

Title: **Analysis of Pile Foundations and Load Tests**

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Subjects: Building Case Study
Geotechnic/Foundation

Publication Date: 2014

Original Publication: Suzhou Zhongnan Center: In Detail

Paper Type:

1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

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Analysis of Pile Foundations and Load Tests

桩型选择与试桩设计

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This chapter describes the pile design and the static loading tests of the megatall Suzhou Zhongnan Center tower and its deep basement. Large-diameter and super-long bored piles were adopted to support the main tower. Full-scale loading tests of four piles embedded in two different bearing strata were carried out. For the two piles embedded in the 13-2 fine sand layer, the pile toe depth is 110 meters from grade level, and the maximum test load is 40,000 kN. For the other two piles embedded in 13-1 silty sand layer, the pile toe depth is 95 meters. Punching failures were observed after the test loads reached 26,000 kN and 32,000 kN, respectively. Tension piles were used to resist the buoyancy at the podium basement space area. The tension capacity was enhanced by post-shaft grouting. Testing results show that the ultimate tension capacities of three test piles with shaft grouting are 6,600 kN, 7,800 kN and 9,000 kN respectively. The design, construction and loading of test piles provided technical support information and guided the pile foundation design of this project.

主塔楼自重荷载大且风和地震荷载工况复杂，纯地下室区抗浮突出，桩基的设计和施工难度大。结合本工程土层性状及近年来桩基技术发展，对苏州中南中心大厦桩型选择进行了分析，主塔楼承压桩采用了大直径超长灌注桩，试桩桩径为1100mm，开展了两种持力层的对比试验共4组，其中A型试桩2组，以13-2粉细砂层为持力层，桩端埋深约110m；B型试桩2组，以13-1粉砂夹粉质粘土为持力层，桩端埋深约为95m。试桩采用桩端与桩侧联合后注浆工艺，桩身混凝土强度达到C55。试验结果表明，A型桩在最大加载值40000kN作用下并未桩顶沉降并未出现陡降破坏，而B型桩分别在27000kN和32000kN后出现明显的陡降破坏。纯地下室区域采用了桩侧后注浆抗拔桩，试桩桩径为800mm，有效桩长约35m，采用3道桩侧后注浆工艺，共进行3组载荷试验，其极限承载力分别为6600kN、7800kN、9000kN。为工程桩的设计和施工提供了指南，为类似超高层建筑桩基选型提供了有益参考。

Introduction

Suzhou Zhongnan Center has a 5-level basement with an embedment depth of around 35 meters. The structural system of the tower consists of reinforced concrete core-tubes, steel-reinforced concrete megacolumns, belt and outrigger trusses, and a composite floor system. The vertical gravity load of the tower is up to 9,300,000 kN, with 50% of the total load resisted by the core-tube. The load in each megacolumn is 360,000 kN and the load in corner column is about 240,000 kN. The projection area of the core-tube in horizontal plan is around 1,250 m² and the average sub-grade pressure is 3,270 kPa. The area of the tower raft is 6,460 m² and the average sub-grade pressure is 3,270 kPa. Under such a load, the bearing capacity and deformation control of the main tower pile foundation are vitally important. In addition, due to the embedment depth of basement and high phreatic water levels, the foundation endures gigantic buoyancy. Handling buoyancy at the podium basement area is a primary challenge.

Considering the pile foundation development in recent years and the soil properties of the site, engineers studied the bearing pile types in the tower area and the tension piles in the podium basement area. A full-scale field test including the bearing capacity and bearing behavior of test piles was conducted. The test provided reference for the design and construction of engineering piles for the Zhongnan Tower and other similar high-rise building pile foundations.

Site Soil Conditions

Suzhou Zhongnan Center is located in the Suzhou Industrial CBD. The construction site is in a river delta and a lacustrine deposit plain landform. The grade level is flat and the elevation is around 4.0m (above sea level). From ground surface to 218 meters below grade, soils pertain to quaternary early Pleistocene Q1 and later sedimentary layers, consisting of saturate clay, silt and sand. The soils can be divided into 13 main layers according to sediment age and physical and mechanical properties, shown in Table 4.5.

工程概况

苏州中南中心设置5层地下室，基础埋深约32m。主塔楼结构体系包含：钢筋混凝土核心筒、钢骨混凝土巨柱、环带桁架和组合楼面体系。其中塔楼平面由纵横各五道剪力墙、八个巨柱和四个角柱组成，如图1所示。巨柱，核心筒，环带桁架同时为抗侧力体系。对于超高层建筑选用重量相对较轻的组合楼面体系，该体系由砼板，压型钢板和钢梁组成。中南中心结构复杂、荷载大，结构自重约930万kN，核心筒约占50%，单个巨柱荷载约36万kN，角柱荷载约24万kN。核心筒投影面积约1250m²，平均基底压力达3270kPa。塔楼厚板面积约6460m²，平均基底压力达1440kPa。如此大的荷载，对主塔楼基础的承载力和变形控制都提出了较高的要求。此外，基础埋置深度大、潜水水位高，基础承受巨大的水浮力，纯地下室区域抗浮问题突出。

结合本工程土层性状及近年来桩基技术发展，对苏州中南中心大厦塔楼区域承压桩桩型和纯地下室区域抗拔桩桩型选择进行了分析，开展了现场试桩承载力静载试验，为桩型的确定、承载力取值，及承载与变形特性的认识提供了依据。指导了工程桩的设计和施工，为类似超高层建筑桩基选型提供了有益参考。

The soils from grade to a depth of 90 meters below grade are mainly composed of silty clay and silt interbedded with silty clay. Due to the high clay content, those layers are not adequate to be the pile foundation-bearing stratum of the main tower. The dense (13-1) silty sand layer and (13-2) fine sand layers are good bearing strata.

Selection of Pile Types

Steel-pipe piles have typically been used for such supertall buildings as the 420-meter Jin Mao Tower and the 492-meter high Shanghai World Financial Center in the 1990s. Due to the limitation of construction equipment ability, it is difficult for steel pipe piles to penetrate through the deep and thick sand layers to reach soils of high bearing capacity. Therefore, the ultimate bearing capacity of a single pile used in those two high buildings is not more than 10,000 kN. Moreover, the cost of steel piles is very high. To attain the same capacity as bored piles, the cost of a steel-pipe pile is about 50% more expensive. Compared with the steel-pipe piles, bored piles have the advantages of controlling soil compaction and reducing construction noise. Since 2000, the development and improvement of the design and engineering methods of bored piles with post-grouting has meant that the bored pile has become the most popular pile type used for the supertall buildings.

The total load of the Zhongnan Center core required the bearing capacity of a single pile to be more than 15,000 kN. In the history of previous high-rise construction in Suzhou and other areas with similar soil conditions, the diameter of piles had been no more than 1,100 mm and the length had been no more than 90 meters from grade level. Further, the allowable capacity had been no more than 12,000 kN. Although, the large-diameter and super-long bored piles with post-grouting were clearly the necessary choice, the choice of the bearing layer for the bored pile was still difficult. Based on the geological conditions of the site, layer 13-1 and layer 13-2 were possible candidates to be the bearing layer

Soil layer name 土层名称	Thickness 厚度	γ / /m	c /kPa	Φ /°	fs /kPa	fp /kPa
(1) fill 填充层	3	—	—	—	—	—
(4) silty clay 粉质粘土	4.3	19	35	17.5	40	—
(5) Sandy silt 砂质粘土	7.4	18.6	6	32.5	50	—
(6) silty clay 粉质粘土	8.9	18.5	17	21	35	—
(8) ₁ silty clay 粉质粘土	3.2	19.3	48	16.5	65	—
(8) ₂ silty clay interbeded with silt 粉质粘土与淤泥夹层	8.3	18.6	22	22.5	55	—
(9) Silty sand 粉质砂土	12.9	18.6	1	33	75	1800
(10) ₁ silty clay 粉质粘土	12.2	17.9	27	16	55	800
(10) ₂ silty clay 粉质粘土	10.5	18.7	25	21	65	1000
(11) Silt interbeded with silty clay 淤泥与粉质粘土夹层	9.4	18.8	12	29	80	2000
(12) ₁ clay 粘土	9.8	18.1	31	17.5	65	1300
(12) ₂ silty clay 粉质粘土	7.2	19.7	56	16.5	75	1600
(13) ₁ Silty sand 粉质粘土	4.4	19.1	1	34	90	2800
(13) Interlayersilty clay 粉质粘土	5.8	19.6	46	19	75	1600
(13) ₂ fine sand 细砂	43.3	19.4	0	35	95	3000

Table 4.5. Soil properties of the site
表4.5. 场地地质条件

地质概况

苏州中南中心地位于苏州工业园区金鸡湖湖西CBD商圈核心区，地貌类型为三角洲、湖积平原，场地内地势较平坦，场地地面高程约为4.0m。在218.7m~250m范围内为全风化~强风化基岩，218.7m深度以上范围的地基土均为第四系早更新世Q1及其后期的沉积土层，主要由粘性土、粉土、砂土组成。根据土层的沉积年代与物理力学性质，主要分为13个层次。场地土层及参数如表1所示，桩基相关土层分布及特点如表4.5所示。

埋深90m范围内为第4~12层土，主要为粉质粘土和粉砂夹粉质粘土，其粘粒含量高，不适宜作为本项目主塔楼桩基持力层。其下的13-1粉砂层和13-2粉砂层皆是较理想的主塔楼桩基持力层。

桩型选择

塔楼承压桩桩型选择

上世纪末在上海建设的420.5m高层建筑上海金茂大厦和492m上海环球金融中心采用了钢管桩。2000年以来随着施工工艺的成熟，灌注桩成为超高层建筑的主要桩型，通常采用后注浆工艺提高承载力并减小沉降。相对钢管桩，灌注桩避免了噪音、挤土效应等环境影响问题，且施工工效高，经济性好。当前国内在建的600m超高层建筑皆采用了大直径钻孔灌注桩。苏州已建成的最高建筑苏州东方之门为71层，建筑高278m，采用了1000mm直径的灌注桩，以13-1粉砂层为持力层，桩端埋深约95m，最大加载至19300kN。正在建设的苏州国金中心为92层，建筑高约450m，采用了1000mm直径的灌注

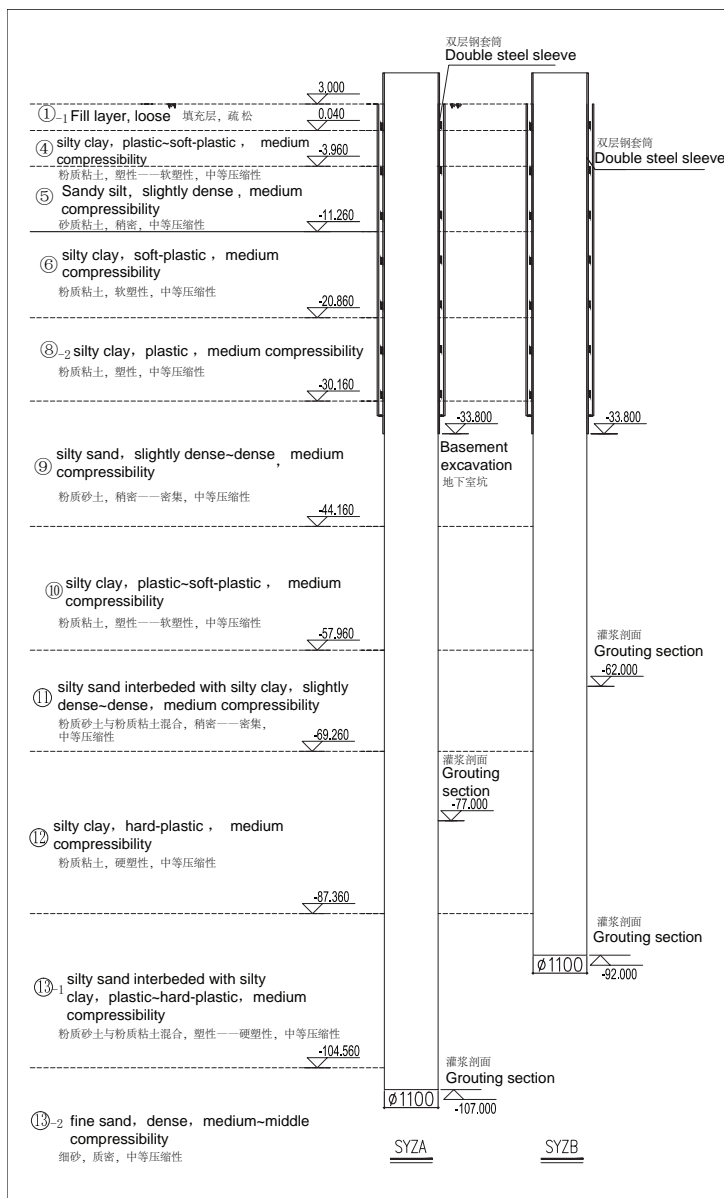


Figure 4.14. Profile of soil and compression pile
图4.14 土层及试桩剖面图

for the bored piles. With a buried depth of about 90 meters, layer 13-1 consists of dense silty sand, and the P_c value of a cone penetration test is about 16 MPa; whereas the standard penetration test value is about 68. Layer 13-1 is a good supporting layer for the pile foundation. Underneath the 13-1 layer is a silty clay layer, whose cone penetration test P_c value is only about 4 MPa, where the standard penetration test value is about 25. The existence of a soft layer brings uncertainty to the choice of 13-1 as a supporting layer for the tower pile foundation. When the layer of 13-1 was chosen to be the supporting layer, according to local experience, the bearing capacity of a single pile with normal diameter would be unlikely to reach 15,000kN. Furthermore, the existing soft substratum will have negative influence on the group piles' settlement. The 13-2 layer consists of dense fine sand and the P_c value of its cone penetration test is about 24 MPa. Situated at 105 meters below the grade and with a thickness of about 40 meters, the 13-2 layer is a better bearing layer than the 13-1 layer. The disadvantage is that the bored pile would have to be prohibitively long, with a drilling depth of 110 meters from grade level. Based on the above analysis, layers 13-1 and 13-2 are two candidates for pile bearing layers. The pile-loading comparison tests were developed to provide valuable results to help engineer the selection of the supporting layer.

Pile Selection of the Podium Region

The five-story tall podium has a 30-meter-deep basement. The water table is about 0.5 meters below the ground surface, which necessitates anti-buoyancy structural interventions. It is

桩，以13-1粉细砂层为持力层，桩端埋深约90m，试桩最大加载至24000kN。

本工程主塔楼荷载大，预估单桩承载力达15000kN，根据国内软土地区在建的600m超高层建筑并结合苏州本地超高层建筑的经验，必将采用大直径超长的后注浆灌注桩，预估桩径不小于1100mm，桩端持力层的选择是一个难点。第13-2层细砂层分布稳定，层厚约40m，呈密实状态，静力触探 q_c 约24MPa，标贯大于50击，是理想的持力层，但该层层顶埋深达到约105m。第13-1层粉细砂层层顶埋深约90m，呈密实状态，静力触探 q_c 约16MPa，也是较好的持力层。但该层下卧有可塑至硬塑状的粉质粘土夹层，静力触探 q_c 约4.0MPa。因此，桩端进入13-1层粉细砂层不能太深，需离下部软弱夹层不小于4倍桩径。由于本工程基础埋深约35m，以13-1层为持力层时，桩端埋深约95m，实际有效桩长为60m，根据实步估算及前述两个以该层为持力层超高层建筑桩基静载试验，其单桩承载力较难满足15000kN特征值的要求。此外，13-1层以下的粉质粘土夹层也会对群桩沉降带来不利影响。为了进一步探讨13-1层为塔楼桩基持力层的可行性，后续开展了以13-2层和13-1层分别为持力层的桩基静载试验。

纯地下室抗拔桩桩型选择

本工程纯地下室区域基础埋置深度约30m，苏州地区抗浮水位可取地面以下0.5m，因此基底承受巨大的水浮力，远大于纯地下室区域结构自重。据初步估算，一个8.4m见方柱网承受的水浮力达10000kN以上。按4桩布置方式初步估算，单桩抗拔承载力特征值约2500kN。

常规的等截面抗拔桩仅靠桩周侧摩阻力提供抗拔力，且灌注桩成孔施工广泛采用泥浆护壁工艺，往往形成桩身泥皮降低侧阻及抗拔承载力。本项目纯地下室面积大、埋置深，抗拔桩的工程量与投资较大，如何对现有抗拔桩型进行改进，提高承载力并降低造价是业主迫切关心的问题。

扩底抗拔桩通过改变桩端截面提高承载力，桩侧后注浆抗拔桩则通过注浆改善桩土接触面特性提高承载力，两者皆以较小的混凝土或水泥浆材料增加获取显著的承载力提高，已成为桩基础的一个发展方向。

estimated that uplift force due to buoyancy could reach 10,000 kN for the typical column bay of 8.4 m x 8.4 m. The tension force in single piles is about 2,500 kN when four tension piles are placed in a typical bay.

It is known that the tension capacity of a normal bored pile is provided by the skin friction of the pile. Compared with driven prefabricated piles, the tension capacity of bored piles is smaller because of the slurry protection drilling method, in which the mud paste weakens the skin friction. As there will be a large quantity of tension piles, the owner and engineers had an extensive discussion about how to improve the tension pile capacity and reduce the construction cost.

The pedestal pile changes the cross-section of the pile tip to increase the tension capacity. The pile with shaft-grouting can increase the tension capacity by changing the interface property between the pile and the soil. Engineering practice has shown that both types of tension piles can increase the uplift bearing capacity significantly with limited construction cost increase.

For example, the tension piles with shaft grouting were used in the 606-meter Wuhan Greenland Center. The diameter of the side-grouting uplift piles on that project was 700 mm and the effective pile length was 22 meters. It is estimated that without grouting, the pile length would have to have been more than 29 meters. The savings from pile-length reduction are significant.

At the Suzhou Zhongnan Center, the buried depth of the basement is about 30 meters. Experience has shown that, when the pile bearing layer is deep, the pedestal tension pile is not always the best choice, because it is hard to control. The formation of the expanded head is imprecise and the construction efficiency is low. Comparatively, when the pile length is long, it is a better choice to use the tension pile with grouting, because it is more feasible to control construction quality and cost. Consequently, tension piles with side grouting were the better choice for this project.

Design of Test Piles

Test Piles of Tower Building

According to the calculated building loads of the Suzhou Zhongnan Center tower, the required bearing capacity of a single pile is more than 15,000 kN. Whether the supporting layer is 13-1 or 13-2, the bored pile would still have to be very long. Constructors in Suzhou have little experience of bored piles with such high capacities. Therefore, a pile loading test should be done first to test the feasibility. Pile tests may reveal some technical problems, which include the borehole quality. Pile tests also reveal the construction efficiencies of large-diameter and super-long bored piles in the deep and thick sand layers, the quality of high-strength concrete constructed underwater, the technique of toe-shaft post grouting, and the bearing capacities and settlement properties under loading.

The diameter of the test piles and reaction piles is 1,100mm. Full-scale loading tests of four piles embedded in two different bearing strata were carried out. Type A piles, labeled SYZA1 and SYZA2, are embedded in the 13-2 fine-sand layer. The pile toe depth is 110 meters. Type B piles labeled SYZB1 and SYZB2 are embedded in the 13-1 silty-sand layer. The pile toe depth is 95 meters. All four test piles are post-grouted, bored piles. The predicted maximum testing load is 40,000 kN. Grade C55 concrete was used first for the test piles to ensure the pile body would not be crushed under such a large testing load. The arrangement of the test piles and reaction piles is shown in Figure 4.15. Sections of the soil profile and the test pile are shown in Figure 4.14.

Grade P42.5 fresh Portland cement was used for post-grouting. A total of 3,500 kg of cement was used for toe post-grouting of single piles. The water cement ratio is 0.5-0.6. There were

正在建设的华中第一高楼武汉绿地中心纯地下室区域采用了桩径为700mm的桩侧后注浆抗拔桩，有效桩长为22m，比常规抗拔桩减少7m，效益明显。据初步估算，在相同800mm桩径下，常规等截面桩有效桩长约45m，而采用扩底抗拔桩和等截面抗拔桩可将桩长减小10m，其经济效益明显。

由于本工程基础埋置深度达30m，采用扩底抗拔桩的桩端埋深约65m，扩底施工难度大，且调换扩底钻头的工效也较低。因此，本工程采用桩侧后注浆抗拔桩，由于桩径较大、桩长较长，其施工可行性和承载力的提高比例都更有保证。

试桩设计

承压桩试桩

根据苏州中南中心荷载的要求，单桩极限承载力不小于30000kN，必将选择桩端埋深95~110m的大直径超长灌注桩。如此高承载力的大直径超长桩在苏州地区没有先例，需要通过桩型试验论证成桩的可行性和质量的可靠性。包括深厚砂层中大直径超长钻孔桩的成孔质量与工效，特别是垂直度、沉渣的控制；桩端桩侧联合后注浆工艺参数与可靠性；高强度等级的混凝土在水下浇筑后是否能满足要求；桩基极限承载力取值。以上述主要技术问题为出发点，从试桩设计、施工、检测等方面进行了精细的桩型试验设计，解决工程关心的问题。

苏州中南中心主塔楼承压桩的试桩及锚桩均采用直径为1100mm的灌注桩。试桩试验分为4组，每组包括1根承压试桩和4根锚桩。为了减少工程量，试锚桩的布置如图4.15所示，共4根试桩9根锚桩。为了进行不同持力层的比较，A型试桩2组，以13-2粉细砂层为持力层，桩端埋深约110m；B型试桩2组，以13-1粉砂夹粉质粘土为持力层，桩端埋深约为95m。为了得到极限承载力，本次试桩最大加载能力要求达40000kN，为了保证试桩桩身强度不破坏，首次将试桩桩身混凝土等级设计为C55，同时为工程桩采用高标号混凝土提供经验，锚桩的桩身混凝土设计强度等级为C35。图4.15试桩与锚桩的平面安排。图4.14 土壤与试桩剖面。

three grouting pipes fixed on the pile reinforcement cage for post-toe grouting. There was one grouting section about 30 meters above pile toe for shaft-side post-grouting. A total of 1,500 kg of cement was used for this shaft-side post-grouting. The water-to-cement ratio used for shaft-side post-grouting was 0.6-0.7. Post grouting should be operated after the strength of the pile concrete reaches 70% of the design strength. Pile shaft grouting should be operated earlier than toe post-grouting to prevent the cement slurry from escalating along the shaft and weakening the effect of toe grouting.

In order to directly measure the bearing capacity of the pile within the effective length, double steel sleeves were used to separate the pile shaft from the soil above the final excavation elevation of the foundation pit. As shown in Figure 4.14, the diameters of external and internal sleeves were 1,310 mm and 1,200 mm, respectively. The thickness of both the external and internal sleeves was 14 mm. Steel ring ribs were installed every 5 meters along the external surface of the internal sleeve. The net distance between the ring ribs and the internal surface of the external sleeve was about 9 mm. It was necessary to seal the bottom between the external and internal sleeves to keep the slurry out.

Test Piles at Podium Basement Area

The diameter of the podium tensile pile was 800 mm. There were three test piles and four reaction piles in the loading test. The pile length is about 60 meters, and Grade C35 concrete was used for the test piles. All three test piles were shaft-grouted bored piles. There were three grouting locations along the pile shaft, and the lowest grouting location was 3 meters above the pile tip. The other two grouting locations were spaced at 12 meters. A total of 600 kg of cement was used for each grouting location. The interface between pile and soil is the channel of shaft grouting. Because the pressure of the upper part of the shaft is less than the lower part, the cement slurry will always escalate along the shaft upwards. In order to restrict the extent of

试桩皆采用桩端注浆结合桩侧注浆的联合注浆工艺。桩端注浆采用P42.5级新鲜普通硅酸盐水泥配制的浆液，水泥用量为3500kg，水灰比为0.5~0.6。桩身对称设置3根注浆管，下端与单向阀式注浆器相连，桩端注浆器应插入孔底以下0.2~0.5m。本工程有效桩长较长，根据规范和类似工程经验，可设置2~3道桩侧后注浆以提高承载力。但从便于施工和节约造价的角度，试桩仅设置一道桩侧注浆断面，位于桩端以上约30m处，桩侧压浆水泥用量加大至1500kg。桩身混凝土达到设计强度的70%后开始注浆，先进行桩侧注浆，再进行桩端注浆，桩端注浆分二次进行，第一次注浆水泥用量为2t，第二次注浆水泥用量1.5t。第二次注浆在第一次注浆完成1~2小时后进行。

试桩采用双套管隔约35m开挖段桩身与土体的接触，以直接测试有效桩长范围内的桩基承载力。如图4.14所示，外套管内径为1310mm，内套管内径1200mm，壁厚皆为14mm。内外套管之间每隔5m设置环形的防失稳支撑肋，支撑肋与内套管焊接，支撑肋与外套管内壁的间距为9mm。为防止混凝土和桩侧注浆的浆液沿内、外套管之间空隙上泛，需对外套管管底进行封堵，采取有效措施保证确实隔离。

抗拔桩试桩设计

抗拔桩试桩皆采用直径为800mm的灌注桩，桩端埋深约65m，桩身混凝土设计强度等级为C35。共设置3组试桩，包括3根抗拔试桩和4根反力桩。抗拔试桩为桩侧后注浆抗拔桩，每根试桩设置3道桩侧后注浆断面，最下一道注浆断面离桩端约3m，其上每隔12m设置一道注浆断面。每道注浆断面的水泥用量为0.6吨。桩侧注浆由上而下进行，桩侧每个断面注浆间隔时间不小于1小时。

由于纯地下室区域埋置深度达30m，而工程桩有效桩长约30m，开挖段桩侧摩阻力对整根桩承载力的影响巨大。为了便加精确地通过试桩评价工程桩的承载力，也采用了长达30m的双套管隔离开挖面以上的桩侧摩阻力。外套管内径为1000mm，内套管内径900mm，壁厚皆为10mm。

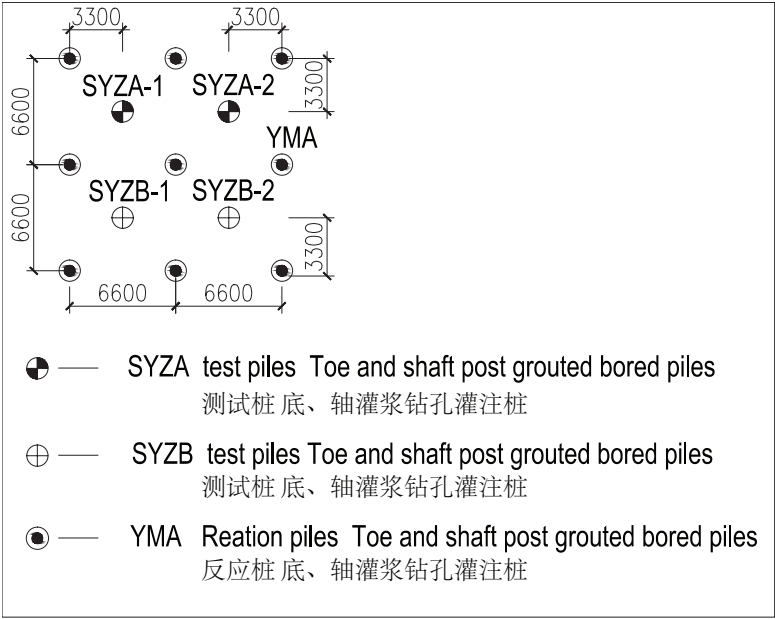


Figure 4.15. Arrangement of test piles and reaction piles
图4.15. 试锚桩平面布置图

rising cement slurry, the grouting sequence is top-down, because the condensation of upper grouting may prevent the escalation of lower grouting.

As with the tower pile tests, double steel sleeves were used in podium pile tests to separate the pile shaft from soil. Above the final excavation elevation was the foundation pit. The external and internal sleeves were 1,000 mm and 900 mm in diameter respectively. The thickness of both the external and internal sleeves was 10 mm.

Results and Analysis

Construction Implementation

The test piles and reaction piles were constructed by a GPS-20 boring machine. The boreholes were formed by a normal-circulation rotary drilling method. The methods to scour the boreholes were pump suction and reverse-circulation washing. During the piles' construction, the pile boreholes were supported using high-quality bentonite slurry. In order to maintain the bentonite support capabilities, a decontamination plant was used to filter the silty sand. The sand ratio of the slurry should be lower than 4%. This is beneficial for controlling the whole diameter and feculence. Three-ring and double-waist hoop bits were used to improve the quality of the boreholes. The average construction time to complete one borehole was 70 hours. The average time to place one reinforcement cage of a test pile into the borehole was eight hours. The average time to fill the borehole with concrete was 4.0 hours. The total time to construct one test pile was five days. Concrete consumption of one pile was 70 m³. The minimum diameters of the piles lay between 1,100 mm and 1,108 mm. The maximum diameters of the piles lay between 1,259 mm and 1,503 mm. The average vertical deviation of the piles was 1/300. The feculence thickness at the bottom of the boreholes lay between 6.0 cm and 10.0 cm with an average of 7.33 cm. The filling coefficients (the ratio of the actual concrete volume to theoretical volume) lay

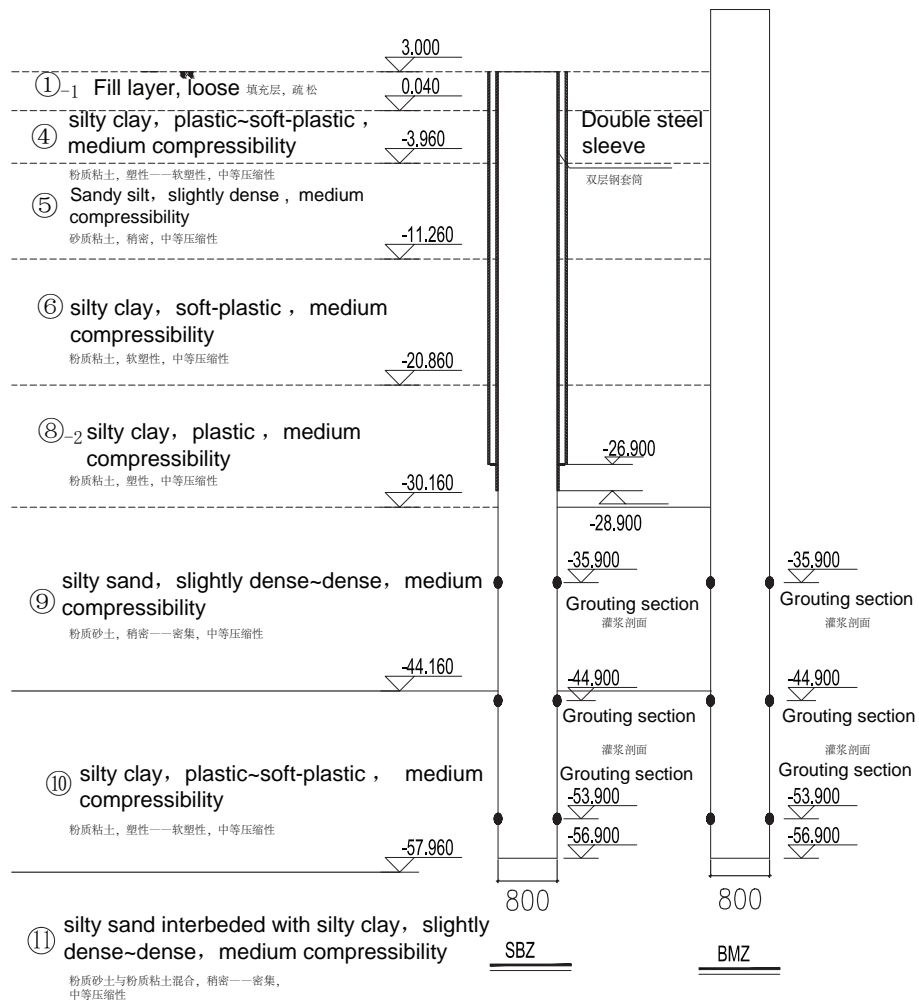


Figure 4.16 Profile of soil and tension pile

图4.16 抗拔桩试桩剖面图

静载荷试验结果

施工效果

主塔楼承压桩试锚桩施工选用GPS-20型工程钻机, 正循环成孔、气举反循环清孔的成孔工艺, 护壁泥浆全部采用优质纳基膨润土人工造浆, 并采用泥浆净化装置过滤泥浆中的粉细砂, 将含砂率控制在4%以内, 保证泥浆的持壁性能, 有利于孔径和沉渣的控制。为了保证成孔的稳定性提高垂直度, 钻头采用三翼双腰箍钻头。单桩的平均成孔时间约70小时, 锚桩钢筋笼下笼平均时间8小时, 试桩钢筋笼下笼平均时间12小时, 平均浇灌时间4.0小时。一根桩的施工时间总计约120小时。桩身最小直径为1100~1108 mm, 最大直径为1259~1503 mm; 桩身垂直度平均为1/300; 沉渣厚度为6.0~10.0 cm, 平均为7.33cm; 充盈系数为1.02~1.05, 平均为1.03。

抗拔桩采用GPS-15型钻机, 正循环成孔和清孔的成孔工艺。单桩的平均成孔时间约50小时, 成桩时间总计约80小时。桩身最小直径为800 mm, 最大直径为901~1038 mm; 桩身垂直度平均为1/400; 充盈系数为1.07~1.12, 平均为1.09。

承压桩载荷试验结果

图4.17为各试桩桩顶、工程桩顶、桩中及桩底处的Q-s曲线。其中, 试桩SYZA1、SYZA2的Q-s曲线为缓变形, 在最大加载值4000kN下, SYZA1累计沉降量83.17mm, SYZA-2累计沉降量101.88mm, 桩端变形分别为8.4mm和11.2mm, 荷载位移曲线均为缓变形, 没有出现陡降破坏。桩顶沉降主要为桩身压缩, 桩身压缩量占桩顶沉降的80%以上, 卸载后回弹率皆达65%以上。

根据规范, 当Q~S曲线呈缓变形时, 取桩顶总沉降S=40mm所对应的荷载值为极限承载力, 当桩长大于40m时应考虑桩身的弹性压缩。对于SYZA1来说, 在最大加载值4000kN作用下, 试桩顶变形为83.17mm, 但工程桩顶处的变形为46.64mm, 虽然大于40mm但其对应的有效桩长达到75m, 桩身压缩约38mm, 因此, 可将SYZA1极限承载力判定为

Pile number 桩号	Pile toe burying depth 桩端埋深	Effective Pile Length 有效桩长	Maximum load 最大荷载 /kN	Pile head movement 桩头弯矩 /mm	Pile toe movement 桩端弯矩 /mm	resilience 弹性	Resilience ratio 弹性比	Ultimate load 极限荷载 /kN
SYZA1	110	75	40,000	83.17	8.4	57.77	69.46%	>40,000
SYZA2	110	75	40,000	101.88	11.12	67.65	66.40%	36,000
SYZB1	95	60	30,000	154.46	68.57	47.89	31.00%	32,000
SYZB2	95	60	34,000	159.07	78.66	48.96	30.78%	27,000

Table 4.6. Settlement and resilience of compression piles under the maximum load
表4.6. 承压桩在最大加载值下的沉降和回弹

between 1.02 and 1.05 with an average of 1.03, which means the drilling hole quality was very good and there was no large-diameter expansion or shrinkage.

The tension piles were constructed by a GPS-15 boring machine. The boreholes were formed by the normal-circulation rotary drilling method. The methods to scour the boreholes were pump suction and reverse-circulation washing. The average time was 50 hours to form one borehole. The minimum diameter of the piles was 800 mm. The maximum diameters of the piles lay between 901 mm and 1,038 mm. The average vertical deviation of the piles is 1/400. The filling coefficients lay between 1.07 and 1.12, with an average of 1.09.

Loading Test Results of Tower Compression Bearing Piles

Load-settlement curves of the four test piles are shown in Figure 4.17. With the increase of the test load, the settlements of piles SYZA1 and SYZA2 grew slowly and firmly. Under the load of 40,000 kN on the top of the piles, the pile top of SYZA1 settled 83.17 mm and the pile bottom settled 8.4 mm. The SYZA2 pile top settled 101.88 mm and the pile bottom settled 11.2 mm. In each stage of loading, the settlement of the pile top changed smoothly without punching failure. Punching failure occurs when the settlement under the current loading stage is five times that of settlement under the previous loading stage. Both SYZA1 and the SYZA2 did not fail. The pile self-deformation under compression is the chief component of pile-top settlement, and it accounted for more than 80% of total pile-top settlement in this experiment. After unloading the piles, the rebound ratios of both piles were over 65%.

According to the specifications, when the Load-Settlement Curve is slowly changing, the bearing capacity of the pile is equal to the test load when the pile-top settlement reaches 40 mm. The elastic compression deformation of piles should be considered when the length of the pile is over 40 meters. Although the settlement of the actual pile top of SYZA1 is under a maximum load of 40,000 kN, it is 46.64 mm, greater than 40 mm or the effective length of the pile. SYZA1 is 75 meters and pile compression is about 38 mm. Therefore, the ultimate bearing capacity of pile SYZA1 is determined as 40,000 kN. The actual settlement of the pile top of SYZA2, under a maximum load of 40,000 kN, is 63.4 mm, greater than SYZA1. The ultimate bearing capacity of pile SYZA1 was determined to be 36,000 kN.

40000kN. SYZA2大最大加载值40000kN作用下，试桩顶变形为101.88mm，工程桩顶处的变形为63.4mm，明显大于SYZA1。SYZA2在36000kN作用下试桩顶变形为85.79mm，与SYZA1相近，取其极限承载力为36000kN

如图4.17(a)、(b)所示，试桩SYZB1、SYZB2在桩顶荷载增加至30000kN和34000kN时，桩顶位移急剧增大呈陡降破坏，且工程桩桩顶、桩中、桩端三个位置沉降量接近，表明桩体发生刺入破坏，试桩SYZB1刺入变形量约为45mm，试桩SYZB2刺入变形量约为78mm，卸载后回弹率仅为30%，表明桩周及桩端土体承载力达到极限。取陡降起始点对应的荷载为极限承载力，试桩SYZB1、SYZB2的极限承载力分别为27000kN，32000kN。

静载试验结果表明，13-2粉细砂层为持力层的A型桩在最大加载40000kN没有发生破坏，按沉降控制其极限承载力不小于36000kN。以13-1粉砂夹粉质粘土为持力层的B型桩则皆加载至破坏，其极限承载力可取27000kN。可见A型桩由于桩端持力层比B型桩好，且有效桩长增加10m，其承载力明显更高，是主塔楼工程桩的主要桩型。在工程桩设计时，可根据群桩计算结果及变刚度调平设计的理念，在巨柱外围区域荷载较小的桩基采用B型桩。

Pile number 桩号	Pile toe burying depth 桩端埋深	Effective Pile Length 有效桩长	Maximum load 最大荷载 /kN	Pile head movement 桩头弯矩 /mm	Pile toe movement 桩端弯矩 /mm	resilience 弹性	Resilience ratio 弹性比	Ultimate load 极限荷载 /kN	Displacement corresponding to Ultimate load 极限荷载对应位移/mm
SBZ1	60	30	9,000	42.45	10.03	29.7	69.96	>9,000	42.45
SBZ2	60	30	8,400	104.93	75.45	22.85	21.78	7,800	32.86
SBZ3	60	30	7,200	104.68	74.88	22.28	21.28	6,600	26.92

Table 4.7. Settlement and resilience of tension piles under the maximum load
表4.7 抗拔桩在最大加载值下的上拔和回弹

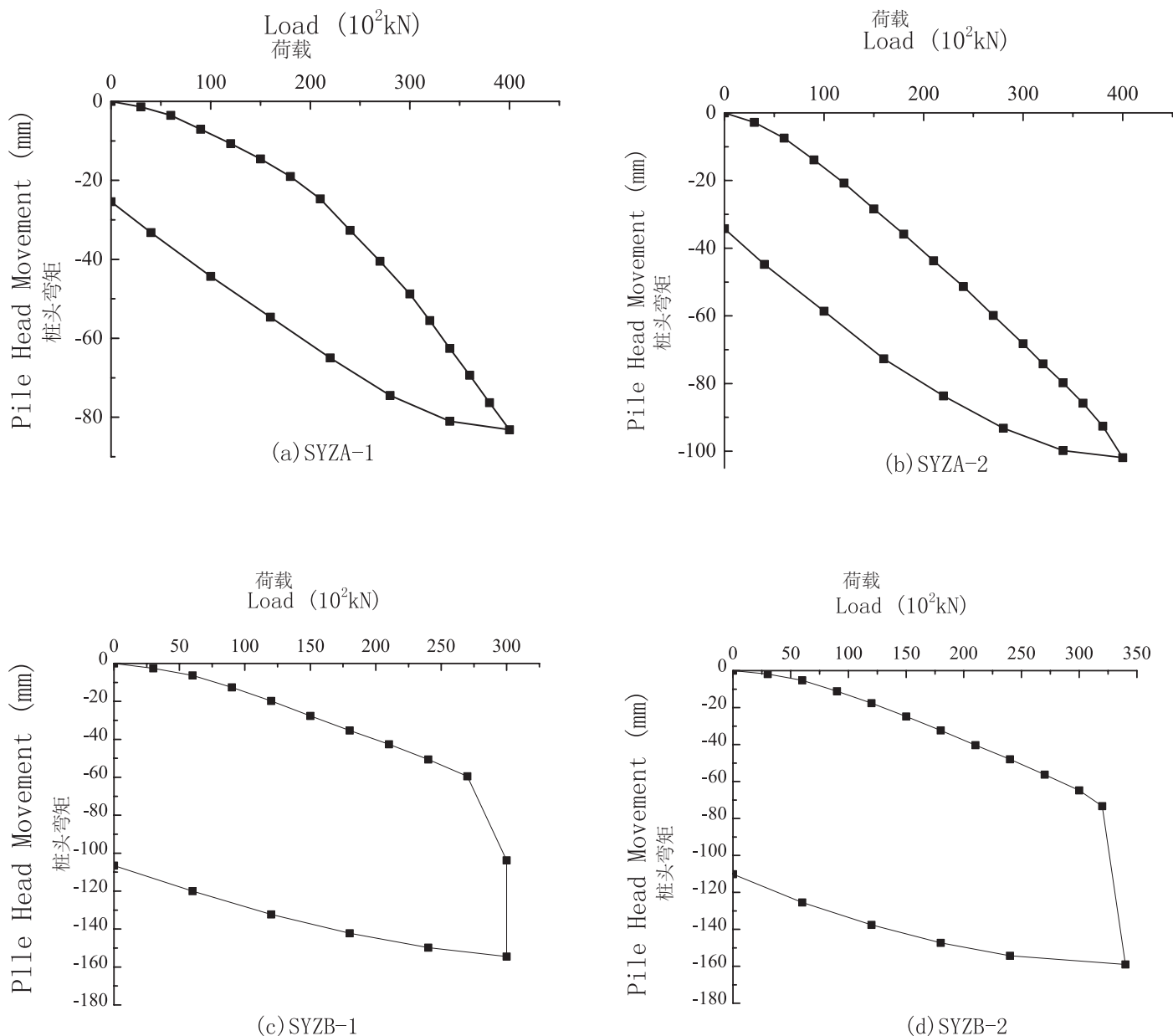


Figure 4.17. Q-S curves of compression piles
图4.17. 承压桩静载Q~S曲线

As shown in Figures 4.17a and b, the load-settlement curves are almost linear before the piles are loaded to reach failure. The settlements of pile SYZB1 and SYZB2 increased rapidly after the failure loads were reached. The settlement values at three locations (the pile top, the middle and the toe) are almost the same. This indicates that punching failures occurred. The punching settlements of pile SYZB1 and SYZB2 are 45 mm and 78 mm, respectively. The rebound ratios are about 30%. The ultimate bearing capacity of piles SYZB1 and SYZB2 were determined as 27,000 kN and 32,000 kN respectively.

Test results show that pile A, embedded in layer 13-2, did not fail under the maximum 40,000 kN load and that the ultimate bearing capacity was not less than 36,000 kN, according to deformation control. Pile B, embedded in layer 13-1, failed in the process of loading and the ultimate bearing capacity was 27,000 kN. Because pile A is supported on a better bearing stratum and its effective length is 10 meters longer than pile B, the bearing capacity of pile A is better. Pile A was therefore chosen as the main pile to support the tower. Pile B may be placed in the area where the pile load is relatively small according to foundation analysis at the detailed design stage.

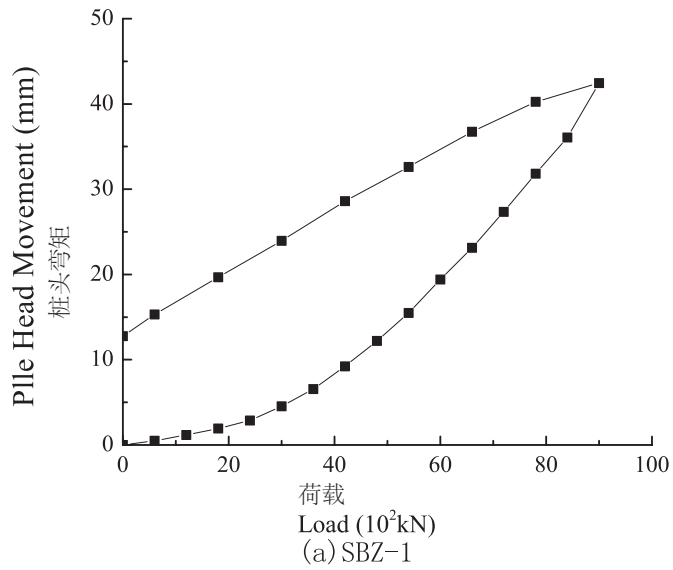
Loading Test Results of Tension Piles

With the increase of loading, the settlement of pile SBZ1 grows slowly. Under the load of 9,000 kN, the upward movement of SBZ1 is 42.56 mm, and the the ultimate tension capacity is determined as 9,000 kN. When the load on SBZ2 and SBZ3 grows to 8,400 kN and 7,200 kN, respectively, the upward movements increase sharply and exceed 100 mm. Rebound ratios are

抗拔桩荷载试验结果

试桩SBZ-1的Q~S曲线为缓变型，在加载至9000kN作用时，桩顶上拔位移为42.46mm，抗拔极限承载力可取为9000kN。试桩SBZ-2、SBZ-3分别加载至8400kN、7200kN时，桩顶上拔量急剧增大，累计变形量皆超过100mm，卸载后回弹率仅为20%。取Q~S曲线陡降起始点对应的荷载为极限承载力，试桩SBZ1、SBZ2的极限承载力分别为7800kN和6600kN。

静载试验结果表明，桩侧后注浆抗拔桩极限承载力皆能达到5000kN预估值的的要求。在工程桩设计时，桩长有进一步优化的空间，但同时也应看到3根试桩承载力的离散性较大，工程桩施工应重视对质量的控制。



about 20%. The ultimate tension capacities of pile SBZ2 and SBZ3 were determined as 7,800 kN and 6,600 kN.

The test results show that the ultimate tension capacity of all bored piles with shaft grouting can meet the requirements of 5,000 kN. The length of a pile can be further optimized at the detailed pile-design stage. The test results of three piles vary greatly. Great attention should be paid to the quality control of shaft grouting during the construction.

Conclusion

Suzhou Zhongnan Center is one of the tallest buildings under construction in China. The bearing capacity and deformation control of pile foundations are strict because of the large building loads. The buoyancy problem is serious because of the dilemma of having a deep basement and a high water table. It is a difficult task to find the pile foundation solution that is suitable for a site with soft soils highlighted by clay and silty clay. Based on the geological conditions of the site and the local experiences, the large-diameter and super-long bored piles with toe-shaft grouting were used for the tower. The shaft-grouting uplift piles were used in the podium of the underground space region.

Static load tests of the piles with diameters of 1,100 mm showed that when the pile with 75 meters' effective length is supported on the 13-2 fine sand layer, the ultimate bearing capacity is more than 36,000 kN. When the pile with 65 meters' effective length is founded in the 13-1 silty sand layer, the ultimate bearing capacity is about 27,000 kN. The bearing capacity of the pile

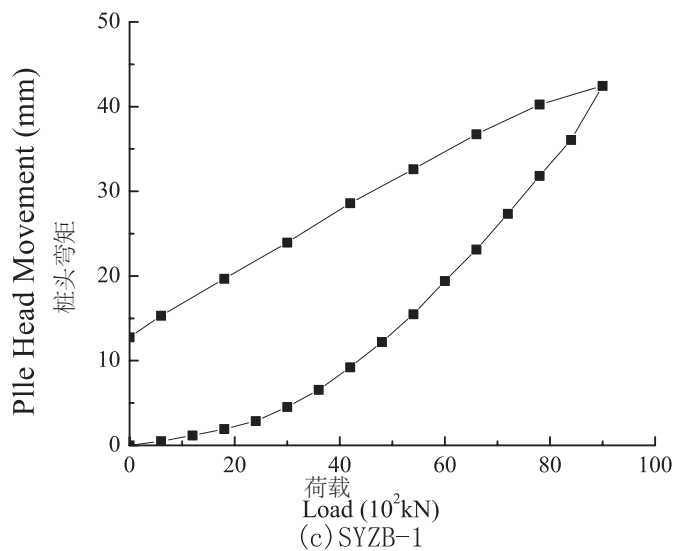
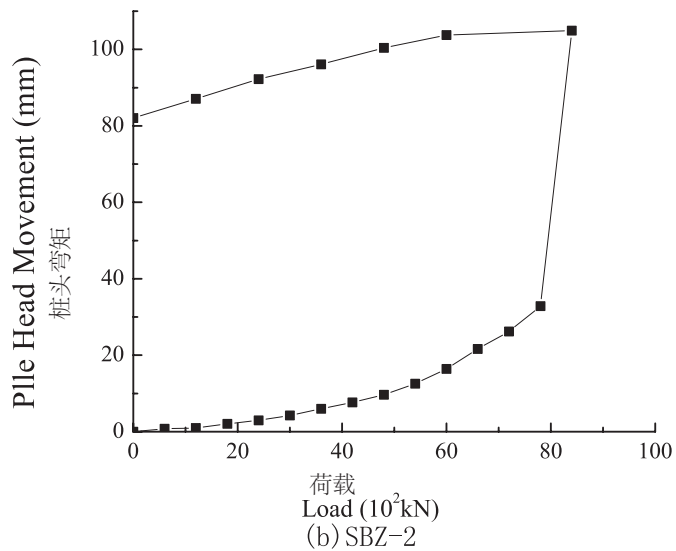


Figure 4.18. Q-S curves of tension piles
图4.18. 抗拔桩静载Q~S曲线

is greatly impacted by its supporting soil layer. Further, it is necessary to consider the requirements of the force and deformation control for the selection of the pile bearing stratum. The ultimate bearing capacity of the tension pile can be enhanced significantly by shaft grouting. While the tension pile with shaft grouting is 800 mm in diameter and 30 meters in effective length, the ultimate bearing capacity is more than 6,600 kN. Engineers verified the feasibility of pile construction and acquired the bearing capacity through pile tests. The results provided valuable information for the detailed design and construction of the pile foundation of this project, and can serve as guidelines for other similar high-rise buildings.

结论

苏州中南中心大厦是国内在建的最高建筑之一，主塔楼荷载大，桩基础的承载力和变形控制要求高，基础埋置深度大，纯地下室抗浮问题突出。场地为深厚的粘土、粉土和砂性土，桩基的选型与设计难度大。结合本工程土层性状及近年来桩基技术发展，对苏州中南中心大厦桩型选择进行了分析，主塔楼采用桩端与桩侧联合后注浆的大直径超长灌注桩，地下室采用桩侧后注浆抗拔桩。

开展了现场单桩承载力静载试验，试验结果表明，对于直径为1100mm的灌注桩，当以13-2粉细砂层为持力层时，极限承载力不小于36000kN；当以13-1粉砂夹粉质粘土为持力层时，其极限承载力为27000kN。持力层和桩长对单桩承载力的影响明显，工程桩设计需根据不同受荷及变形控制要求，选择不同的持力层。桩侧后注浆可大幅提高单桩抗拔承载力，对于800mm直径，有效桩长为30m的桩侧后注浆抗拔桩，其极限承载力大于6600kN。

桩型试验验证了施工可行性、桩基承载力及桩身质量，同时确定了一套指导工程桩大面积施工的标准化指南，为苏州中心工程桩的设计与施工打下了坚实的基础，为类似超高层建筑桩基设计提供了有益参考。

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