Optimization Analysis of Key Technologies of Super High-Rise Buildings with Soft Soil Foundation

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Abstract. The frequency of super high-rise buildings has gradually increased in larger cities. Compared with ordinary buildings, super high-rise buildings involve more difficult technologies of construction. Soft soil foundation is one of the unfavorable foundation types for engineering construction because of its high sensitivity and low bearing capacity. Therefore, the combination of super high-rise buildings and soft soil foundations will greatly increase the insecurity of the project. Although related methods of soft soil treatments have been proposed and optimized in recent years, there is still a lack of targeted construction methods combing for super high-rise buildings, which is of vital significance to improve the safety and efficiency of future construction projects. Based on the case analysis of Jinmao Tower, Shanghai World Financial Center and Shanghai Tower in the Lujiazui zone, this paper summarizes the optimization of key technologies of super high-rise buildings under the background of soft soil foundation. The author hopes to provide a clear reference for future projects by systematically sorting out the construction projects in this typical area.

Keywords: Super high-rise; soft soil foundation; steel pipe pile; underground diaphragm wall.

1. Introduction

As the world economy continues to grow, human production and construction activities are increasing day by day. The problem of land scarcity has emerged in important cities of many countries, with mega-cities in particular. Hence the concepts of "smart growth" and "compact cities" come into being [1]. With the advancement of technology, super high-rise buildings have gradually become one of the choices for urban development. Burj Khalifa Tower in Dubai with a height of 828m, Merdeka 118 in Kuala Lumpur with a height of 679m and Shanghai Tower in Shanghai with a height of 632m are all good examples. They can not only improve the quality of people's production and life but also meet the demands of people's material and spiritual civilization.

At the same time, when carrying out municipal construction, it is inevitable to encounter bad geological conditions, among which soft soil foundation is one of the geological types with a great threat. It will not only affect the construction of municipal engineering, resulting in safety accidents and quality hazards in the construction process but also affect the safety of municipal engineering after it is put into use, reducing the service life of municipal engineering. So far, many solutions have been developed to deal with soft soil foundations. General treatment methods of soft soil foundation in construction engineering include grouting construction technology, sand layer replacement and sandstone cushion, mixing pile technology, and drainage consolidation technology [2]. A study compares certain technologies applied in the Water conservancy project such as geopolymer treatment and vacuum preloading method by Zeng [3].

For super high-rise buildings, on the one hand, due to their huge volume, the final load transmitted to the foundation is much larger than that of general buildings, and on the other hand, the loads on the superstructure are more complex. Therefore, they have a higher dependence on a solid foundation, which also means that soft soil is a greater threat to the safety of super high-rise building construction. 1885 is believed to be the time when the world's first skyscraper was built. From then on, a large number of super-high buildings have been built, some of which are located in areas with soft soil foundations. For the reference for more construction in the future, there is still a lack of combing and research on the key technologies of super high-rise building construction under soft soil foundation. Therefore, the author supposes it is necessary to conduct related research on it.

Shanghai has a typical soft soil foundation and its foundation soil is very rich in water. Lujiazui Finance and Trade zone has been developing rapidly since the reform and opening up of China. Since the end of the 20th century, three super-high rises have been completed successively, which is a typical successful case in the field of geotechnical engineering. Because the construction time of the three buildings is different, the development level of construction technology and the specific engineering situation provide the ideal conditions to analyze the optimization of the key technologies of super high-rise buildings under the soft soil foundation. The main body of this paper will be divided into four parts. The first part is to introduce the engineering characteristics of soft soil foundation, and then the foundation construction schemes of Jinmao Tower, Shanghai World Center and Shanghai Center are analyzed in turn.

2. Engineering characteristics of soft soil

2.1. Physical properties of soft soil

Fine-grained soil with a natural pore ratio greater than or equal to 1.0 and natural water content greater than the liquid limit is considered soft soil, which includes silt, silty soil, peat, peaty soil,etc. [4]. Silt is clay that is deposited in still or slow-flowing water and formed by biochemical processes, whose natural water content is greater than the liquid limit and whose natural pore ratio is greater than or equal to 1.5. Silty soil refers to clay or silt whose natural water content is greater than the liquid limit and whose natural pore ratio is greater than or equal to 1.0 but less than 1.5. Peat is soil containing a large amount of undecomposed humus with organic matter content greater than 60%, while peaty soil ‘s organic matter content is greater than or equal to 10% and less than or equal to 60% [5]. With high natural water content and large pore ratio, soft soil shows the state of soft plastic to flow plastic in most cases. Furthermore, its high compressibility and low strength make unfavorable foundation conditions for construction on it [6].

2.2. Engineering problems on soft soil foundation

First of all, the soft soil foundation will cause excessive settlement deformation, and the settlement duration is relatively long [7]. When construction is carried out on a soft soil foundation, the foundation will settle after bearing large external force and load, and it will also appear obvious deformation, which seriously affects the safety and stability of the construction. As a result, the construction of this foundation may lose its use value. For instance, Kansai International Airport in Japan has witnessed much higher than expected settlement during construction and use, largely increasing the engineering cost and maintenance costs.

The second problem lies in the nonuniform settlement of the foundation, which will not only make the building inclined, but also increase the bearing capacity of the building resulting in cracks on the wall and floor [8]. If the difference is serious, it will cause the whole building to tilt affecting the normal function of the building and finally the safety of people's lives and property. Apart from these, the soft soil foundation is mainly distributed in layers and the thickness and depth are random in space. And the time effect of loading and unloading on soft soil is obvious. All of the above contributes to the great difficulties of buildings on a soft soil foundation.

However, the requests for the super high-rise building construction project highlight the negative influences of soft soil foundations. Firstly, the very high vertical pressure on the base raises the requirement of the bearing capacity of the foundation. Secondly, the response of super-tall buildings to wind loads and seismic effects is more significant than that of ordinary ones. It generates larger horizontal forces and moments in the foundation, decreasing the stability of the foundation against sliding and overturning [9]. Moreover, super high rises are also more sensitive to deformation, especially the tilt problem caused by nonuniform settlement, which will cause large horizontal displacement at the top of the structure and is likely to affect the use of equipment such as lifts and human comfort. As a result, it is of vital importance to find out the appropriate technologies for a super high-rise building construction on soft soil foundations.

3. Shanghai foundation background

This paper aims to take the Lujiazui area of Shanghai as an example to analyze the optimization of key techniques of super-high rise under the soft soil foundation. The first step is to know the local soil conditions. Shanghai lies at the mouth of the Yangtze River and is built on a flood plain, under which is more than 280m of soft soil [10]. Chinese geotechnical experts have used ‘tofu’ to describe the foundations of the Lujiazui area.

Its base soils are all Quaternary estuarine ~ coastal facies, coastal ~ neritic facies sedimentary layers, mainly composed of saturated cohesive soil, silty soil and sandy soil. The layers②～⑥ are clay layers with a moisture content between 23% and 48%, and the soil properties are relatively weak; Layer⑦ is a medium-dense ~ dense silty sand layer and silt layer; Layer⑧ that usually exists in Shanghai and should belong to silty clay is missing under this area; Layer⑨ is a saturated and dense sand layer. Layer⑦ is the first confined aquifer in the Shanghai area. The buried depth of the confined water level is 8.50 ~ 10.60m, and the water level is high from November to April and low from May to October. Because of the absence of Layer⑧, Layer⑦ and Layer⑨ are connected, which causes the water is extremely rich and the confined water head is high [11].

4. Case study

4.1. Jinmao Tower

Constructed since 1994 and opened in 1999, Jinmao Tower is the first of three super-high buildings in the Lujiazui area. Covering about 200,000 square meters, the main building of it has 88 floors with a height of 420.5 meters. At the time of its construction, it was the tallest building in China and the third tallest in the world after City Center Plaza in Kuala Lumpur, Malaysia and the Sears Tower in Chicago, USA. Therefore, both the soft soil foundation and the unprecedented height greatly increased the difficulty of construction. This section covers three techniques.

4.1.1 Underground Diaphragm Wall

At begin, special slotting equipment is used along the periphery of the support or deep excavation project to build the guide wall on the ground. Under the protection of a special mud wall, each excavation of a certain length of the groove should reach the specified depth. After the trough is cleared, the steel cage is hoisted into the trough, and then the underwater concrete is poured with the conduit method. The concrete is filled from the bottom and the mud is replaced from the trough, so a unit trough section is built. According to this process, these adjacent trough sections are built underground into a continuous reinforced concrete wall.

To explain this technique figuratively, if a sand pit is dug on the beach, the surrounding sand will immediately slide into it. The underground diaphragm wall is like a circle of plastic plates inserted in the sand which can block the surrounding sand from sliding down.

4.1.2 Full Cast-in-place Reinforced Concrete Support

In terms of the pit support design, the original plan by the US firm SOM was to use a diagonal anchor solution. Since this method was not mature enough to apply on the soft soil foundation and the construction cost was relatively high, it was abandoned at that time.

In the final support design, the construction of the main tower completely avoided the support system reaching the ground without obstruction. To be specific, four concrete diagonal supports are used in the tower pit and three concrete internal supports in the podium pit to create a large space for the tower foundation excavation, which not only reduced construction costs but also solved the problem of partitioning and phasing of the main building podium. This technique is of great significance in improving the stability of the foundation pit.

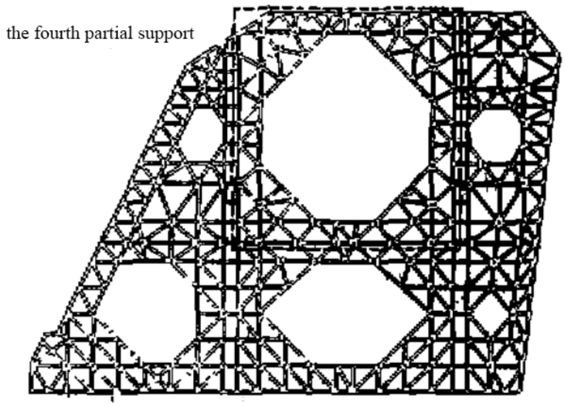

Fig. 1 The layout of the foundation pit support [12]

Figure 1 indicates how the project set the foundation pit support to ensure the main tower to reach the ground without the obstruction of support system.

4.1.3 Treatment of confined water

Although engineers had carried out sufficient investigation and analysis, there have been some accidents during the construction of the foundation pit of Jinmao Tower. Because a confined water observation hole did not do closed treatment, when pit excavation reached -17m, soil pressure reduced as the depth of excavation increased. As a result, the confined water of Layer ⑦2 developed from bubbling and seepage to a large quantity of water gushing phenomenon.

To deal with the accident, the first step is to use the bearing method to press the steel pipe close to the impermeable layer to insure a solid outer wall; that is followed by pressure density grouting around the surge water mouth to prevent the collapse during the sealing process; after the pressure-dense grouting reaches a certain strength and the water pressure value within the steel pipe is measured, the final step is to seal the mouth of the steel pipe, press barite powder slurry into the mouth, and quickly press the confined water into the impermeable layer, and then use cement slurry to seal the well.

When carrying out projects under complex conditions, techniques related to the treatment of emergencies are also worth studying and analyzing, which can guarantee safe and smooth construction.

4.2. Shanghai World Financial Center

The Shanghai World Financial Center, which opened in 2008, is a multi-functional skyscraper located in the Lujiazui Financial and Trade Zone. It has 101 floors above ground with a height of 492m and 3 floors underground. Due to the limited ability of high-strength prestressed concrete pipe piles to enter the dense sand layer and combined with the design and construction experience of the Jinmao Tower, the Shanghai World Financial Center Tower finally decided to use steel pipe piles.

4.2.1 Steel Pipe Pile

Steel pipe piles can withstand large impact forces, penetrate hard soil layers, and effectively drive into hard soil layers to obtain higher bearing capacity. When designing steel pipe piles, it’s necessary to focus on the feasibility of forming piles and supporting structural measures, calculation of occlusion effect bearing capacity, anti-corrosion requirements and durability measures.

Super high-rise buildings generally use open steel pipe piles. During the pile driving process, part of the soil at the end of the pile will pour into the pipe to form a ‘soil plug’. The height and occlusion effect of the ‘soil plug’ vary with many factors such as soil properties, pipe diameter, wall thickness, and the depth of the pile entering the bearing layer. Different occlusion degrees will lead to two different failure modes: soil plug punching failure at the pile end and punching failure of the foundation soil at the pile end. To explain this technique figuratively, if a sand pit is dug on the beach, the surrounding sand will immediately slide into it. The underground diaphragm wall is like a circle of plastic plates inserted in the sand which can block the surrounding sand from sliding down.

4.2.2 Pile foundation plane design

Combining soil conditions and load requirements, the final foundation construction plan for Shanghai World Financial Center Tower is: the central area adopts 225 steel pipe piles with a length of 60.7m and a type of ϕ700×18, the bearing layer is ⑨$_2$ gravel-bearing medium-coarse sand layer; the peripheral area uses 952 steel pipe piles with the length of 41.7m and the type of ϕ700×15, the bearing layer is ⑦$_2$ silt-fine sand layers. The base raft is designed with variable thickness. The thickness of the raft in the core tube area is 4.5m, and the thickness of the raft in the surrounding area is 4m.

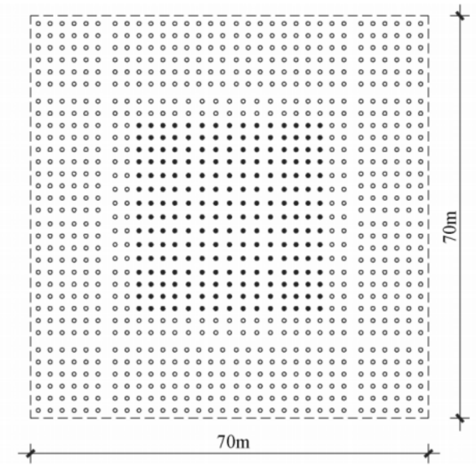

Fig. 2 Pile foundation plane layout diagram [13]

Figure 2 indicates the final construction scheme of Shanghai World Financial Center adopting steel pipe pile foundation.

4.3. Shanghai Tower

The Shanghai Tower project is also located in the core area of Shanghai Lujiazui Financial and Trade Zone. As the last completed super high-rise in Lujiazui, the main building of it has 127 floors above ground with a height of 632 meters. During the construction of its foundation pit, apart from its difficulties, engineers also need to ensure the safety of nearby super-high buildings. The collapse of the foundation pit caused by soft soil flow will bring an irremediable chain reaction.

4.3.1 Underground Diaphragm Wall

Like the Jinmao Tower, Shanghai Tower has also adopted the underground diaphragm wall, but its technique has been further optimized. Since the average specific penetration resistance of layer⑦2 is 26.91 MPa, the underground diaphragm wall with a depth of 50 m and a thickness of 1.2 m adopts the groove-forming process combined with grabbing and milling. The upper 30 m soil is directly grabbed by the real sand groove forming machine; after entering the depth below 30 m, it is milled by hydraulic groove milling machines. At the same time, the underground diaphragm wall adopts the locking pipe combined with the V-shaped steel plate joint, which can effectively reduce the pull-out resistance and prevent the concrete from flowing around.

In addition, some sleeve milling joints were made in the circular underground diaphragm wall of the main building. The process is to contruct the first-stage groove sections, then insert the second-stage groove section between the two first-stage groove sections, and use the groove milling machine to directly cut the concrete that has been formed into the groove section to form a joint which has a good water-stop effect. In this process, the joint box is eliminated, which can completely solve the hidden danger of concrete flow around.

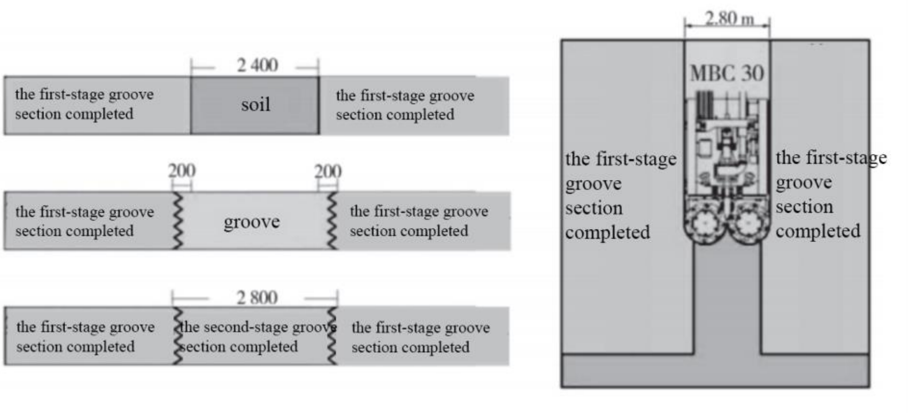

Fig. 3 Schematic diagram of milling construction technology for underground diaphragm wall sleeve [14]

Figure 3 indicates the process flow of underground diaphragm wall construction for Shanghai Tower.

4.3.2 Decompression and dewatering construction of tube wells

According to the existing construction experience, precipitation is a very important part of the large foundation pit construction in the Lujiazui area. There are 12 decompression and dewatering wells with a depth of 55m and 3 observation wells with a depth of 45m in the foundation pit; outside the foundation pit, the decompression and dewatering wells with a depth of 65 m and 55 m, each with 14 wells, are arranged at intervals. Moreover, in the process of decompression and precipitation, informatization construction is adopted. The operation plan can be adjusted at any time to meet the requirements of protecting the surrounding environment. The construction also adopts multiple power supply measures to ensure safety.

5. Conclusion

In the paper, it can be found that there are many difficulties in the construction of super high-rise building foundations when it comes to soft soil, and thus relevant technologies are constantly developing and improving. For example, according to the specific situation of the project, the construction scheme adopts a grouting pile or steel pipe pile, and although Jinmao Tower and Shanghai Center both use the underground diaphragm wall, the construction technology has been further improved. In addition, due to the large water content of soft soil, precipitation is of great significance in foundation pit construction. If the groundwater situation cannot be timely monitored, and confined water cannot be properly treated, it is extremely easy to cause engineering accidents, affecting the project safety and increasing the construction cost. Although accidents should be avoided as much as possible, emergency treatment techniques are also constantly improving.

This study also has some limitations. The author only chooses Shanghai as a representative area with a soft soil foundation, which may lack universality in the selection of some technologies. Some similar technologies are likely to choose when applied in the same area. Therefore, data from more areas of the world with similar geological settings should be further collected. Apart from this, despite rapid technological development, the three buildings in the Lujiazui zone were built close to each other in geological terms. Although it is first built, Jinmao Tower is barely more than 20 years old. According to the engineering characteristics of soft soil, it has an obvious time effect. The paper lacks some control techniques for the possible excessive settlement under long-term use.

In the future, more super-high buildings will be built, and the research on soft soil foundations will not stop. Combining the development of both, more advanced technologies will be explored. For super-high rises, safety is always the priority. However, the treatment of soft soil foundation often occupies a large part of the investment raising the cost to a large degree. It is hoped that future research can improve the economic benefits of construction projects while ensuring safety.

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