A new type of PHC pile-sinking technology: Drilling with PHC Pipe Cased Pile and its development directions

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Abstract. Pile foundation has unique advantage in reducing the settlement of the upper structure and improving the foundation bearing capacity, while Drilling with PHC Pipe Cased Pile (DPC Pile) is a newly developed non-extruded soil PHC tubular pile which integrates drilling-pile sinking-dumping simultaneously to solve the pile sinking problem of large diameter (800 ~ 1400mm) pipe pile. It solves the problem of pile sinking caused by large pile diameter or hard soil layer, breaks the situation that the pipe pile foundation can only be limited to small diameter and size, and broadens the applicable scope of engineering geology of pipe pile. It realizes the full rock-socketed of the pile tip (which can enter the middle and weak weathering stratum), improves the bearing capacity of single pile, and gives full play to the advantages of pipe pile material with higher strength. It has little damage to the pipe pile and little noise, being relatively environmentally friendly, as well as plays a major demonstration role in leading the new direction of the development of green, energy-saving and environmental protection pile foundation, conforming with the advanced development trend of upgrading traditional advantageous industries to high-tech manufacturing and construction technology with promising market.

1. Introduction
Pile foundation is a base form with high bearing capacity, wide application scope and long history, of which the upper load is transmitted to the soil layer with good bearing capacity deep underground through pile foundation, so as to meet the requirements of bearing capacity and settlement. Meanwhile, pile foundation can bear horizontal load, the uplift load, and the vibration load, being widely used in high-rise buildings, ports, bridges and other projects\textsuperscript{(1)}.

The present commonly used form of pile foundation are bored pile and PHC pipe pile, with reaching over 3000mm grouting pile diameter of the former one, which can regulate the pile diameter to meet the needs of different projects on the bearing capacity, whereas hole collapse are easily encountered in construction with this pile type to cause hard control of the quality of pile body and the environment and underground water pollution by a large number of sludge discharge from adopting the slurry supporting\textsuperscript{(2-3)}; prestressed high strength concrete pipe pile (PHC pipe pile) overcome the problems as pollution of the bored piles and hard control of the quality of the bored piles, however,
being limited by construction technique of hammering method or the static pressure method, the application of the PHC pipe pile is 300 ~ 600 mm in diameter, of which the smaller diameter may become an obstacle for it to be the main force of the large and medium-sized port wharf and high-rise buildings and other large projects\cite{4,5}.

PHC pipe pile has outstanding advantages in pile forming speed, environmental protection, mechanized construction speed, site management and quality stability, etc., in order to promote the industrial application of large diameter of which, Chinese scholars took the lead in developing complete sets of equipment and construction technology for Drilling with PHC Pipe Cased Pile\cite{6,7}. Successful development of Drilling with PHC Pipe Cased Pile solves hard problem of pile sinking caused by large diameter of pile and hard soil layer, gives full play to the advantages of pipe pile material with high strength, being environmental friendly, and conforms with advanced development trend of traditional advantage industry upgrading to high-tech manufacturing and construction technology, possessing wide market prospect.

2. Construction Technology of DPC Pile

DPC Pile\cite{8,9} is a new type of large-diameter (800 ~ 1400mm) non-extruded PHC pipe pile which integrates drilling-pile sinking-dumping simultaneously, whose construction characteristics are shown in Figure 1, being able to realize simultaneous drilling-pile sinking-dumping through the following steps:

1. As shown in Figure 1b, funnel pile boots are welded at the bottom of PHC pipe pile to squeeze the soil around the pile into the internal cavity of the pile pipe and bring it out of the ground.

2. As shown in Figure 1c - Figure 1e, the extendable-retractable bit is connected with the long auger drill pipe, that the bit and pipe can enter the soil layer through the pipe pile cavity when the bit is in the retractable state; Thereafter, the drill bit extends, and drill with the extending drill bit through the long auger pipe. The drill hole diameter is about 20mm larger than the external diameter of PHC pipe pile, which ensures that PHC pipe pile will sink synchronously with the drill bit in the case of low pile sinking resistance, with the residue being brought out to the ground through spiral blades in the internal cavity of the pipe pile, so as to reach simultaneous drilling, pile sinking and dumping, and to the design depth of the pipe pile by means of pile extension. After the construction, retract the bit and reverse the drill pipe to exit the pipe pile.

3. Since the diameter of the drilling hole is about 20mm larger than the external diameter of the PHC pipe pile, there is no direct contact between the pipe pile body and the soil, but to form a circular columnar clearance with a thickness of about 10mm between the hole wall and the external wall of the PHC pipe pile, as shown in Figure 1g and Figure 1h, that grouting at the pile side should be carried out through the grouting pipe embedded in the pipe wall of the pipe pile to fill the annular gap and bond the soil at the pile side.

The construction technology of DPC Pile solves the problem of pile sinking caused by large pile diameter or hard soil layer, breaks the situation that the foundation of pipe pile can only be limited to small diameter and size, broadens the application scope of engineering geology of pipe pile, realizes the full rock-socketed of the pile tip (which can enter the middle and weak weathering stratum), and improves the bearing capacity of a single pile by the end-bearing force of the pile end rock-socketed and the frictional resistance of the cement grouting at pile side, so as to give a full play to the advantages of pipe pile material with higher strength. This construction process synchronizes drilling, pile sinking and soil dumping to reach a fast construction speed, brings little damage to the pipe pile without using mud protection, hammering and static pressure, enjoys little noise, being relatively environmentally friendly, as well as plays a major demonstration role in leading the new direction of the development of green, energy-saving and environmental protection pile foundation, conforming with the advanced development trend of upgrading traditional advantageous industries to high-tech manufacturing and construction technology with promising market.
3. Research progress of DPC Pile

In 2007, Tang Mengxiong team\textsuperscript{[10]} of Guangzhou Institute of Building Science Co., LTD. proposed the concept of Drilling with PHC Pipe Cased Pile (DPC Pile for short), describing in detail about the design method, construction process and the performance advantages of the DPC Pile. After more than ten years of development, a wealth of achievements have been made with the representative achievement is as follows: Based on theoretical analysis and experimental research, Tang Mengxiong\textsuperscript{[11]} proved, in the aspects of cracking moment, tensile resistance and clamping force, that it is feasible to remove the hoop in the design and manufacture of DPC pile; Chen et al\textsuperscript{[12]} introduced the whole set of construction technology and equipment of large-diameter DPC pile, finding that, through field test, DPC pile of rock-socketed and grouting at pile side possessing obvious advantages in bearing capacity, which is closely related to grouting effect and formation modulus; Tang et al\textsuperscript{[13]}, through field test and finite element analysis of bearing capacity of DPC pile, studied the shear failure characteristics of slurry-soil contact interface and deformation characteristics of pile side soil to reveal the bearing mechanism of DPC pile, finding that the load redistributed in the slurry-soil system when grouting after DPC pile, so as to improve the bearing capacity greatly; Zhao Fan\textsuperscript{[14]} developed the DPC pile boot device and the quick connection device, designed the physical simulation test of the vibration table of the DPC pile, and studied the anti-seismic performance of the DPC pile; Yang Xiaosong\textsuperscript{[9]} carried out field tests on the vertical compressive bearing capacity of DPC pile to find out that the maximum ultimate bearing capacity could reach 1.7 times that of the cast-in-place or driven piles of the same diameter kind; He Song et al\textsuperscript{[5]} revealed the action mechanism of DPC pile-soil contact surface, and clarified the failure mode of the failure surface located in the grouting-soil layer to obtain the shear strength parameters of the contact surface; Hu Hesong et al\textsuperscript{[15]}, with considering the influence of grouting in pile-soil structure layer on up-directed critical stress ratio based on the grouting physical model test of DPC pile, constructed a stress-strain equation of modified Cambridge model that can describe strain softening. Q-S curve on DPC pile site shows\textsuperscript{[16]} that the bearing capacity of the DPC pile is obviously better than that of the cast-in-place pile and the prestressed pipe pile under the same conditions, whose grouting effect at the pile side determines the pile side friction and ultimate bearing capacity to a certain extent.
4. Development tendency of DPC pile

4.1. Research and development of quick joint with sealing function

As shown in Figure 2, at present, welding method is usually used to connect the ring-shaped connecting plate of two pipe piles when connecting with DPC pile, whose welding quality depends on the skill level of technicians, taking a longer time (generally more than one hour); the high temperature around the welding seam in welding weakens the mechanical properties of the adjacent concrete and do harm to the anti-corrosion treatment of metal parts; high-temperature weld is easy to be quenched and brittle on meeting groundwater, while enough time is needed to cool down, that all these problems will seriously affect the service life [17] of pipe piles. The present existing mechanical quick joint possesses a complicated structure with high cost, easy-corroded and damaged of internal spring, and no sealing function, that may lead leak at the pile side when DPC pile is used for grouting, and sets expansion head usually, which increases the resistance to pile sinking and causes inconvenience to construction [18]. Therefore, it is of great importance to develop a mechanical pipe pile connection device with using sleeve, bolt and anchoring reinforcement, which should be economical, practical and be with sealing function to ensure the rapid mechanical connection of two large-diameter pipe piles to improve the construction efficiency, as well as to ensure the good sealing performance of the joint position after connection to avoid the groundwater, slurry injection etc. outside of the pipe pile entering the internal cavity to result in failure of grouting and core-filling.

![Figure 2 The connection of two pipe piles (ring disc plate)-welded connection](image)

4.2. Research and development of quick joint with sealing function

As shown in figure 3, steel pile boots with high strength are usually fixed on the end plate by welding in order to improve the penetration power of pile body and reduce the resistance of pile sinking when use DPC pile, so that the welding quality is hard to control. Meanwhile, the construction period is often prolonged to ensure enough cooling time to avoid quenching and embrittlement, which may lead difficulties in corrosion treatment of steel material in the complex underground environment, so as to affect the durability of the pipe pile foundation. Therefore, it is of great importance to develop a kind of concrete pile boots that are manufactured and maintained simultaneously with pipe piles to overcome the existing problems such as high cost of steel pile boots, difficulty in ensuring welding construction quality, long construction period and poor durability.
4.3. Quantitative characterization of grouting material

As shown in Figure 4, grouting is obtained after excavation of soil mass through the indoor physical model test of pile side grouting of DPC pile, while the size and quantitative characterization in 3D space of which is greatly crucial to evaluation of grouting effect and the improvement of grouting technology and parameters. Therefore, it is suggested in this paper that high-precision 3D scanner can be used to scan the grouting material obtained after excavation of soil, and multi-frequency phase-grating technology with external interpolation method can be used to quickly acquire the point cloud data of the grouting material with large area of high resolution, so as to obtain 3D coordinate data and spatial point position information of the grouting material to quantitatively characterize the roughness, 3D geometric dimensions (including length, width, thickness, quantity, area, volume, etc.) and spatial distribution morphology of the slurry veins in the grouting root system, and to quantitatively compare the grouting effects and optimize the grouting technology and parameters.
4.4. Visual analysis of slurry flow process
Because visualization physical model test of the pile side grouting of DPC pile can intuitively observe and record the flow diffusion process of the grout, this paper suggests, when conducting physical model test of the grouting, that the front of the model box can be transformed into high strength transparent glass, choosing transparent acrylic tube or transparent PVC tube as the model pile, setting up 3D scanner and high-speed camera at the side of the transparent glass to observe and record the flow process and related parameters of slurry in the pile-soil annular gap through transparent pile, so as to realize visualization analysis of progressive flow process of pile side grouting.

4.5. Method for measuring the physical and mechanics parameters of grout
At present, methods for testing grout expansibility, resistance to water dispersion, microscopic creep characteristics, slurry time-varying characteristics, slurry filtration characteristics and slurry stability are not so mature, failing to reach a consensus in the industry, that related test equipment are in urgent need to be researched and developed to reach a consensus in the industry, forming a series of test standard, so as to carry out comparison and analysis of physical and mechanical properties between different materials.

4.6. Theoretical analysis of slurry flow diffusion
In case of pile side grouting of DPC pile, the slurry flows vertically along the annular clearance, and diffuses radially to the soil along with the radial direction at the same time, that not a single set of flow diffusion theory of pile side grouting of DPC pile about this has been formed till now, therefore, this paper suggests: analyze relationships of vertical height, radial diffusion radius and grouting pressure, flow rate and quantity, soil permeability coefficient, etc. of different flow type slurry in the “pile-soil annular gap” to deduce the mechanics equation about flow diffusion of pile side grouting of non-extruded soil PHC pipe pile, establish the flow diffusion mechanics model of pile side grouting and fracture mechanics criterion, and study the influence of key grouting parameters on the flow diffusion law of pile side grouting, so as to provide theoretical guidance for pile side grouting of DPC pile.

4.7. Research and development of technology of DPC pile side grouting
The DPC pile technology is too unique to form a special grouting process till now, and the composite grouting process is found to possess certain advantages in DPC pile grouting through comparative analysis, with ultrasonic vibration being helpful to the grout flow diffusion, therefore, the paper boldly suggests that joint grouting process of ultrasonic vibration grouting and static pressure grouting is a good choice, and a part of negative pressure grouting after extraction of pile-side soil air can be considered in the stratum with great difficulty of grouting.

4.8. Research and development of grouting materials
According to the construction technology characteristics of the DPC pile side grouting, in order to improve the grouting effect and further increase the pile side friction resistance, grouting material ratio is optimized through carrying out orthogonal tests, based on cement slurry with adding the expansion agent, water reducer, early strength agent, etc., focusing on the physical and mechanical properties of different grout, such as fluidity, expansibility, early strength, grout-soil bonding strength, slurry groutability and water resistance dispersion, etc., to develop a series of grouting materials suitable for different stratum environments and different types of overburden soil, so as to carry out piecework grouting for different stratum.

5. Conclusion
(1) DPC Pile is a newly developed non-extruded soil PHC tubular pile which integrates drilling-pile sinking-dumping simultaneously to solve the pile sinking problem of large diameter (800 ~ 1400mm) pipe pile. It solves the problem of pile sinking caused by large pile diameter or hard soil layer, breaks
the situation that the pipe pile foundation can only be limited to small diameter and size, and broadens the applicable scope of engineering geology of pipe pile.

(2) DPC pile realizes the full rock-socketed of the pile tip (which can enter the middle and weak weathering stratum), and improves the bearing capacity of a single pile by the end-bearing force of the pile end rock-socketed and the frictional resistance of the cement grouting at pile side, so as to give a full play to the advantages of pipe pile material with higher strength.

(3) The construction technology has little damage to the pipe pile and little noise, being relatively environmentally friendly, as well as plays a major demonstration role in leading the new direction of the development of green, energy-saving and environmental protection pile foundation, conforming with the advanced development trend of upgrading traditional advantageous industries to high-tech manufacturing and construction technology with promising market.

(4) At present, as to DPC pile, important research progress has been made in the aspects of construction technology, complete set of construction equipment, bearing mechanism, precise pipe pile manufacturing, anti-seismic performance, bearing performance of core-filled pipe pile, feasibility analysis of removing casing collar, and shear failure mechanism of slurry-soil contact interface.

(5) Research and development of quick joint with sealing function, quantitative characterization of grouting material, visual analysis of slurry flow process, method for measuring the physical and mechanics parameters of grout, theoretical analysis of slurry flow diffusion and so on will tend to be the future development direction.

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