

Application and Development of the Super-large Diameter Column Foundation of Bridge

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Abstract. With the increase of span, the structural form of bridge foundation is seeking for development. The super-large diameter column foundation has become one of the best alternatives for bridge substructures. With the development of bridge foundation, the application status of the super-large diameter column foundation is combed. Its construction methods are briefly summarized, such as artificial digging, embedding prestressed pipe and super-large diameter bored pile, which promote the application of single column foundation. In the future, engineers can also get inspiration from the offshore wind turbine and seek new development ideas. Combined with the application of super-large diameter column foundation in the cross-sea bridge at home and abroad, the unique advantages and the problems needed to be solved in the practical application of the super-large diameter column foundation of bridge are pointed out, and its development is prospected.

1.Introduction

Column foundation of bridge includes pile-column foundation and pipe-column foundation, which are deep foundation. Pile-column foundation mainly refers to solid-pile foundation, which is usually constructed by digging and drilling. Pile-column foundation has the characteristics of high bearing capacity and wide application range. Pipe-column foundation mainly refers to hollow circular foundation, which contains prestressed concrete pipe-column and steel pipe-column. Pipe-column foundation has the characteristics of reducing masonry volume, improving construction quality and realizing prefabrication of factories, which is suitable for bridge site conditions such as deep water and undulating rock surface. In the bridge engineering, the foundation with diameter larger than 2.5m is generally defined as the large diameter foundation. But in order to realize the single-column foundation without cap for deep-water cross-sea bridges, the diameter usually reaches 4m or more, which is called "super-large diameter foundation". This paper introduces the development of super-large diameter column bridge foundation and briefly summarizes its construction methods. Combining with the application of super-large diameter column foundation in overseas and domestic bridges, especially the unique advantages of single-column foundation in practical application and the problems that need to be solved, the development prospects of it are prospected.

2.Development of super-large diameter column foundation

2.1. Pile-column foundation



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The diameter of the bored-pile foundation of the main bridge of the New Bayi Bridge in Nanchang, Jiangxi Province, which opened to traffic in 1997, reaches 4m^[1]. The layout of main bridge foundation caps of New Bayi Bridge in Nanchang is shown in figure 1^[2]. Since then, bored and cast-in-place pile foundation has been widely used in bridges in China. The main tower foundation of Poyang Lake Bridge built in 1999 is super-large diameter bored piles with rock-socketed depth of 7m^[3].

Because of the difficulty, the high risk and the high cost of underwater construction of cap, engineers in China have developed the technology of composite section pier without cap, which has been first developed and applied on land and cross-river bridges. In 1986, a new concept of variable cross-section pile-column foundation without cap was put forward for Jiujiang Bridge in Guangdong Province. After many engineering practices, in 1991, Xiangtan Second Bridge realized the use of single row piles with super-large diameter column without cap, which diameter reached 5.0m, as shown in figure 2^[4, 5].

2.2. Pipe-column foundation

During the construction of Wuhan Yangtze River Bridge in 1953, Chinese pioneered the construction method of pipe-column foundation. In 1958, the pipe-column foundation was applied to the new bridge of Zhengzhou Yellow River Bridge, and its diameter increased to 3.6m. In 1993, the Yabadu Bridge in Hunan Province adopted a variable cross-section of single pipe-column foundation structure with diameter of 3.8m/3m. In 1995, the Taoyuan Yuanshui Bridge adopted two separated non-capped pipe-column foundation with a maximum diameter of 7.5m, as shown in figure 3^[6].

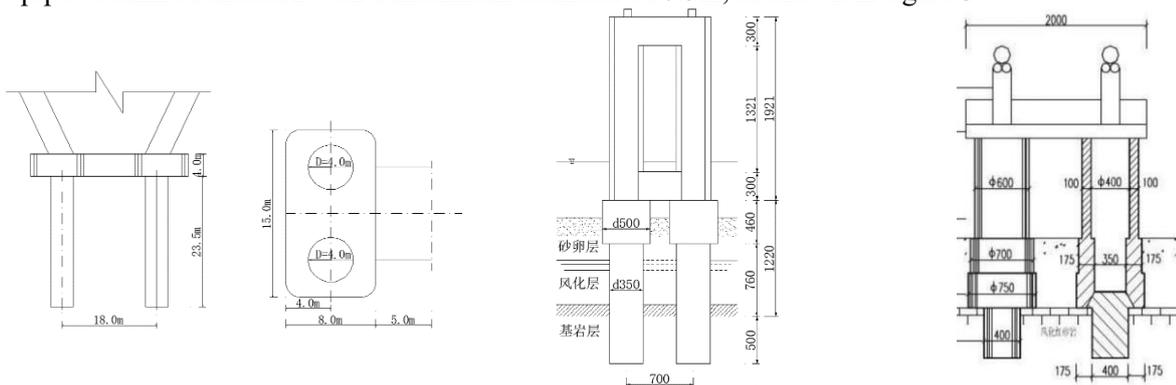


Figure 1. Layout of main bridge foundation cap of New Bayi Bridge

Figure 2. Pile-column foundation of Xiangtan Second Bridge

Figure 3. Pipe-column foundation of Taoyuan Yuanshui Bridge^[6]

2.3. Brief summary of column foundation engineering application

Super-large diameter column foundation is widely used in bridge engineering in China, and it has good prospects for development. The application of super-large diameter column foundation is summarized as shown in table 1.

Table 1. Column foundation of super-large diameter bridge

Bridge Name	Construction Time	Bridge Type	Maximum Span /m	Bridge Width /m	Type of Foundation	Pile Diameter /cm	Pile Length /m
Jiujiang Bridge	1988	cable-stayed bridge	160	16	bored pile-column foundation without cap	φ 300/250/200	70
Xiangjiang Second Bridge	1992	continuous beam	90	20	bored pile-column foundation without cap	φ 500/350	18
Yuanshui Bridge	1991	continuous beam	140	16	bored pile-column foundation without cap	φ 400/350	12
Yabadu Bridge	1993	continuous beam	30	12	buried pipe-column foundation without cap	φ 380/300	35
Nanhuadu Bridge	1994	cable-stayed bridge	50	17	buried pipe-column foundation without cap	φ 300/250	35
Shiguishan Bridge	1994	continuous rigid frame	80	12	buried pipe-column foundation without cap	φ 500/400	40
Qiushui	1994	double curved arch	54	12	digged pipe-column	φ 600/300	12

Bridge		bridge			foundation without cap		
Lugu Bay Bridge	1994	stone slab ribbed arch bridge	48	21	digged pile-column foundation without cap	φ 510/500	24
Taoyuan Yuanshui Bridge	1995	arch bridge	108	17	digged pile-column foundation without cap	φ 750/600	20
Tongling Yangtze River Bridge	1995	cable-stayed bridge	432	23	bored pile-column foundation without cap	φ 460/400/280	108
New Bayi Bridge	1997	cable-stayed bridge	160	26	buried pipe-column foundation	φ 450/400	17
Guanyin Bridge	1998	stone slab ribbed arch bridge	52	21	digged pipe-column foundation without cap	φ 500/400	10
Xiangjiang South Bridge	1998	continuous beam	85	24	digged pile-column foundation without cap	φ 350/280/180	18
Poyang Lake Bridge	1999	cable-stayed bridge	318	27.5	buried pipe-column foundation	φ 500/400	37
Tianma Bridge	2000	continuous beam	75	26	digged pile-column foundation without cap	φ 800/600	17
Wuliting Bridge	2003	tied arch bridge	120	30	buried pipe-column foundation without cap	φ 400/560/350	11
Tianxinzhou Bridge	2009	cable-stayed bridge	504	27	buried pipe-column foundation without cap	φ 450/400	60

3. Construction technology of super-large diameter column foundation

The construction technology of column foundation of bridge in China has made a series of breakthroughs in construction machinery and methods since 1950s. For the super-large diameter column foundation, some construction technologies have been developed, such as artificial digging, embedding prestressed pipe, sinking and digging pipe, super-large diameter bored pile.

3.1. Technology of artificial digging

The cost of artificial digging method is low, which does not need large-scale machinery and equipment. It not only can be easy to guarantee the construction period and construction quality, but can meet the construction requirements of complex stratum environment^[7, 8].

In 1997, the main pier of Xiangjiang South Bridge in Changsha adopted two variable cross-section large diameter column foundations by digging^[8, 9]. At present, the largest diameter of artificially excavated column foundation of bridge in China is the super-large diameter pipe-column foundation of Shenzhen Bridge with a diameter of 15 m, as shown in figure 4^[10].

3.2. Technology of embedding prestressed pipe

The super-large diameter drilled-embedded single pipe-column foundation eliminates the large volume of cap concrete which is difficult to construct., which combines the advantages of bored pile and prefabricated pile. It can not only effectively prevent the collapse of holes in the process of bored pile formation, but also avoid the difficulty of driving prefabricated pile or the excessive deviation of piling. Segmental prefabrication of pipe string can realize factory construction.

As the representative of the super-large diameter drilled-embedded single pipe-column foundation, the diameter of the single pipe-column foundation of the navigation hole of Shiguishan Bridge in Changde, completed in 1994, reaches 5m, as shown in figure 5^[6].

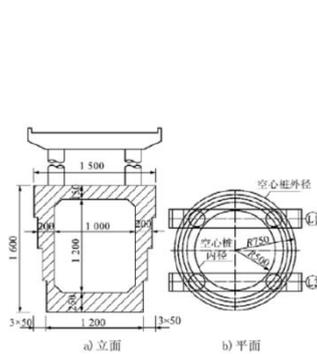


Figure 4. Super-large diameter pipe-column foundation of Shenzhen Bridge^[10]

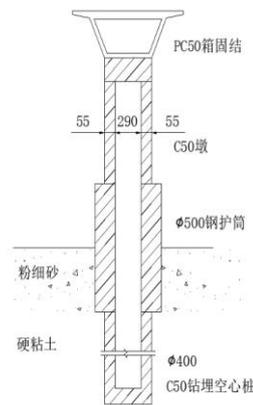


Figure 5. Single pipe-column foundation of Shiguishan Bridge

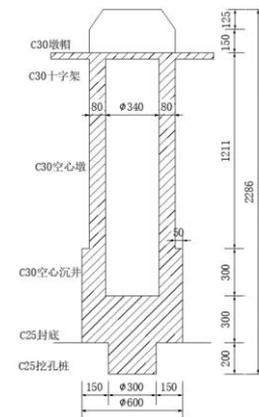


Figure 6. Vertical profile of sinking pipe foundation of Qiushui Bridge

3.3. Technology of sinking and digging pipe

The technology of sinking and digging pipe is a bridge foundation construction technology which combines the traditional construction methods of caisson and hole digging. It has the characteristics of simple technology, short construction period and material saving, which is suitable for all kinds of long-span bridge foundations^[11]. This technology was applied in the Guanyin Bridge in Zhangjiajie in 1995 at first, and has been developed on many cross-river bridges. The foundation design of the overbank platform of the Qiushui Bridge completed in 1994 adopts the super-large diameter light circular caisson with a height of 6 m, an outer diameter of 6 m and an inner diameter of 3.4 m. The caisson connects with the super-large diameter pipe-column, which outer diameter is 5 m, forming a variable cross-section large-diameter sinking-pipe-column foundation, as shown in figure 6^[12].

3.4. Technology of bored pile

Super-large diameter bored pile-column foundation has the advantages of large bearing capacity of single pile, short construction time, safety and reliability. The main pier of Tongling Yangtze River Bridge in 1995 was designed as a bored pile-column foundation with a diameter of 4.6m/4.0m/2.8m. Wuliting Bridge, which has a span of 120 m and a width of 30 m, adopts the super-large diameter and variable cross-section bored pile-column foundation of 4 m/5.6 m/3.5 m, as shown in figure 7^[13].

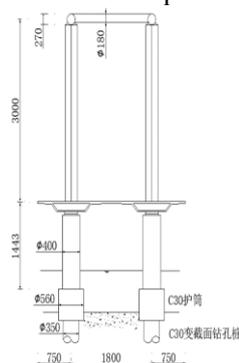


Figure 7. Super-large diameter bored pile foundation of Wuliting Bridge

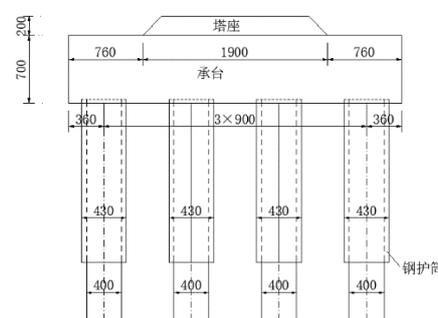


Figure 8. Main pier foundation of Puqian Bridge^[14]

4. Application of super-large diameter column foundation in cross-sea bridges

With the renewal of construction equipment and the improvement of construction methods, the application of super-large diameter column foundation has gradually developed from bridges in land and rivers to deep-water bridges in the ocean, which the diameter and length are also increasing. The

bored pile-column foundation not only has a good adaptability to marine hydrological and geological environment, but has a wide application range and good seismic effects. The main pier of the Puqian Bridge in Hainan Province in the complex marine environment of strong wind and corrosiveness adopts group-pile foundation, under which 16 variable cross-section super-large diameter bored pile-column foundations of 4.3m are connected, as shown in figure 8^[14].

In recent years, it has been widely used in large-scale cross-sea bridges and has broad prospects for development. The approach bridge in water area of Jiashao Bridge, which was completed in 2013, adopts the structure form of super-large diameter bored single-column foundation, as shown in figure 9^[15-18]. Its piers and piles are directly connected without caps or tied beams, mainly in order to adapt to the complex hydrological conditions in the bridge site, to reduce the water resistance of piers and the risk of ship collision. It also try not to damage the landscape of tidal in Qiantang River.

The Yushan Bridge, a branch project of the main channel of Zhoushan Port in Ningbo, has 153 single-column piles with super-large diameter and variable cross-section. The diameter of the piles varies from 2.2m to 5m. The substructure of non-navigable holes of Yushan Bridge is shown in figure 10. Pile-column foundation of Yushan Bridge is mostly composite steel pipe, which means when bored cast-in-place pile is constructed, steel retaining barrel is not only a hole-forming protective measure, but also a part of pile foundation to bear load. Composite steel pipe was proposed in the construction of Hong Kong-Zhuhai-Macao Bridge, which has a good flexural capacity and large bearing capacity with simple construction technology. In recent years, it has been widely used in pile foundation engineering of cross-sea bridge and deep-water port^[19].

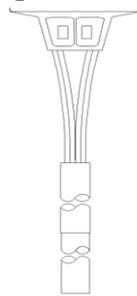


Figure 9. General structural sketch of single-column pier of Jiashao Bridge

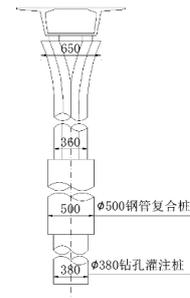


Figure 10. Non-navigable hole lower structure sketch of Yushan Bridge

Super-large diameter column foundation has also been successfully applied in overseas cross-sea bridge projects, among which the Federal Bridge in Canada and the Rion-Antirion Bridge in Greece are the most representative. The Federal Bridge, completed in 1997, is the longest bridge in Canada and the longest bridge in ice water in the world. The bridge has 65 single-tubular foundations with a diameter of 10m, as shown in figure 11. The foundation is assembled by segmental prefabrication, as shown in figure 12^[20]. Prefabricated assembling not only avoids site construction in bad environment, but can guarantee construction quality and shorten construction period. Because the bridge located in ice water, it is easy to be affected by drift ice. The column foundation is designed with a conical steel shield below the average sea level of 4m to 2.6m above, in order to reduce the impact of drift ice^[21].

Rion-Antirion Bridge in Collins Bay, Greece, opened to traffic in 2004, is located in the earthquake area with magnitude 7. Because the water depth of the bridge site is 65m, and the seabed soil condition is poor, the whole bridge adopts floating concrete structure. The seabed is strengthened by 200 hollow steel pipe networks with the length of 30 m and the diameter of 2 m. The foundation is isolated from the seabed and becomes a sliding foundation, as shown in figure 13^[22]. Rion-Antirion Bridge adopts super-large diameter hollow single-tubular column foundation. Four high-strength reinforced concrete columns at the main tower incline toward the center, which are connected at the top of the main tower to provide sufficient stiffness to withstand asymmetric operation load and seismic force. Rion-Antirion super-large diameter hollow column foundation is shown in figure 14^[23].

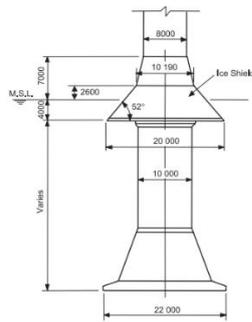


Figure 11. Single-tubular foundation of Federal Bridge

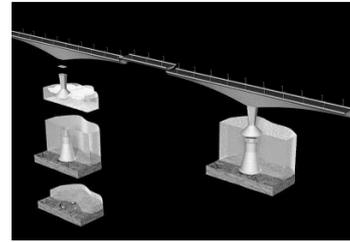


Figure 12. Prefabricated assembly diagram of foundation of Federal Bridge^[20]

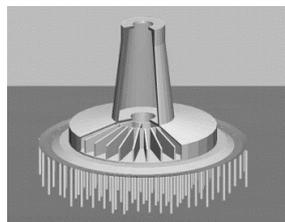


Figure 13. Sliding foundation of Rion-Antirion Bridge



Figure 14. Super-large diameter hollow single-tubular column foundation of Rion-Antirion^[22]

5. Development of super-large diameter column foundation

Super-large diameter column foundation is widely used in land and cross-river bridges, which construction technology is relatively mature. For deep-water cross-sea bridges, the natural environment and geological conditions are more complex and harsher. More harmful factors, such as ship collision and earthquake, need to be considered. Super-large diameter single column foundation structure is novel, simple and beautiful. It has strong adaptability to geological conditions, large flexural rigidity and high stability. It cancels complex cap construction and reduces underwater volume, thus reducing the risk of ship collision. At present, the bridge foundation is developing towards a larger, deeper and more economical direction. In recent years, the super-large diameter single column foundation and bored cast-in-place composite steel pipe foundation, which are used in the cross-sea bridge engineering, have good prospects for development.

Root foundation is a new type of variable cross-section foundation. It reserves jacking holes in pile foundation or sidewall of caisson, then pushes prefabricated roots from reserved holes into soil layer, and forms a kind of bionic foundation similar to tree roots after ensuring the close consolidation of root keys and sidewall^[24]. Because of the compaction and stress diffusion of the push-in key, the bearing capacity of surrounding soil and the bearing capacity of foundation is greatly improved^[25]. After the root foundation was put forward, experiments and applications are carried out in Huai River Bridge, Ma'anshan Yangtze River Bridge, Wangdong Yangtze River Highway Bridge and Chizhou Bridge. The anchorage foundation of Chizhou Yangtze River Bridge is composed of 16 large diameter hollow root-piles and caps. The outer diameter of the hollow root-pile is 5m, the length of the pile is 26m and the wall thickness is 0.9m. The construction schematic of root-pile and root-key is shown in figure 15. Compared with the traditional pile-column foundation, the root foundation improves the bearing capacity of the foundation. However, the pile, the root-key and the soil constitute a more complex interaction system^[26], which requires engineers to carry out research in depth.

With the increase of power generation of offshore wind turbines in China, the application of large diameter single-pile foundation in offshore wind turbines is becoming more and more common, which has great reference significance and reference value for the design and construction of pile-column foundation of deep-water cross-sea bridges. The common foundation forms of offshore wind turbines are gravity foundation, cylindrical foundation, single-pile foundation, three-pile foundation, jacket foundation and so on^[27]. Among them, the super-large diameter single-pile foundation structure is

simple in form, clear in force, and fast in construction, which accounts for more than 65% of wind farms at home and abroad^[28]. Single-pile foundation in wind turbines is suitable for many kinds of soil seabed conditions with water depth less than 25m. For example, the surface silt in Bohai Sea and some parts of East China Sea is thinner, where steel pipe-column or bored pile-column foundation can be used. The diameter of a single-pile in China's offshore wind turbines can reach 7m, and the burial depth is generally 20m-40 m^[29]. In 2016, the design of Rudong 150 MW offshore wind turbines in Zhongguang Nuclear Power Station is based on single-pile foundation structure. The diameter of steel pipe is between 6 m and 6.7 m, and the length is between 75 m and 94 m, as shown in figure 16. The construction of super-large diameter single-pile foundation of Rudong 150 MW offshore wind turbines in Zhongguang Nuclear Power Station is shown in figure 17^[30]. The sliding foundation of Rion-Antirion Bridge is reinforced by hollow steel pipe network, which is similar to the tubular foundation of offshore wind power structure to some extent. Thus, the development of single-pile foundation in design and construction of offshore wind turbines can provide innovative ideas and feasible schemes for super-large diameter column foundation of deep-water bridges.

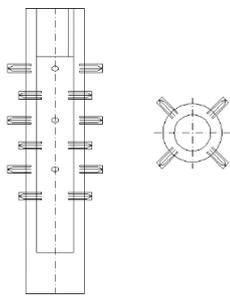


Figure 15. Diagram of root-pile and root-key



Figure 16. Foundation of Rudong 150 MW offshore wind turbine



Figure 17. Construction of single-pile foundation^[30]

6. Problems to be solved for super-large diameter column foundation

Although super-large diameter column foundation is more and more widely used in engineering, its theoretical and experimental research is still in the initial stage. Its design and calculation methods and construction methods are not perfect. Especially in the application of super-large diameter column foundation in cross-sea bridges, there are many problems to be solved.

With the increase of diameter and length of pile, construction equipment and technology are facing many difficulties and challenges. For example, in the process of super-large diameter pile foundation, with the increase of diameter, the unstable factors of wall increase. The pore-forming resistance increases in series, which puts forward higher requirements for technology^[31]. Complex natural conditions such as tides, strong winds and waves have brought many new problems to construction of bridge foundation. Up to now, there is no complete sets of key technologies for design and construction of steel-pile foundation in marine environment^[14].

For the super-large diameter column foundation in cross-sea bridges, considering the long-term action of wind, wave and other loads, the horizontal cyclic loading characteristics are remarkable, which will produce cyclic cumulative deformation and cause adverse effects on the foundation^[32]. However, there is no unified recognition of the response characteristics of super-large diameter piles under horizontal cyclic loading, and there is a lack of a widely accepted design calculation method^[33].

Super-large diameter single-column pile in cross-sea bridges need to consider the damage caused by strong tide, drifting ice or ships, which requires high strength of pile. In recent years, composite steel pipe is a better foundation form. However, the research at home and abroad does not involve the role of mud, anti-corrosion coatings and shear rings embedded in steel pipes. The existing research results are not fully applicable to the complex pile foundation engineering of cross-sea bridges^[34]. In addition, the problem of anti-corrosion and anti-collision of steel casing needs further study by researchers.

When the seabed is cohesionless soil, the soil around the column foundation is prone to scour under the action of wave and current, which greatly weakens the bearing capacity of pile foundation^[29].

In recent years, the impact of scouring on the horizontal bearing capacity of pile foundation has gradually attracted the attention of engineering. The specific stress conditions of super-large diameter column foundation need to be further studied by engineers.

7. Conclusion

Bridge engineering needs continuous innovation in order to have better progress and development. Super-large diameter column foundation, especially single column foundation, has its unique advantages for deep-water cross-sea bridges with complex environment. It has been widely concerned by academia and engineering, and there are many successful application cases at home and abroad. The development of construction methods such as technology of sinking pipe and technology of super-large diameter bored pile have further promoted the application of super-large diameter single column foundation. In the future, engineers can also get inspiration from the offshore wind turbine and seek new development ideas. Generally speaking, the super-large diameter column foundation has become one of the best options for deep-water bridges and has broad prospects for development.

Acknowledgments

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