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Design and Environmental Protection Measures During Excavation
基坑维护设计和环境保护措施

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The total foundation pit area of the Suzhou Zhongnan Center is 26,260 square meters and is divided into two areas: one area consists of five underground floors and the other has two underground floors. The foundation pit depth ranges from 13.1 to 32.3 meters. This chapter discusses the engineering design of the foundation pit and protection measures for Suzhou Center, adjacent to the southeast, and the metro line 1 tunnel to the north. The five underground floors adopt the design scheme of a podium building top-down construction method in the first order, and the tower-building bottom-up construction method in the second. The two-floor area began bottom-up construction after the top-down construction of the five-floor area finished. The envelope structure adopts the design scheme of an "envelope/basement diaphragm wall." A number of strengthening measures, such as securing the reasonable construction schedule arrangement with the adjacent foundation pit, adding slant concrete supports and consolidating measures of passive-area soil were put into effect. Corresponding key technology is reasonable, reliable, and meets the safety demands of foundation-pit engineering and protection requirements of the surrounding environment.

该工程基坑总面积为26260m²，分地下五层区和地下二层区，挖深为13.1～32.3m，属于大面积超深基坑工程。本文重点阐述了本工程基坑设计方案以及对东侧、南侧邻近苏州中心基坑和北侧地铁一号线隧道的保护技术性措施。本工程地下五层区采用"裙楼先逆作，塔楼后顺作"、地下二层区在地下五层逆作完成后顺作、围护体采用"两墙合一"地下连续墙的设计方案，并采取了合理安排和邻近基坑交叉施工工况、加设斜向混凝土支撑、被动区土体加固等加强措施。相应的关键技术措施合理、可靠，较好地满足了基坑工程自身的安全需求及对周边环境的保护要求。

Introduction

The building's foundation pit is mainly composed of an area with two underground floors, a second area with five underground floors beneath the podium building and an area beneath the tower building with five underground floors. All areas have underground structures, and different areas have different excavation depths, ranging from 13.1 to 32.3 meters. Each presents complex problems, such as the interaction of adjacent synchronous or asynchronous foundation pit construction, as well as other key technical problems, like the force between adjacent supporting structures, the sharing of envelope systems, etc.

The currently operational Suzhou metro line 1 tunnel lies to the north of the project site. Xingyang Street and Suhui Road, beneath which with a large number of municipal pipelines underneath are located, lie to the southwest. The B-4 area of Suzhou Center Plaza has some foundation pit construction synchronous with that of the Suzhou Zhongnan Center. Therefore, the effects of an excavation project on the surrounding environment needed to be addressed.

In addition, this project base adjoins and sometimes crosses a deep confined aquifer, so there is the possibility of the foundation pit heave-piping. Severe confined water pressure challenges the foundation pit engineering, and corresponding measures must be taken.

Project Profile

Foundation Pit Profile

The foundation pit is about 26,260 square meters in area, of which the area with five underground floors comprises about 23,430 square meters; the area with two underground floors has a foundation pit area of about 2,830 square meters. The area with two underground floors is located on the north side of the project, and is a long and narrow rectangle with an excavation depth of 13.1 meters. The area with five underground floors is located on the south side of the project, and takes the shape of an irregular pentagon with an excavation depth of 27.7 meters (the local deep pit is 28.6 meters) below the podium and 32.3 meters beneath the tower.

引言

整个项目主要由地下二层区域、地下五层区域裙楼区和地下五层区域塔楼区几个不同挖深的地块构成，由于各地块均存在地下结构，整体开挖深度约为13.1～32.3m不等，项目实施时将面临较为复杂的相邻基坑同步或异步施工的相互影响问题，以及由此可能会涉及的相邻地块支护结构间传力、围护体系共用等一系列关键技术问题。

基地北侧为正在运行的苏州地铁一号线隧道；基地西南侧为星阳街、苏惠路，道路下埋置大量市政管线；基地东侧、南侧邻近苏州中心广场若干待建和在建基坑，其中苏州中心基坑B-4区存在与本基坑工程同步交叉实施的工况。因此，本工程开挖对周边环境的保护问题需要重点考虑。

此外，本工程基底已接近或进入深部的承压含水层，存在导致基坑突涌的可能性，因此本基坑工程面临极为严峻的承压水影响，必须对承压水层采取针对性的措施。

工程概况

基坑概况

本工程基坑总面积约为26260m²，其中地下五层区基坑面积约为23430m²，地下二层区基坑面积约为2830m²。本工程地下二

The whole project area foundation pit detail partition can be seen in Table 4.1 and Figure 4.1.

Environment Profile

This project is located in the core area of the CBD in the west of the lake in Suzhou Industrial Park. The tunnel of the currently operational Suzhou metro line 1 is in the north. Xingyang Street is located to the west and Suhui Road is to the south. The neighboring Suzhou Center project is under construction to the east and southeast. Overall, municipal roads, underground pipelines, the plots of Suzhou Center nearby and the tunnel of the metro line are the main protection objects of this project. The environmental protection demand is very high, especially around the metro tunnel. In the east and south of the site, there are several built and under-construction foundation pits of Suzhou Center Plaza. According to the current construction progress of the neighboring area, the construction of foundation pits at the B-1, B-2, B-2a and B-2b areas of the Suzhou Center will be completed before excavation of the tower begins. But the construction of the B-4 plot will be synchronous. The site environment and the situation of surrounding blocks are shown in Figure 4.2.

Geological Profile

The excavation depth of the area with five underground floors is from 27.7 to 32.3

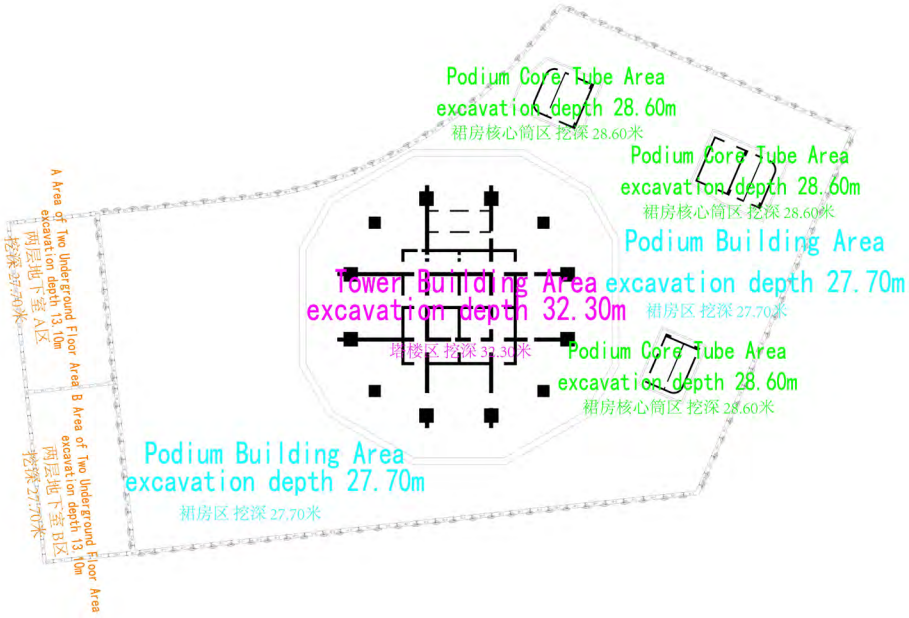

Figure 4.1. Plan sketch of foundation pit partition
图4.1. 本工程基坑分区平面示意图

层区基坑位于项目北侧，呈狭长矩形分布，开挖深度为13.1m; 地下五层区位于项目南侧，呈不规则五边形，裙楼区开挖深度为27.7m (局部深坑为28.6m)，塔楼区开挖深度为32.3m (见表4.1及图4.1)。

环境概况

本工程位于苏州工业园区湖西CBD核心区域，基地北侧紧邻运营中的苏州地铁一号线区间隧道，西侧邻近星阳街，南侧邻近苏惠路，东侧和东南面为在建苏州中心项目。总体来看，基坑周边市政道路、地下管线、周边苏州中心各地块以及基地北侧的地铁一号线隧道均为本工程的保护对象。本工程环境保护要求较高，其中尤以苏州地铁一号线隧道保护要求最高。基地东侧和东南角邻近苏州中心广场若干待建或在建基坑，根据目前了解的周边地块工期进度，其中B-1、B-2、 B-2a、B-2b区基坑在本基坑工程开挖前结束，但B-4区存在与本基坑工程同步交叉实施的工况。基地周边环境及周边各地块现状见图4.2所示。

Area 区域		Bottom Surface Relative Elevation 底板面相对标高	Plate Thickness (mm) 底板厚度(mm)	Basement Relative Elevation 基底相对标高	Excavation Depth (m) 挖深(m)
Area with five underground floors 地下五层区域	Podium Building Area 裙楼区	-26.900	1,600 (2,500)	-28.700 (-29.600)	27.70 (28.60)
	Tower Building Area 塔楼区	-26.900	6,200	-33.300	32.30
Area with two underground floors 地下二层区域	–	-12.900	1,000	-14.100	13.10

Table 4.1. Details of each partition excavation (Source: Building and structure drawing of Suzhou Zhongnan Center project)
表4.1. 各分区开挖信息表 (来源: 苏州中南中心建筑与结构图纸集)

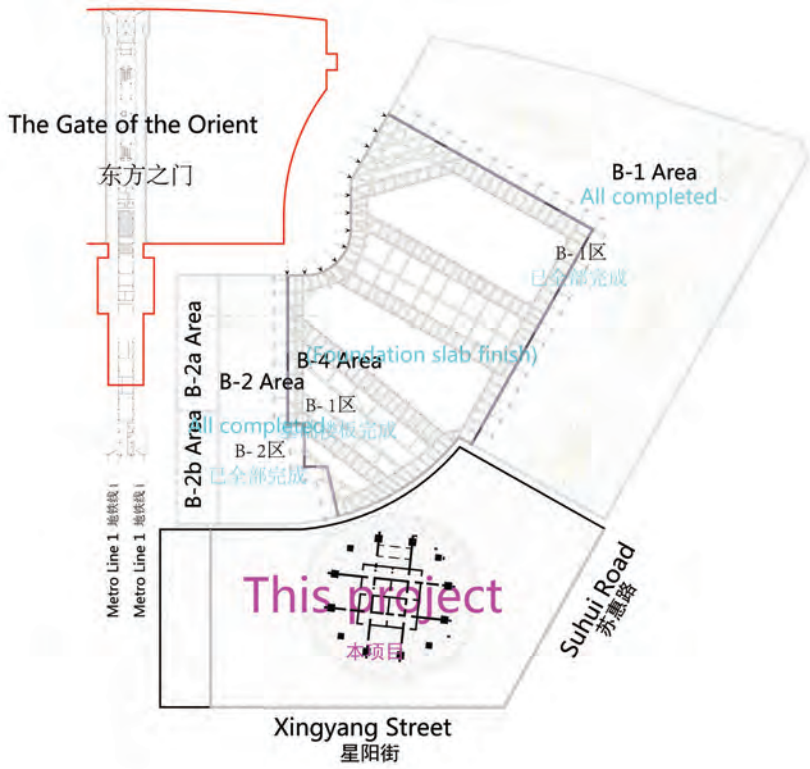

Figure 4.2. Plan of surrounding environment
图4.2. 周边环境平面图

地质概况

本工程地下五层区基坑开挖深度为27.7~32.3m，基坑开挖范围内涉及到第⑤层微承压含水层，基坑开挖面接近或位于第⑨层承压含水层中，且深部的第⑪层承压含水层存在导致基坑突涌的可能性。

地下二层区基坑开挖深度为13.1m，基坑开挖范围内涉及到第⑤层微承压含水层问题。因此，基坑工程面临严峻的承压水问题，复杂的水文地质条件是本基坑工程设计与施工中必须重点考虑并给予妥善处理的问题之一。本工程地基土物理力学参数如表4.2所示，典型地质剖面如图4.3所示。

Soil Layer Code and Name 土层物理力学性质综合成果表	Status 状态	Severe γ (kN/m³) 重度γ	Direct Shear Test Index (consolidated-quickly shear) 直剪(固快)		Permeability Coefficient 渗透系数
			c(kPa)	φ(°)	k(cm/s)
① fill 填土	loose 松散	19.1	15	10	
④ silty clay 粉质粘土	plastic 可塑	19	32	15.6	1.0E-06
⑤ sandy silt 砂质粉土	slightly dense to medium dense 稍密~中密	18.6	4	31.5	8.0E-04
⑥ silty clay 粉质粘土	soft plastic 软塑	18.5	15.1	19.3	5.0E-05
⑧$_1$ silty clay$_1$ 粉质粘土	plastic to hard plastic 可塑~硬塑	19.3	45.6	15.4	1.0E-06
⑧$_2$ silty clay with silt$_2$ 粉质粘土夹粉土	plastic 可塑	18.6	20.6	21.6	3.0E-05
⑨ silty sand 粉砂	medium dense to dense 中密~密实	18.6	0.3	32.5	2.0E-03
⑩$_1$ silty clay$_1$ 粉质粘土	soft plastic to plastic 软塑~可塑	17.9	28.5	15.2	3.0E-06
⑩$_t$ silty sand$_t$ 粉砂	medium dense 中密	18.6	0.3	29.5	1.0E-03
⑩$_2$ silty clay$_2$ 粉质粘土	plastic 可塑	18.7	25	21	5.0E-06
⑪ silty sand with silty clay 粉砂夹粉质粘土	medium dense to dense 中密~密实	18.8	8.9	27.3	3.0E-04
⑫$_1$ clay$_1$ 粘土	plastic 可塑	18.1	31	17.5	3.0E-06

Table 4.2. Parameters list of foundation soil's physical mechanics properties (Source: Geotechnical investigation report of Suzhou Zhongnan Center project (September, 2013))
表4.2. 土层物理力学性质综合成果表 (来源: 苏州中南中心项目岩土调查报告 (9月，2013))

meters. The excavation scope involves layer 5 (micro-artesian water); the excavation surface layer is close to or located in layer 9 (confined aquifer) and layer 11(confined aquifer) presents the risk of heave-piping.

The excavation depth of the area with two underground floors is 13.1 meters. The excavation scope involves layer 5. Therefore, this project has a severe confined water pressure problem. Physical and mechanical parameters of the foundation soil of this project are shown in Table 4.2, and its typical geological profile is shown in Figure 4.3.

Design of Excavation Engineering

Overall Design Scheme

The construction in the area with five underground floors generally follows the top-down method at the podium part and the bottom-up method at the tower part. In other words, the area with five underground floors is constructed as a whole pit by the top-down method, with the tower part reserving large openings. After the podium is constructed down to the bottom of the pit, the underground structure of the tower can then be constructed upwards. The construction of the area with two underground floors will commence after the underground structures of the five-floor area is completed. Based on the general scheme and the ground conditions of the construction site, it is appropriate to excavate to the bottom of the B2 floor vertically on the side next to block B. A sloping excavation along the common side is appropriate under the protection of the brace of the first-floor side span. The structure of the B2 floor can be used as a platform to facilitate simultaneous construction underground and above ground. This approach can reduce to some extent the amount of subsurface excavated soil, which is good for minimizing the duration of excavation and ultimately speeds up the project.

The area with two underground floors in this project was to be constructed after the excavation process of the area with five underground floors and the structures in the

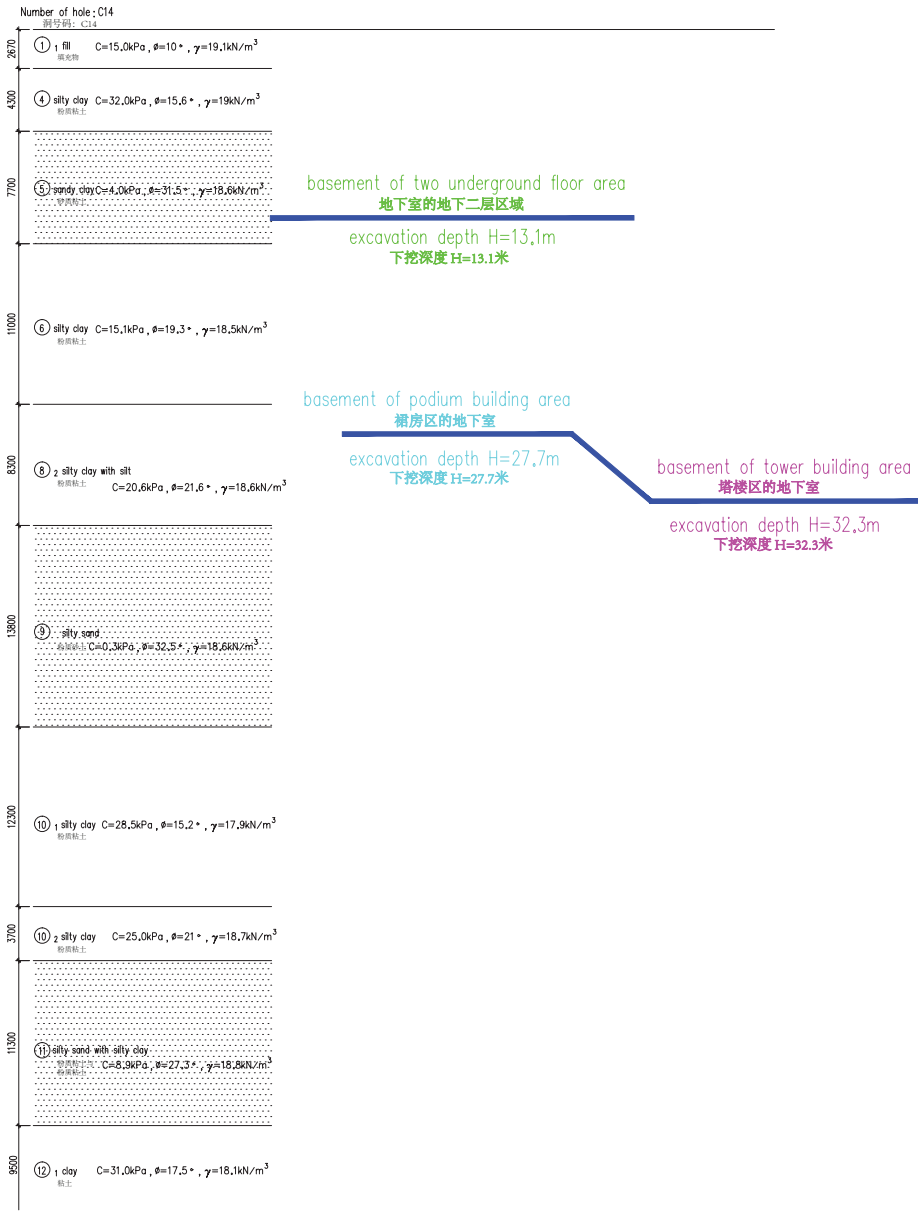

Figure 4.3. Typical geological section
图4.3. 典型地层剖面图

基坑工程设计

总体方案设计

本工程地下五层区总体采用"裙楼先逆作，塔楼后顺作"方案，即地下五层区作为整坑采用逆作法实施，其中塔楼区域留设大开口，待裙楼逆作至基底后顺作塔楼地下室结构，地下二层区待地下五层地下结构施工完成后顺作施工。在此总体方案基础上，结合场地土层情况，本工程有条件在首层边跨结构支撑作用下，通过普遍区域留土放坡、邻近B地块结构侧垂直开挖的方式开挖地下二层底，以地下二层结构作为逆作施工界面层地上地下同步施工，该方式一定程度上减少逆作暗挖土方方量，有利于压缩土方开挖工期加快工程进度。

本工程地下二层区基坑顺作待地下五层区基坑工程结束、地下室结构完成后进行。地下二层区和地下五层区围护体剖面如图4.4、图4.5所示。

围护结构方案设计

采用"两墙合一"地下连续墙作为围护结构，地下连续墙既作为基坑开挖阶段的挡土止水围护结构，同时作为地下室结构外墙，即两墙合一。地下连续墙混凝土强度等级C35（水下混凝土按相关规范提高）。

根据本工程基坑挖深及周边环境情况，本工程地下五层区普遍区域地下连续墙厚度拟

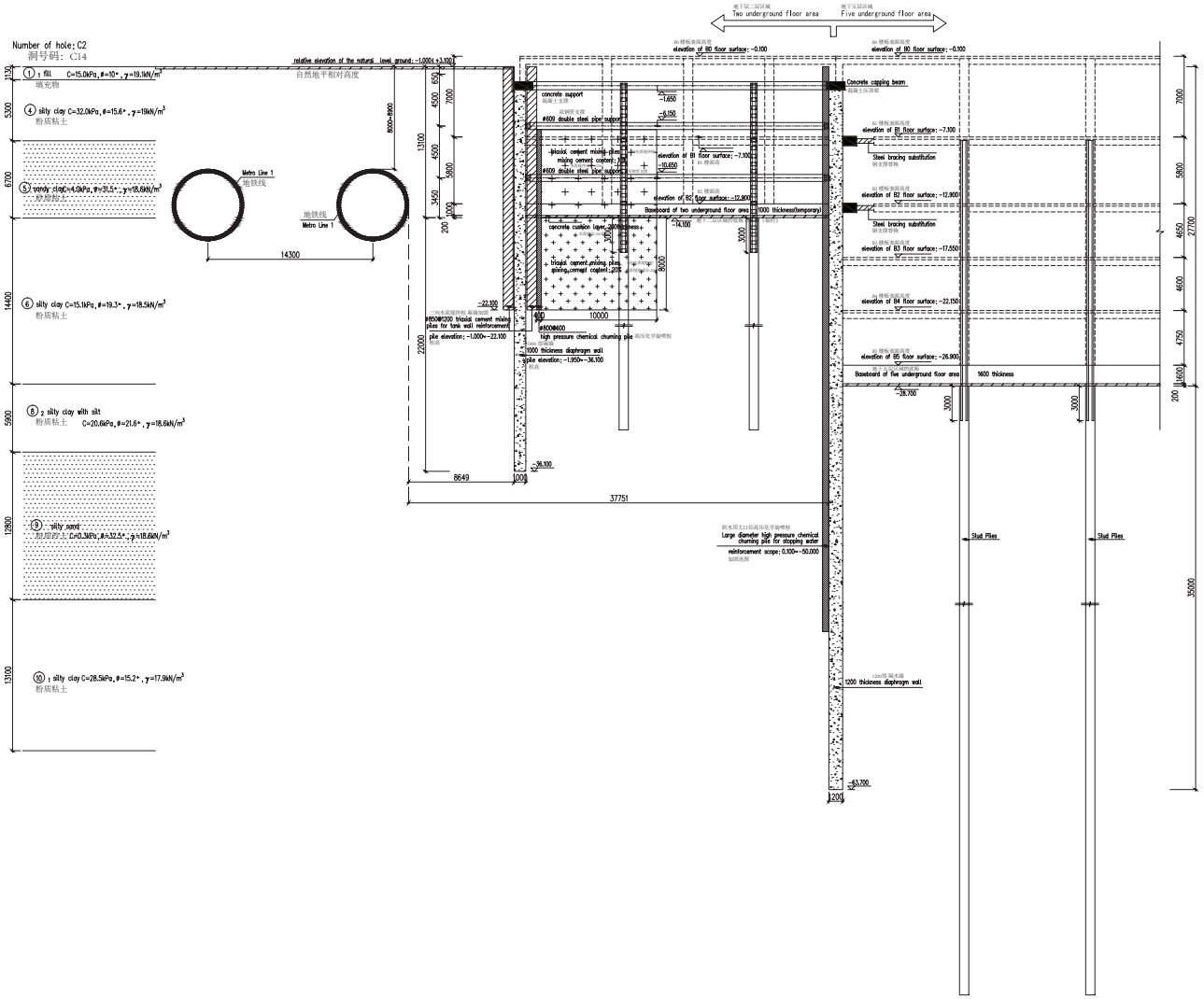

Figure 4.4. Sectional view of envelope/basement diaphragm wall in the area with two underground floors
图4.4. 地下二层区"两墙合一"地下连续墙剖面图

basement were completed. Figure 4.4 and Figure 4.5 show the sectional view of the bracing structures in the area with two underground floors and in the area with five underground floors.

Design of the Envelope Structure

Envelope/basement walls are adopted as the bracing structures, that is to say, they are the envelope and waterproofing structures at the excavation stage. Once in the service stage, the diaphragm walls can be used as the permanent outside walls of the basement. The diaphragm walls are made of C35-grade concrete (the grade will be raised underwater according to relevant codes).

Based on the depth of the excavation and the surrounding conditions, the thickness of the diaphragm walls of the common district in the area with five underground floors are set at 1,200 mm. The thickness of the walls can be optimized to a reduced 1,000 mm on the side next to the block B of the Suzhou Center because of the limited earth pressure over the bottom of the excavated pit of the block B. The thickness of the walls of some local districts in close proximity to the tower remains 1,200 mm. The diaphragm walls toe the area with five underground floors and will be embedded 35 meters below the bottom of foundation pit of the podium.

The widths of the dual-purpose diaphragm walls in the area with two underground floors are set to 1,000 mm, which is adequate to meet the demands for restricting the deformation of the envelope structures and protecting the adjacent metro tunnel. The diaphragm wall footers of the area with two underground floors will be embedded 22 meters below the bottom of foundation pit in the area with two underground floors.

The plane layout of the bracing structures is illustrated in Figure 4.6 as follows.

The joints connecting the diaphragm wall panels in both the area with five underground floors and the area with two underground floors are I-shaped.

取1200mm。对于邻近苏州中心B地块一侧，B地块基底标高以上的留土只作用有限土压力，故该侧地下连续墙厚度可优化至1000mm，局部靠近主塔楼区域地下连续墙厚度仍为1200mm，地下五层区域地下连续墙插入地下五层裙楼区基底深度为35m。

本工程地下二层区设置1000mm厚"两墙合一"地下连续墙，可满足支护变形控制要求及邻近地铁保护要求，地下二层区域地下连续墙插入地下二层区基底深度为22m。

本工程基坑围护体平面布置见图4.6所示。

本工程中地下五层区和地下二层区的地下连续墙槽段接头均采用工字形接头。

水平支撑体系

地下五层区逆作区利用结构梁板代替水平支撑，地下各层结构在塔楼区域设置圆形大空间出土口，并利用电梯井、楼梯等结构永久开口位置预留空间较大的出土口。各出土口周边均设置混凝土边梁，并根据结构楼板缺失的情况在出土口内设置临时支撑，通过严密的组织管理优化逆作施工阶段结构楼板的受力，确保基坑工程的安全。

Lateral Supporting System

The structural beams in the area with five underground floors are used as alternatives for the lateral struts. Large-size circular access openings are settled, bounding the tower in each floor, as well as structures with permanent opening holes like lift shafts and staircases. Concrete edge beams should be placed around each access opening. Furthermore, temporary struts are placed in the access openings where the structural slabs are thereby missing. The stress condition at the construction stage with a top-down method should be optimized to ensure the safety of the excavation project.

A system of diagonal and knee braces is adopted in the first RC lateral supporting system in the area with two underground floors. The first course of struts and enclosing purlins are made of C30-grade reinforced concrete. The cover thickness for the main steel bars in all the bracing members is 30 mm. The relevant information for the first supporting system is listed in Table 4.3.There are two courses of lateral steel supports below the first RC lateral supporting system without enclosing purlins. The steel tubes are supported directly on the diaphragm walls after pre-stressing. The steel type is Q235B. The relevant information for the second and third supporting systems is listed in Table 4.4.

地下二层区第一道钢筋混凝土水平支撑采用对撑结合角撑的支撑体系，第一道钢筋混凝土支撑及围檩混凝土强度等级为C30，支撑杆件主筋保护层厚度均为30mm。第一道支撑体系相关信息如表4.3所示。地下二层区域在第一道钢筋混凝土水平支撑下设置两道水平钢支撑体系，不设围檩，施加预应力后直接顶撑于地墙围护体上，钢材牌号为Q235B。第二、三道支撑体系相关信息如表4.4所示。

本工程顺逆双向结合水平支撑体系布置如图4.7所示。

竖向支承体系

地下五层区设一柱一桩竖向支承系统，体系由钢立柱和立柱桩组成。裙楼逆作

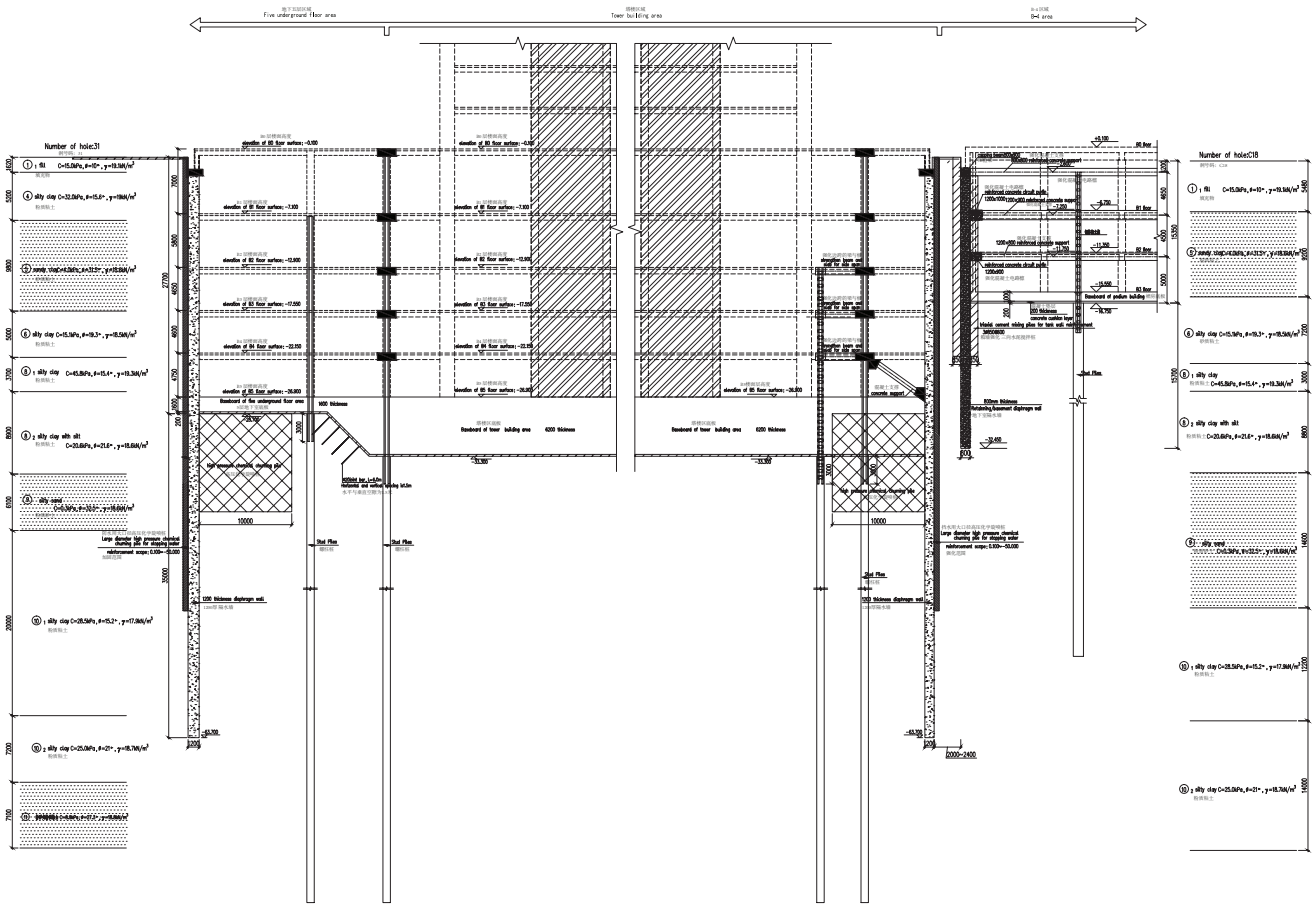

Figure 4.5. Sectional view of envelope/basement diaphragm wall in the area with five underground floors
图4.5. 地下五层区"两墙合一"地下连续墙剖面图

Item 项目	Capping beam 压顶梁/围檩	Longitudinal brace/knee brace 对撑、角撑	Connecting Rod 连杆	Support center elevation 支撑中心标高
the first supporting system 第一道支撑系统	1200×800	1000×700	700×700	-1.650

Table 4.3. The relevant information for the first supporting system in the area with two underground floors (Source: Review plan of Suzhou Zhongnan Center project foundation pit supporting design)
表4.3 地下二层区第一道支撑体系相关信息（来源: 苏州中南中心项目地基基坑支撑设计审阅平面）

The lateral supporting system, which uses a combination of top-down and bottom-up method, is shown in Figure 4.7.

Vertical Supporting System

One-column-for-one-pile technology is adopted as the vertical supporting system in the area with five underground floors. The steel columns in the podium part constructed by the top-down method are concrete-filled steel tubular columns, made of 550*16 steel tube, 600*20 steel tube and 650*20 steel tube with C60 concrete filled inside. The steel columns in the tower part and some local openings are 500*500 angle steel lattice columns made of 4L200*20, Q345B angle steel. The diameters for the erect column piles in the area with five underground floors are all 1,100 mm, most of which will continue to be used as the engineering piles for the main structure.

The temporary vertical supporting system is settled in the two-floor basement region, consisting of temporary steel columns and bored piles. The temporary steel columns are 460*460 angled steel and the lattice columns are made of 4L140*14, Q235B angled steel and welded together with batten plates. The steel column toe is embedded into the bored pile for at least 3 meters. The erect column piles are supposed to be designed to take advantage of the engineering piles, and bored piles with diameter of 0.8 m are installed where no engineering piles are available. The concrete strength grade of the pile body is C30 (the strength grade shall be raised by one level under water).

区域钢立柱采用550×16钢管、600×20钢管和650×22钢管内填C60高强混凝土的钢管混凝土柱; 塔楼顺作区以及局部开洞区钢立柱采用4L200×20，截面尺寸为500×500mm，钢材牌号为Q345B的角钢格构柱。地下五层区域的立柱桩径均为1100mm，绝大多数立柱桩将作为主体结构工程桩。

地下二层区设临时竖向支承系统，体系由临时钢立柱和钻孔灌注桩组成。临时钢立柱采用由等边角钢4L140×14和缀板焊接而成的角钢格构柱，截面为460×460，型钢型号为Q235B，钢立柱插入作为立柱桩的钻孔灌注桩中不少于3m。立柱桩设计时应尽量利用工程桩作为立柱桩，无法利用工程桩的位置增打桩径为Φ800的钻孔灌注桩作为立柱桩，桩身混凝土设计强度等级C30（水下混凝土提高一级）。

基坑采用对苏州中心的专项保护措施

为了确保本工程基坑安全及周边基坑、结

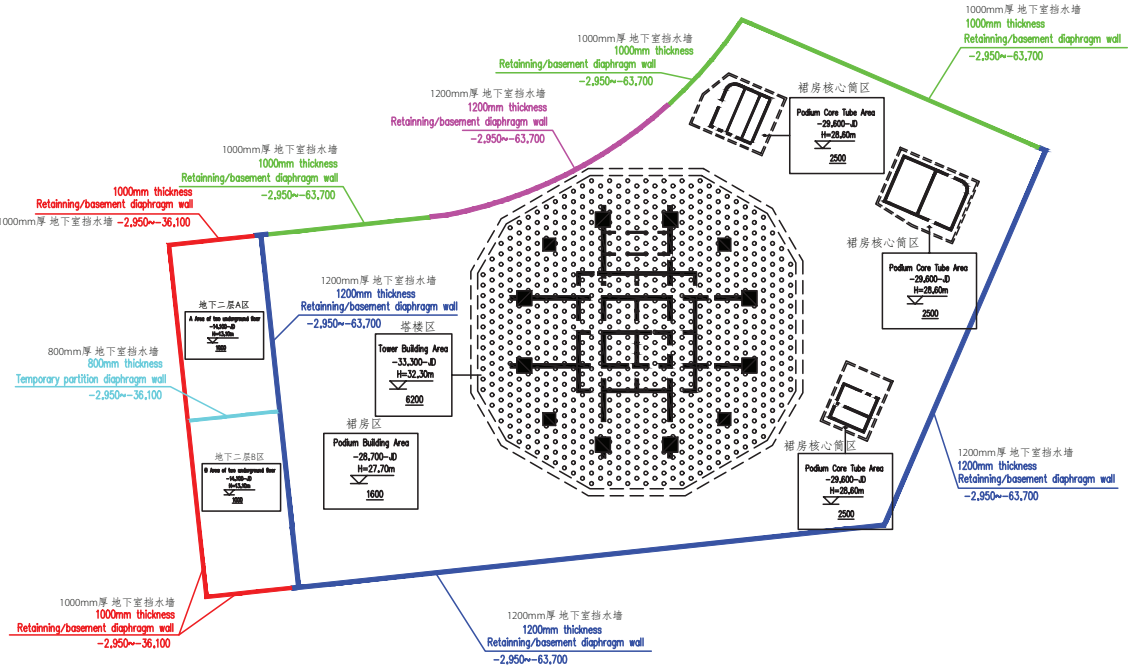

Figure 4.6. The plan layout of the bracing structures
图4.6. 围护体平面布置图

Item 项目	Longitudinal brace/knee brace 对撑、角撑	Connecting Rod 连杆	Support center elevation 支撑中心标高
the second supporting system 第二道支撑系统	φ609X16 Steel pipe support 钢管支撑	H400X400X13X21 Steel connecting rod H400X400X13X21型钢连杆	-6.150
the third supporting system 第三道支撑系统	φ609X16 Steel pipe support 钢管支撑	H400X400X13X21 Steel connecting rod H400X400X13X21型钢连杆	-10.650

Table 4.4. The relevant information for the second and third supporting system in the area with two underground floors (Source: Review plan of Suzhou Zhongnan Center project foundation pit supporting design)
表4.4 地下二层区第二、三道支撑体系相关信息 (来源: 苏州中南中心项目地基基坑支撑设计审阅平面)

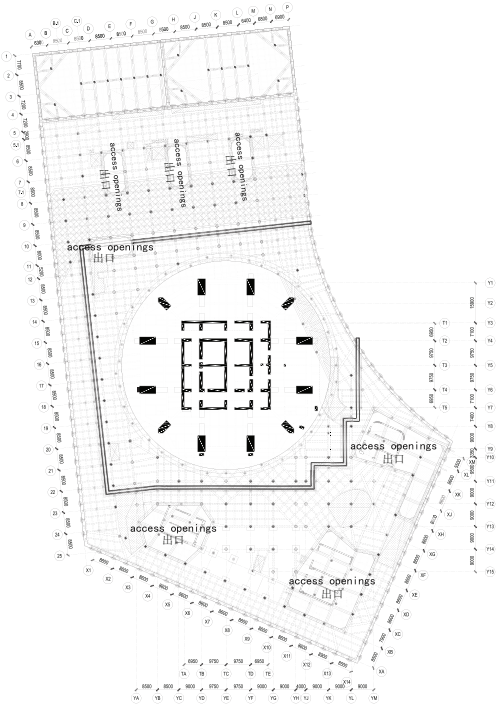

Figure 4.7. Sketch map of lateral supporting system
图4.7. 水平支撑体系示意

Special Protection Measures for Suzhou Center

In order to accomplish the Suzhou Zhongnan Center and the Suzhou Center projects on time and simultaneously, while ensuring the safety of the excavation and the surroundings, the critical construction conditions of Suzhou Zhongnan Center and the B-4 zone of the Suzhou Center were drawn up. The earth beneath the ground floor of Suzhou Zhongnan Center can be excavated only when the underground second floor of Suzhou Center's B-4 zone is completed and meets the design strength requirements. The earth beneath the underground second floor of Suzhou Zhongnan Center can only be excavated when the basement structure of Suzhou Center's B-4 zone is completed and meets the design strength requirements. The analysis result of construction conditions of these two excavations is shown in Figure 4.8. The maximum measured lateral displacement of the diaphragm walls of Suzhou Zhongnan Center is 11.09 mm, and the maximum measured lateral displacement of the diaphragm walls of Suzhou Center B-4 zone is 21.70 mm.

The envelope structure of this foundation-pit excavation project is a diaphragm wall. Diaphragm walls have many advantages, such as strong lateral stiffness, good structural integrity, and perfect sealing effects, which contributes to protecting the Suzhou Center. The diaphragm wall is constructed by a trench-cutting machine, which helps to reduce the disturbance to deep silt layers and consequently to the Suzhou Center. Before the diaphragm walls are constructed, a grooving test is needed. The construction parameters are adjusted according to the influence

构安全，并尽可能满足苏州中南中心和苏州中心的工期计划，拟定本工程与苏州中心B-4区基坑间的关键控制工况为: 苏州中心B-4区地下二层结构施工完成并达到设计强度后，方可开挖苏州中南中心基坑首层结构以下土方; 苏州中南中心B2板以下土方应待B-4区地下室结构施工完成并达到设计强度后方可开挖。两基坑交叉施工工况的计算结果见图4.8，苏州中南中心地下连续墙水平位移最大值为11.09mm，邻近的苏州中心B-4区地下连续墙水平位移最大值为21.70mm。

本工程采用地下连续墙作为基坑支护结构，墙体抗侧刚度大、整体性好、止水效果好，有利于苏州中心的保护。地下连续墙采用铣槽机成槽，以减小对深部粉砂层的扰动，从而减小对苏州中心的影响。在本工程地下连续墙正式施工前，需进行试成槽实验，根据试成槽过程中成槽周边的变形情况调整施工参数，将地下连续墙施工对苏州中心广场结构和基坑的影响降到最低。

本工程地下五层区采用裙楼逆作、塔楼顺作的总体方案，基坑内部的5层水平逆作结构梁板，水平刚度大，有利于控制支护结构的变形。与此同时，圆环边梁东侧离围护墙较近的区域，于圆环边梁内侧设置加强支撑杆件，杆件间以临时封板封闭，有利于该位置围护墙墙身变形的控制，及减小对苏州中心的影响。本工程塔楼东侧靠近围护墙设置了临时斜向混凝土支撑，以

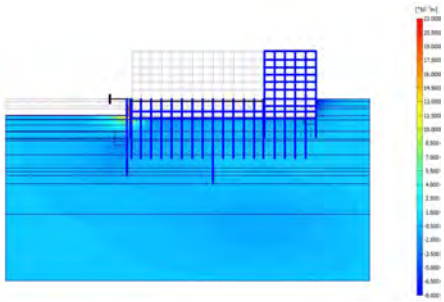

Figure 4.8. Horizontal displacement cloud picture of construction conditions surrounding the underground second floor of Suzhou Center, in which the earth beneath the ground floor is excavated (Suzhou Zhongnan Center excavation is at left, and Suzhou Center excavation is at right)
图4.8. 苏州中心B2板施工完成，苏州中南中心开挖到B2板标高时的水平位移云图 (左侧为苏州中南中心基坑，右侧为苏州中心基坑)

of the grooving test on the environment. Then the adverse impact of diaphragm-wall construction on the Suzhou Center and surroundings can be minimized.

The area with five underground floors supports the top-down construction of the podium building while the tower building is constructed by the bottom-up method. The five floors in excavation have substantial horizontal stiffness, thus helping to control deflection of the envelope structure. At the same time, in the east side of the ring beam, struts were constructed inside the ring beam and temporary closure plates were placed between the struts, thus controlling envelope wall deflection and reducing the influence

进一步控制该侧地下连续墙墙身变形，可减少对苏州中心的影响。塔楼东侧圆环边梁内侧加强措施如图4.9所示，斜向混凝土支撑如图4.10所示。

本工程在塔楼厚板深坑靠近地下连续墙一定范围内采用高压旋喷桩对被动区土体进行加固，加固宽度为10m。这一措施使该侧围护墙墙身变形得到控制，有利于减少苏州中心 (见图4.11) 的结构和基坑的影响。

对于两基坑地墙之间的谷仓土，采取局部设置高压旋喷桩帷幕形成若干隔水分区，并分区采取抽降第⑤层微承压水的方式减少谷仓水土压力，进而减小两基坑相互影响; 对于第⑨层承压水含水层，在开挖降水过程中则应加强水位监测，超过报警值则实施回灌; 对于第⑾层承压水含水层，在开挖降水过程中降压使其对周边环境的影响可控，不作回灌措施。

通过有限元法计算分析可知，中南中心开挖对邻近苏州中心影响为: B-2区地下连续墙水平位移27.8mm，B-2区底板隆起6.9mm; B-4区地下连续墙水平位移24.9mm，B-2区底板隆起5.4mm; B-1区地下连续墙水平位移16.6mm，B-1区底板隆起7.5mm。因此，基坑开挖对邻近苏州中心B-2区、B-4区、B-1区的影响均在可控的范围内。

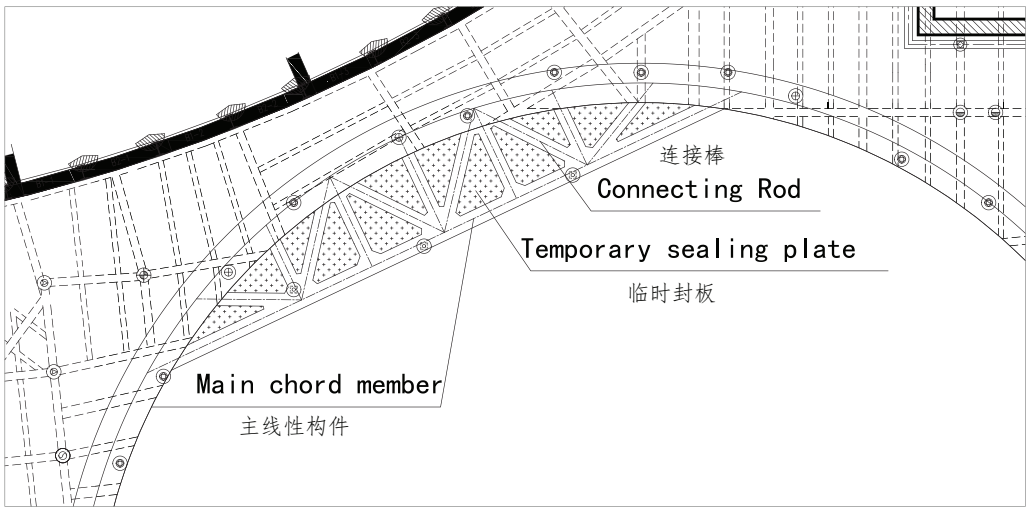

Figure 4.9. The strengthening struts on the east side of the of tower structure and inside the ring beam
图4.9 塔楼东侧圆环边梁内侧加强支撑杆件平面布置图

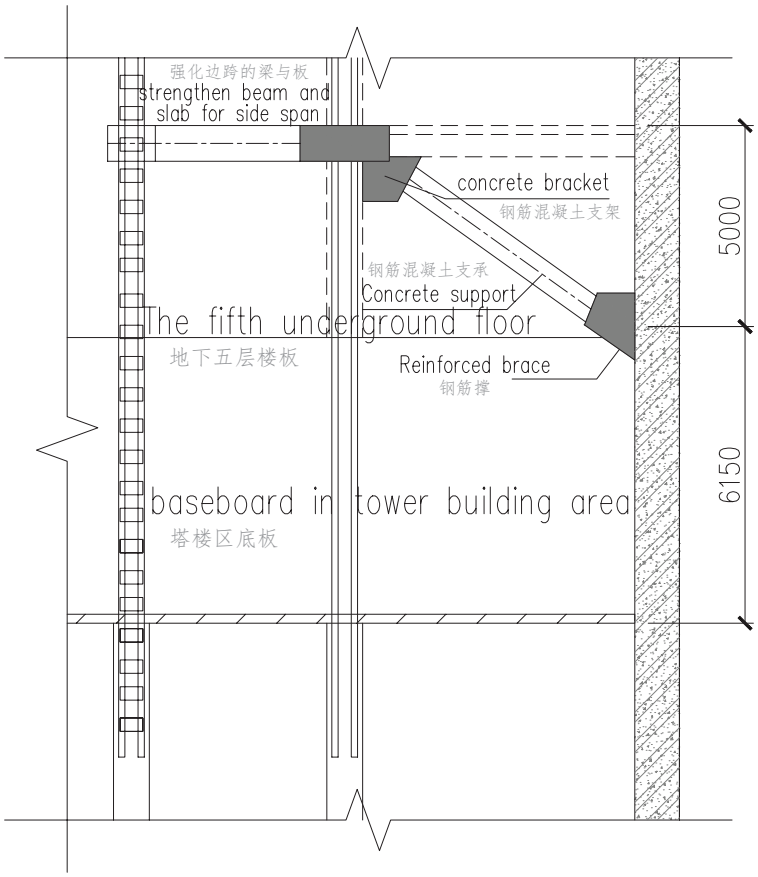

Figure 4.10. Sectional view of the diagonal concrete supports
图4.10 斜向混凝土支撑剖面示意图

on the Suzhou Center. On the east side of the tower structure, temporary diagonal concrete supports are constructed, which also help control the envelope wall deflection and reduce the influence on the Suzhou Center. The strengthening measure on the east side of the tower structure and inside the ring beam is shown in Figure 4.9, and the diagonal concrete supports are shown in Figure 4.10.

A reinforced foundation with a high-pressure jet grouting is used in the tower structure deep zone. The reinforced foundation is 10 meters wide. This measure also helps to control the diaphragm wall deflection and reduce pressure on the Suzhou Center (see Figure 4.11).

For the earth between the diaphragm walls of these two excavations, high pressure jet grouting is used to form several watertight partitions. In each partition, the layer-5 micro-artesian water is pumped to reduce the water-earth pressure, thus reduceing the mutual influence between these two excavations. For the layer-9 confined aquifer, the water level must be monitored during water pumping. If

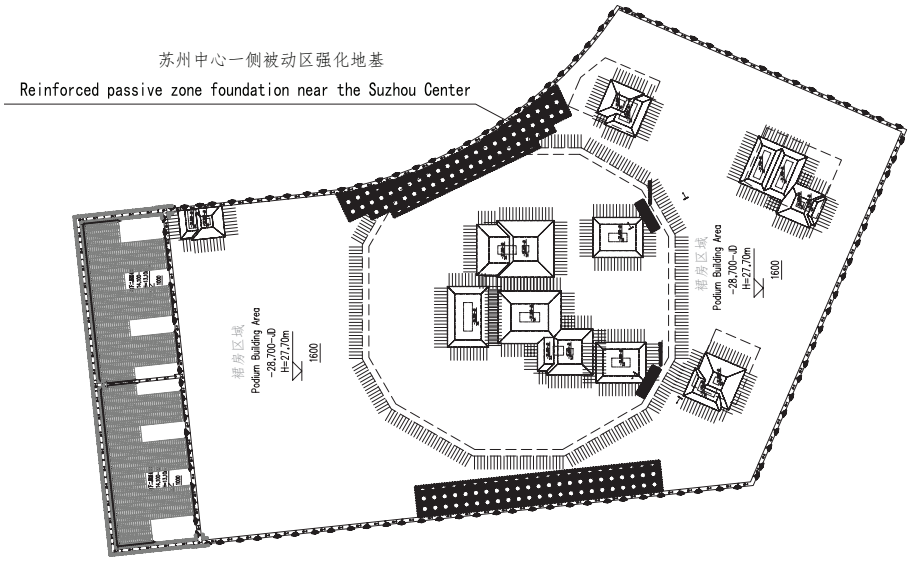

Figure 4.11. Reinforced foundation near the Suzhou Center
图4.11 苏州中心侧边被动区土体加固

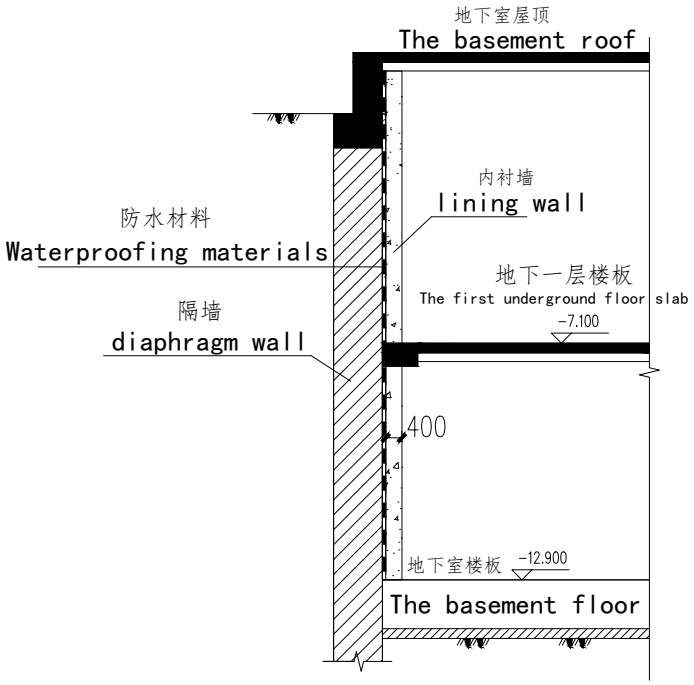

Figure 4.12. Sectional view of lining wall
图4.12 内衬结构墙剖面示意图

it exceeds a given threshold, the groundwater is recharged. For the layer-11confined aquifer, the influence of pumping water on the surrounding environment can be controlled, so there is no need to recharge groundwater.

Through finite element method analysis, the impact of Zhongnan Center excavations on Suzhou Center can be measured. The maximum lateral displacement of diaphragm walls in the B-2 zone is 27.8 mm, and the bottom plate heave in the B-2 zone is 6.9 mm. The maximum lateral displacement of diaphragm walls in the B-4 zone is 24.9 mm and bottom plate heave in B-4 zone is 5.4 mm. The maximum lateral displacement of diaphragm walls in the B-1 zone is 16.6 mm, and the bottom plate heave in the B-1 zone is 7.5 mm. Therefore, the excavation impacts on Suzhou Center's B-4, B-2 and B-1 zone are all in controllable range.

Special Protection Measures for the Metro Tunnel

In the area with two underground floors near the metro tunnel, Φ850@600 tri-axial cement mixing piles are driven in at each side of the diaphragm wall. The pre-reinforcement groove wall can support itself sufficiently to avoid collapsing on the metro tunnel. Also, it strengthens the water-sealing performance of diaphragm wall.

In the area with two underground floors, the waterproofing membrane is pasted inside the diaphragm wall and then the lining walls are constructed. On the one hand, it can be ensured that the diaphragm wall and the lining wall can work together, while on the other, the water-sealing performance of the basement wall can be strengthened further. Basement structure leaks into the metro tunnel can also be controlled during normal use. In the area with two underground floors, a sectional view of the lining wall is shown in Figure 4.12.

The supporting system for the area with two underground floors deploys reinforced concrete support at the higher level and two levels of steel supports below the system structure. Steel more easily compensates for axial forces and supports of real-time monitoring and automatic compensation all day long. The purpose of using steel is to effectively control deformation of the foundation pit envelope structure and to guarantee the safety of the subway tunnel.

In order to improve the pit's passive area soil resistance and reduce deformation, the area with

基坑实施对地铁隧道的专项保护措施

本工程邻近地铁隧道的地下二层区地下连续墙两侧设置单排Φ850@600三轴水泥土搅拌桩作为槽壁加固体。对槽壁进行预加固，可避免成槽期间槽壁坍塌对地铁隧道的影响，且增强了地下连续墙的止水性能。

本工程地下二层区地下连续墙内侧采用了内贴防水卷材后浇筑结构内衬墙的方式以提高正常使用阶段的防水效果。一方面可确保正常使用阶段地下连续墙与内衬结构墙共同受力，另一方面进一步提高正常使用阶段地下室侧壁的防渗效果，避免了永久使用阶段地下二层区地下室结构漏水对地铁隧道造成影响。本工程地下二层区内衬墙剖面如图4.12所示。

本工程地下二层区支撑体系采用第一道钢筋混凝土水平支撑下设置两道水平钢支撑体系的方法，钢支撑采用轴力自补偿系统。该系统可实现全天候钢支撑轴力的实时监控和自动补偿，可有效控制基坑围护结构变形，确保邻近地铁隧道安全。

本工程地下二层在邻近地铁侧对坑内被动区土体采用Φ850@600三轴水泥土搅拌桩进行加固，以提高坑底被动区土体抗力，减小基坑变形。三轴水泥土搅拌桩加固体宽度暂定为10m，呈格栅状布置；三轴水泥土搅拌桩基底以上水泥掺量为10%，基底以下水泥掺量为20%。

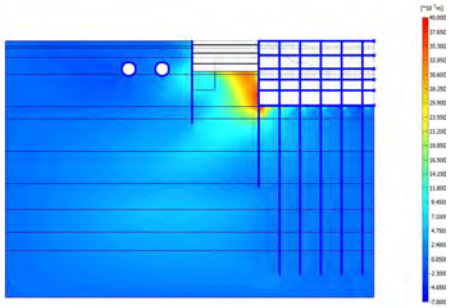

Figure 4.13. Horizontal displacement cloud picture of the influence of Suzhou Zhongnan Center on metro tunnel nearby
图4.13. 苏州中南中心对邻近地铁隧道影响水平位移云图

two underground floors takes Φ850@600 tri-axial soil-cement mixing piles for passive area soil reinforcement. Tri-axial soil-cement mixing piles are temporarily set at 10 meters and presented in a grille arrangement. Tri-axial soil-cement mixing cement content is 10% above the pile bottom and 20% below.

Through finite element method analysis, the impact of the Suzhou Zhongnan Center excavation on the metro tunnel nearby can be obtained. When the five-floor underground zones are excavated to the bottom, the maximum lateral displacement of the tunnel nearby is 3.07 mm, and the settlement of the tunnel is 1.45 mm. When the two-floor underground zones are excavated to the bottom, the maximum lateral displacement of tunnel nearby is 3.90 mm, and the uplift of the tunnel is 1.31 mm. The impact of excavation on the metro tunnel nearby is therefore within a controllable range. A sectional view of the metro tunnels nearby is shown in Figure 4.13.

Conclusion

The Suzhou Zhongnan Center excavation project covers a large area and extends to great depths. Further, the surrounding environment conditions are extremely complex. There are nearby subway tunnels, foundation pits and adjacent underground pipelines. Also, the site maintains complicated hydro-geological conditions and other unfavorable factors, bringing about many difficulties. In the design process, taking reasonable technical countermeasures successfully resolved problems in the design via theoretical research and calculation analysis and experimental demonstrations.

This project undertook top-down podium construction and bottom-up tower construction, It took on protection measures for the nearby Suzhou Center and the metro tunnel. It is an example of successfully implemented super-deep foundation pit design. The technical measures taken in the project for the protection of the adjacent assets and construction sites will provide experience for future generations' deep underground structural work.

通过有限元计算分析可知，中南中心开挖对邻近地铁隧道影响为: 地下五层区开挖至基底时，近端隧道水平位移为3.07mm，近端隧道沉降为1.45mm; 地下二层区开挖至基底时，近端隧道水平位移为3.90mm，近端隧道隆起为1.31mm。因此，基坑开挖对邻近地铁隧道的影响均在可控的范围内。邻近地铁隧道侧剖面如图4.13所示。

结论

苏州中南中心项目基坑工程自身面积较大且开挖深度极大; 周边环境条件极其复杂，有邻近的地铁隧道、邻近的已建或待建的苏州中心基坑、邻近道路管线; 场地水文地质条件复杂等不利因素给本基坑工程的设计带来了很多困难。在设计过程中，通过大量理论研究、计算分析和试验论证，采取合理的技术对策使设计中的问题得到成功解决。

本工程采用"裙楼先逆作，塔楼后顺作"的方案。并采取对周边苏州中心和地铁隧道的保护措施，成功实现了本工程超大超深基坑的设计。本工程对邻近已建或交叉施工的地下结构及地铁隧道的保护所采取的技术性措施将为深层地下结构的建造提供经验。

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