part and the tube-core part of the raft ranges from 10 to 15 kPa. Another attractive phenomenon is that the ground reaction under the corner of the raft (cell group 7) is the smallest and increases slowly. Even when the frame structure is completed, the mean ground reaction in the corner is less than 45 kPa. But under the raft brim, the force is as large as 85 kPa. It may result from the relative uplift of the raft corner.

On the other hand, at the beginning of the construction, the soil reaction increases quickly, when the subsoil is at the resilience and recompression state after excavation. While the tower is constructed to the 5th floor, the weight of the structure is approximately equal to the excavated soil, and the soil beneath the



(a)



(b)

Fig.2 Change curves of earth pressure with the procedure of construction

raft is under the action of additional loads. So the measured soil force remains stable or fluctuates until the completion of the frame structure. It is stated in the following section that the piles mainly shoulder the added weight of the superstructure. However, two months after the completion, the mean soil force increases approximately 20 kPa. Then the collected data shows the ground reaction remains stable again.

Earth pressure cell 402 and 202 were installed in the center of four piles, while cell 401 and 201 were mounted in the mid-point of two piles. The data of the four cells represent the discipline mentioned above. At the same time, from Fig.2(b), it can be concluded that the soil reaction in the center of 4 piles is larger than that in the mid-point of 2 piles. It also represents that within the pile group, the surrounding soil force

increases with the increase of the distance from the pile. So the existence of pile influences the deformation of the raft foundation greatly.

The distribution of soil force under piled raft, like hyperboloid, is shown in Fig.3. Compared with the pure raft, the distribution of ground reaction is much more even^[14].

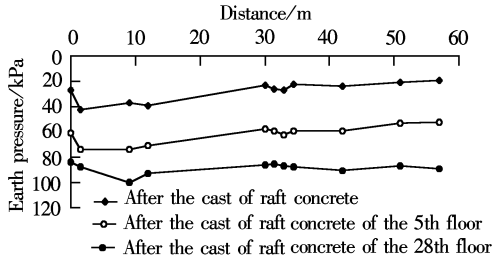


Fig.3 The distribution of earth pressure at A-A section

2.2 Pile head reaction

At the initial stage of the basement construction, shown by the data collected in the field test, the pile head is tensile. After the first floor is cast, the pile head becomes compressed gradually. It may be because of the resilience of the subsoil caused by excavation, which leads to the uplift of the raft, subsequently resulting in the tension on the pile top.

Fig.4 represents the changes of pile top force under different positions of the raft, bound, inside and tube-core, respectively, with the construction of the superstructure. It can be seen from the figures that, firstly, the pile head force of core piles increases fastest, then comes the inside pile, and the bound pile is the slowest. However, after the 9th floor structure is completed, the force increasing speed on the bound piles is the greatest, and that on the core piles is the smallest. The reason for this phenomenon is that at first the loads transferred from the superstructure are centered on the tube-core. But, when the 9-storey structure is built, the frame structure is rigid enough to redistribute the loads. The result of the influence of the overall rigidity is that the bound piles shoulder much greater loads than others. The ratio of the pile head reaction under different parts, $P_{\text{bound pile}} : P_{\text{inside pile}} : P_{\text{core pile}}$, is 1.9 : 1.24 : 1.0.

It should be noted that, two months after the completion of the structure, the pile top force decreases by 50 to 420 kN, while the surrounding soil reaction increases 20 kPa, that is to say, the loads shouldered by piles are transferred partially to the ground. But the following test data shows pile head force increases obviously, even surpassing the former value.

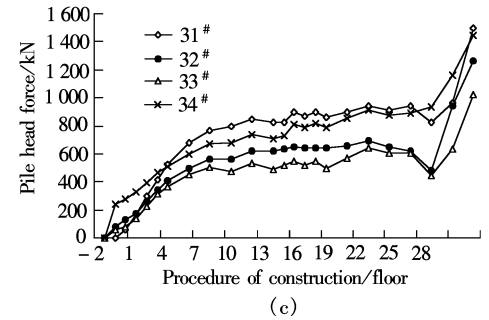
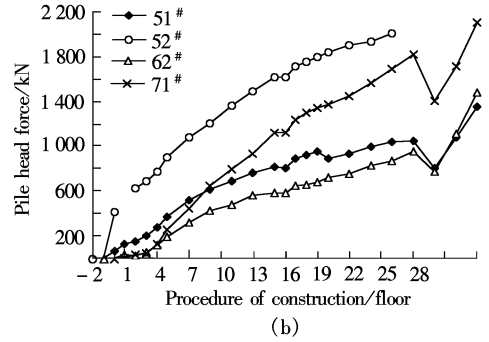
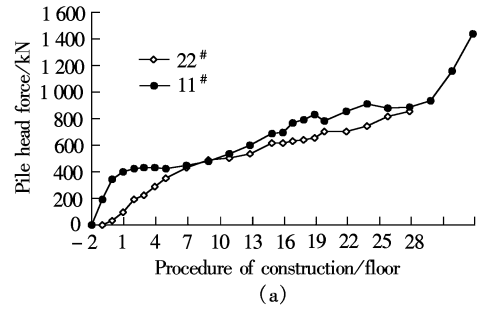


Fig.4 Pile head force change with the procedure of construction. (a) Inside piles; (b) Bound piles; (c) Under tube-core

2.3 The proportion of the loads shared by piles and raft (or soil)

The proportion of the loads shared by piles and raft (or soil) is a complex research subject, which is affected by different factors, such as the properties of soil, pile spacing, pile length, the construction technique of piles, as well as the rigidity of the foundation. According to the subsoil reaction, pile head force measured in field and the calculated superstructure loads, this problem is analyzed in the following section.

In Fig.5, the loads and the percentage of loads shared by raft (soil) are plotted against the procedure of the construction. It can be seen from the figures that, in the initial stage of construction, the loads are mainly shared by the raft. For example, when the first floor of substructure is completed, the percentage of the loads shared by raft is as high as 89%. However, along with the construction of the superstructure, the

ground reaction remains stable, and the load percentage shared by the soil decreases. On the other hand, the pile head force is gradually enhanced. This phenomenon can be explained by the load transferred from the raft to the piles due to the increased overall rigidity of the structure. And finally, a large proportion of the loads is shared by the piles. At the time of the completion of the frame structure, the percentage of the load shared by the soil remains about 15% to 25% .

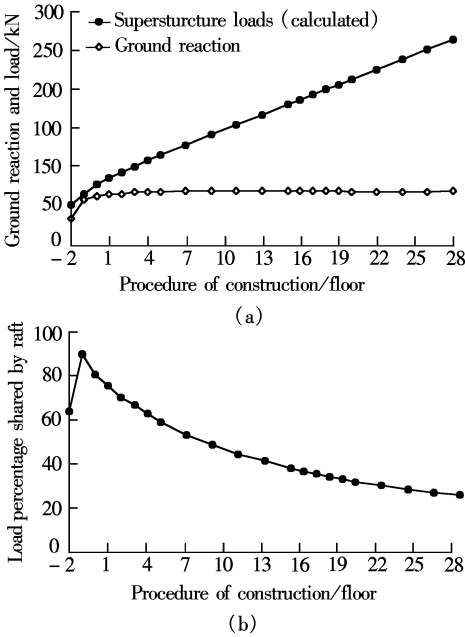


Fig.5 Load percentages shared by the raft change with the procedure of construction. (a) Ground reaction and building loads change with the procedure of construction; (b) Load percentages shared by the raft change with the procedure of construction

Fig.6 represents the change curves of the ground reaction and pile head force under the tube-core and raft bound, respectively. At first, the former is much larger than the latter, which also shows that the raft bears the burden of the main magnitude of loads firstly. Then the pile head force enhances step by step, while the ground reaction remains relatively stable.

3 Conclusion

Through the analysis of the ground reaction, pile head force and the different percentages of loads shared by piles and soil, it can be concluded that the behavior of piles socketed in weak rock is similar to that of friction piles. The existence of interaction between piles and surrounding soil should be considered in the design of piled foundations, which can make the design more economical. The measured data show that 15% to 25% of superstructure loads is shouldered by the

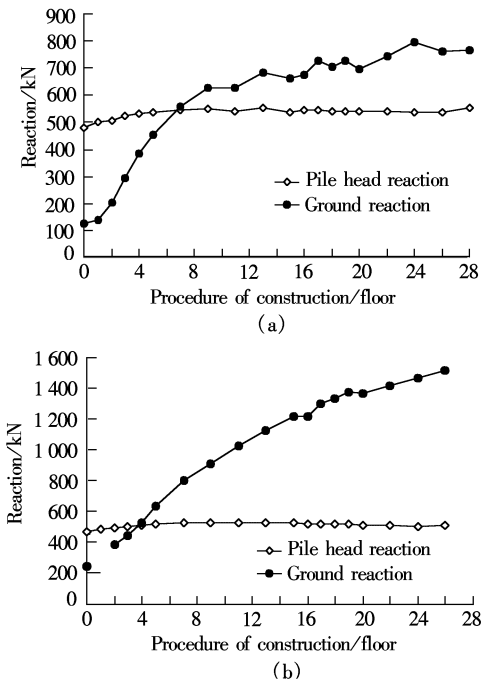


Fig.6 Change curves of pile head and ground reaction. (a) Under tube-core; (b) Under raft bound

subsoil, which should be employed to optimize the piled foundation design method.

The results also demonstrate that at the initial stage of the construction, the loads are mainly shouldered by the raft. With the development of the overall rigidity of the building, more and more loads transfer from the raft to the piles, and at last, about 3/4 of the loads are shouldered by the socketed piles.

The partial deformation of the raft is related to the distribution of the ground reaction. The existence of pile can change the rigidity of raft, leading to the influence of the deflection of the raft. The farther from the pile, the larger the deformation of raft that develops, and the larger the ground reaction that exists. Therefore, it is suggested, if the pile spacing is large (such as $5d$ or $6d$), the ratio of the reinforcement bar in the raft should be adjusted; this aspect requires further study.

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软岩地基上桩筏基础实测分析

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摘 要 软岩地基上的嵌岩桩基础一般都认为是端承桩,设计时假定上部结构荷载全部由桩来承受,而不考虑桩间土的承载力.本文主要根据现场实测的软岩地基上的嵌岩桩桩顶反力和筏底地基土反力数据,分析研究嵌岩桩与筏板及地基土之间的相互影响.结果表明,软岩地基上的嵌岩桩具有摩擦桩的特性,桩间土分担一部分的上部结构荷重,因此,建议软岩地区的嵌岩桩,在设计时也应该考虑桩间土的承载力,从而使设计更经济合理.

关键词 桩筏基础; 软岩地基; 嵌岩桩

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