

Innovative installation techniques for PHC piles

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ABSTRACT: The high population density in Hong Kong necessitates the adoption of heavy infrastructures and high-rise buildings for public and private uses. These heavy infrastructures and high-rise buildings require the support of pile foundations. Among different pile types, the prestressed spun high strength concrete (PHC) pile is probably the most economical. Moreover, it has a smaller carbon footprint than the steel H-pile of comparable design load-carrying capacity. Installation of PHC piles by percussion is probably the most economical. However, noise, vibration and air pollution problems are often inseparable from percussion of piles. Innovative installation techniques for PHC piles to achieve environmental friendliness, quality and rapid construction, and economy are always in demand. Depending on geologic conditions, different innovative installation techniques for PHC piles have been developed and these techniques are presented in this paper.

1 INTRODUCTION

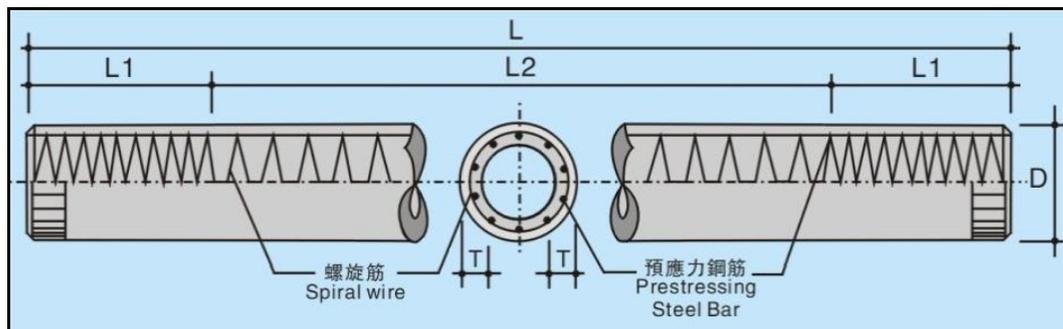
The total area of the Hong Kong Special Administrative Region (HKSAR), China is 2,755km², including 1,104km² of land and 1,651km² of sea. Hong Kong is accommodating a population of approximately 7.1875 million as of mid-2013 and one of the most important financial and trading centers in the world. The average population density of the HKSAR is 6,650 persons/km² as of mid-2013. However, most of the population is being housed in 215km² of urban development because of steep natural terrain and stringent planning controls. Over 400km² have been designated as protected areas including country parks, special areas and conservation zonings. As a result, the most densely populated District Council district is Kwun Tong with a population density of 57,120 persons/km². The high concentration of population and economic activities in such a small area exert an intense demand for infrastructures to sustain the rapid growth of Hong Kong. The demand necessitates the adoption of heavy infrastructures and high-rise buildings for public and private uses. These heavy infrastructures and high-rise buildings require the support of pile foundations. Most of these pile foundations are constructed in the vicinity of commercial and residential activities. Innovative installation techniques for piles to achieve environmental friendliness, quality and rapid construction, and economy are thus always in demand. Innovative techniques for the installation of Prestressed spun High strength Concrete (PHC) piles are presented in this paper.

2 THE USE OF PHC PILES IN HONG KONG

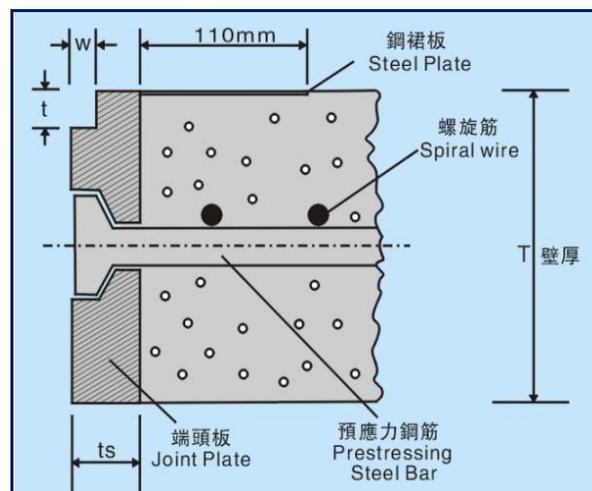
PHC piles are typically manufactured by spinning wet concrete in a formwork with pre-tensioned wires installed. The compressive strength of concrete is approximately 80MPa. The tensile strength of pre-tensioned wires is approximately 1,420MPa. The outer diameter of the pile D varies from 300 to 600mm and the thickness T varies from 70 to 130mm as shown in Figure 1. The design load-carrying capacity of the pile is thus ranging from 900 to 3,500kN. Therefore, many choices of different piles of different design load-carrying capacities are available to satisfy foundation needs. Piles are connected by welding the steel joint plates together to the required total length.

PHC piles are historically known as Daido piles in Hong Kong although the name may be technically incorrect. The original Daido piles were made in Japan where they are installed as replacement piles, as they are inserted into prebored holes followed by grouting of the annular void space between the pile and the prebored hole. However, they are installed by driving in Hong Kong. Since the method of installation has been changed, construction problems such as damage of pile shoe, crushing of concrete near the pile tip, damage of pile head, occurrence of tensile cracks in the pile etc., arise in Hong Kong. Later, Daido piles were manufactured in Hong Kong and similar piles of lower quality manufactured in mainland China also enter the market, resulting in more construction problems due to poor quality unanticipated by the original Daido pile designer. As a result, the use of PHC piles in Hong Kong has diminished for more than a decade.

Recently, the advantageous use of PHC piles in karst formation has stimulated new interest in the use of PHC piles in Hong Kong. However, these piles are still installed by percussion, resulting in noise, vibration and other construction problems, although air pollution problems have been alleviated by the use of hydraulic hammers. It is evident that there is a need for innovative installation techniques for PHC piles in Hong Kong.



(a) Pile details



(b) Joint details

Figure 1 Details of the PHC pile

3 ADVANTAGES AND DISADVANTAGES OF PHC PILES

The design load-carrying capacity of the PHC pile is comparable to that of the steel H-pile. It should be noted that the design load-carrying capacity of a PHC pile of 600mm in diameter and 130mm thick is approximately 3,500kN, similar to that of a Grade 55C 305×305×223kg/m steel H-pile. Moreover, the PHC pile have these advantages over the steel H-pile of similar design load-carrying capacity:

- a) The material cost of steel H-pile is approximately HK\$1,200/m while that of PHC pile is approximately HK\$600/m. Assuming the required pile length is similar, the cost/ton of support load of the PHC pile is approximately a half that of the steel H-pile. Typically, the required length of the PHC pile is shorter than that of the steel H-pile to achieve the similar design load-carrying capacity on site, as the side resistance normally developed along the shaft of the PHC pile is higher than that of the steel H-pile.
- b) The bearing stress at the tip of the PHC pile is smaller than that of the steel H-pile as a result of larger bearing area and higher side resistance. Therefore, the PHC pile is particularly useful in areas of karst formation in Hong Kong, such as Yuen Long and Tin Shui Wai, for reduction of foundation stress exerting on the marble rockhead.
- c) Taking a carbon footprint of $(0.76 \text{ ton CO}_2)/(\text{ton of structural steel})$ and $(0.155 \text{ ton CO}_2)/(\text{ton of reinforced concrete})$, the carbon footprint of the steel H-pile is 0.17 ton CO₂/m and that of the PHC pile is 0.07 ton CO₂/m. Use of more PHC piles can be a significant contribution by the construction industry towards a cleaner and more sustainable environment.
- d) There are many high quality PHC pile manufacturers in the vicinity of Hong Kong. It is much easier to satisfy the material requirements of LEED or BEAM by using PHC piles than using steel H-piles in terms of carbon footprint and transport distance of construction materials. Shortening of transportation distance contributes indirectly to the reduction of fossil fuels and air pollution.

Although PHC piles can be cut on site to suit ground conditions, the cut PHC piles cannot be reused, resulting in the generation of construction waste. However, PHC piles are manufactured in different lengths. If the founding level can be reasonably predicted prior to installation, the quantity of construction waste so generated can be minimized.

4 INNOVATIVE TECHNIQUES FOR THE INSTALLATION OF PHC PILES

Depending on ground conditions, three experience-proven installation techniques for PHC piles with minimal vibration and noise are now available on the market. These techniques are presented in the order of the status of acceptance in Hong Kong herein:

4.1 *Prebored Rock Socketed PHC Piles*

When the rockhead is shallow, the design load-carrying capacity of the PHC pile can be derived economically from a rock socket, similar to the prebored rock socketed steel H-pile. A pile bore is prebored to rockhead with the borehole wall supported by a temporary steel casing. A rock socket is drilled using a drilling bit system that can go through the temporary steel casing and extend at the bottom of the temporary steel casing. The structural element of the pile is inserted after cleaning of the pile bore. The pile is grouted while the temporary steel casing is extracted. For the prebored rock socketed steel H-pile, the structural element is the steel H-pile so that it is inserted to the bottom of the rock socket. For the prebored rock socketed PHC pile, the structural element has two components, i.e. the portion above the rock socket and the portion in the rock socket. The portion above the rock socket is a conventional PHC pile. However, the portion in the rock socket warrants a different design to ensure the design load-carrying capacity of the pile can be derived from the bond strength between the pile and the vertical cylindrical surface of the rock socket. Three different types of rock sockets, i.e. Types A, B and C, are depicted in Cheung et al. (2012). All the three different rock socket details use a structural component welded to a 50mm thick steel capping plate which is welded to the steel joint plate at the tip of the PHC pile. Type A rock socket component uses a pre-fabricated

reinforcement cage welded to a annular steel capping plate. Type B uses a steel H-section welded to a solid capping plate. Type C uses a pre-fabricated reinforcement cage welded to a solid steel capping plate. A bundle of 50-mm diameter high yield reinforcement bars are inserted into the central hollow space of the PHC pile to the bottom of rock socket for Type A and to the solid steel capping plate for Types B and C to maximize the design load-carrying capacity of the pile.

In Hong Kong, the pile drilling machine for the construction of prebored rock socketed steel H-pile is used for the construction of prebored rock socketed PHC piles, i.e. pile bore of diameter 610mm. As a result, only PHC piles of diameter 500mm and thickness 100mm or 125mm can be inserted into the steel temporary casing. Moreover, 8 50-mm diameter reinforcement bars can be inserted into the hollow space of the 100-mm thick PHC pile and only 7 can be inserted into the 125-mm thick pile, resulting in a design load-carrying capacity of approximately 5,000kN which is comparable to a Grade 55C 305×305×223kg/m steel H-pile. The pile type is recognized by the Buildings Department (BD) of the HKSAR Government as Rock Penetration Composite Piles Types I to III after a successful field test performed in 2006. The new pile type with Type A rock socket component was later successfully adopted to support a church building in Hung Shui Kiu, Yuen Long (Cheung et al. 2012). In Macau, a larger pile drilling machine was used for a school project so that temporary steel casings of 714 mm in diameter could be used to accommodate 600-mm diameter PHC piles. As a result, the design load-carrying capacity of the pile well exceeds that of Grade 55C 305×305×223kg/m steel H-pile at a considerable lower material cost.

4.2 *Jacked PHC Piles*

Jacked piles were originally developed for underpinning and foundation remediation works (White, 1975; Tomlinson and Woodward, 2014). Piles are jacked into the ground continuously by a hydraulic jacking system. The pile installation technique has been widely and routinely adopted in many Asian economies such as China, Japan, Singapore, Malaysia etc. (Li et al., 2003; Li, 2011; Li et al., 2011; 廣東省土木建築學會, 2012). The technology is also known as press-in technology in Japan where extensive research has been conducted by the industry. The International Press-in Association (IPA), an academic organization supported by Giken Seisakusho Co. Ltd. of Japan, was established on 16th February 2007 in Cambridge, England to explicate the underground phenomena and mechanisms encountered by the press-in technology in close coordination with various technical fields such as civil, construction, environmental, geotechnical, instrumentation and mechanical engineering. Financial support is provided to researchers in the form of IPA Research Awards. The author has received three of these research awards. Moreover, technical seminars are organized worldwide biannually to disseminate new developments of the technology.

Jack piling has many advantages over pile driving. No noise or vibration is generated by the jacking process. As a result, there is practically no limitation on operation hours, resulting in a considerably higher daily production rate than that of pile driving. The hydraulic system is powered by electricity and no black smoke due to incomplete combustion of diesel is generated. Therefore, most adverse impacts of pile percussion on the nearby environment or sensitive receivers are eliminated. The technique makes it possible to install piles in close proximity of existing buildings or sensitive site areas such as underground structures of the subway system (Yeung, 2013). Jack piling is more cost effective and environmentally friendly. In practice, driven piles are often over-driven to ensure the required design load-carrying capacity can be achieved, resulting in unnecessarily longer piles. Jacked piles are hydraulically jacked to the target design load-carrying capacity with no unnecessary extra penetration, resulting in considerable savings in material, labor costs and construction time. More importantly, every jacked pile is fully load tested during construction for better quality assurance. For PHC piles, as no tension is generated in the pile during jacking, gas arc welding can be used to connect sections of pile, resulting in a significant reduction in construction time and potential damage to the pile. Many construction problems associated with percussion of PHC piles are also eliminated.

As the load-carrying capacity of the pile is increased, the reaction weight required is increased proportionally. The dead weight of the pile jacking machine for the installation of piles of design load-carrying capacity of 3,500kN is approximately 10,000kN. Therefore, the technology is not

applicable for construction sites of small footprints and/or steep terrain, as it is very difficult to maneuver such a large and heavy pile jacking machine under these circumstances.

Steel H-pile is a small displacement pile and PHC pile is a large displacement pile. Therefore, their engineering behavior is not the same, resulting in differences in the construction equipment and procedure, and termination criteria. Moreover, all the potential disadvantages of displacement piles have to be carefully considered and necessary precautions for proper installation of piles have to be taken during construction.

In Hong Kong, applications of jacked piling are limited to steel H-piles and steel sheetpiles to date (Yeung, 2002; Yue and Ho, 2002; Li et al., 2003; Yang et al., 2006; Li et al., 2011). However, jacking of PHC piles is very common in Macau and China (Yeung and Li, 2012).

4.3 Prebored PHC Piles

The technique of installing PHC piles by preboring was introduced to Macau from Japan where the technique was developed. The technique is basically a combination of ground improvement and pile installation. A specialized equipment combining an auger and a soil mixer as shown in Figure 2 is penetrated into the soil to break up the soil to the required depth by an electric motor. A minimal amount of soil is removed during the process. During withdrawal of the equipment, base-forming and side-forming fluids are injected into the soil and mixed well with the soil to increase the tip and side resistance of the soil. The combined auger and soil mixer has to travel up and down a few times during the process.



Figure 2 Auger and mixer used for pile installation



Figure 3 Mechanical splicing of PHC piles

After the combined auger and mixer has been withdrawn, a 12-m long PHC pile is sunk into the liquefied soil by its self-weight. No pile shoe is necessary for the installation. As the PHC pile is hollow, some of the liquefied soil would fill the central hollow space of the pile and overflow. Therefore, the amount of soil displacement generated by the insertion of the pile is minimal, in particular when the surrounding soil is already liquefied by the installation process. The pile is technically a non-displacement pile.

PHC piles are mechanically spliced by screws. The required tightening torque exerted on the screws is measured by a torque meter. The screw tightening sequence is also clearly indicated as shown in Figure 3 and it is strictly followed on site. The quality control and assurance of the mechanical splicing are thus significantly better than welding and no testing of the splicing is required afterwards, so as to shorten the time required for splicing. After the last PHC pile has been installed, the PHC pile is screwed into the ground by the electric motor through the use of a specifically designed helmet. The installation process is complete after the soil has been cured to the required strength. The technology has been applied successfully for the foundation construction of a secondary school in Macau.

The complete construction process is recorded automatically by an on-board computer in real-time for quality control and assurance. The movement of the auger head, the amount of base forming fluid

used, the amount of side-forming fluid used etc. are recorded automatically and continuously as a function of time. Typical construction records for a prebored PHC pile are shown in Figure 4.

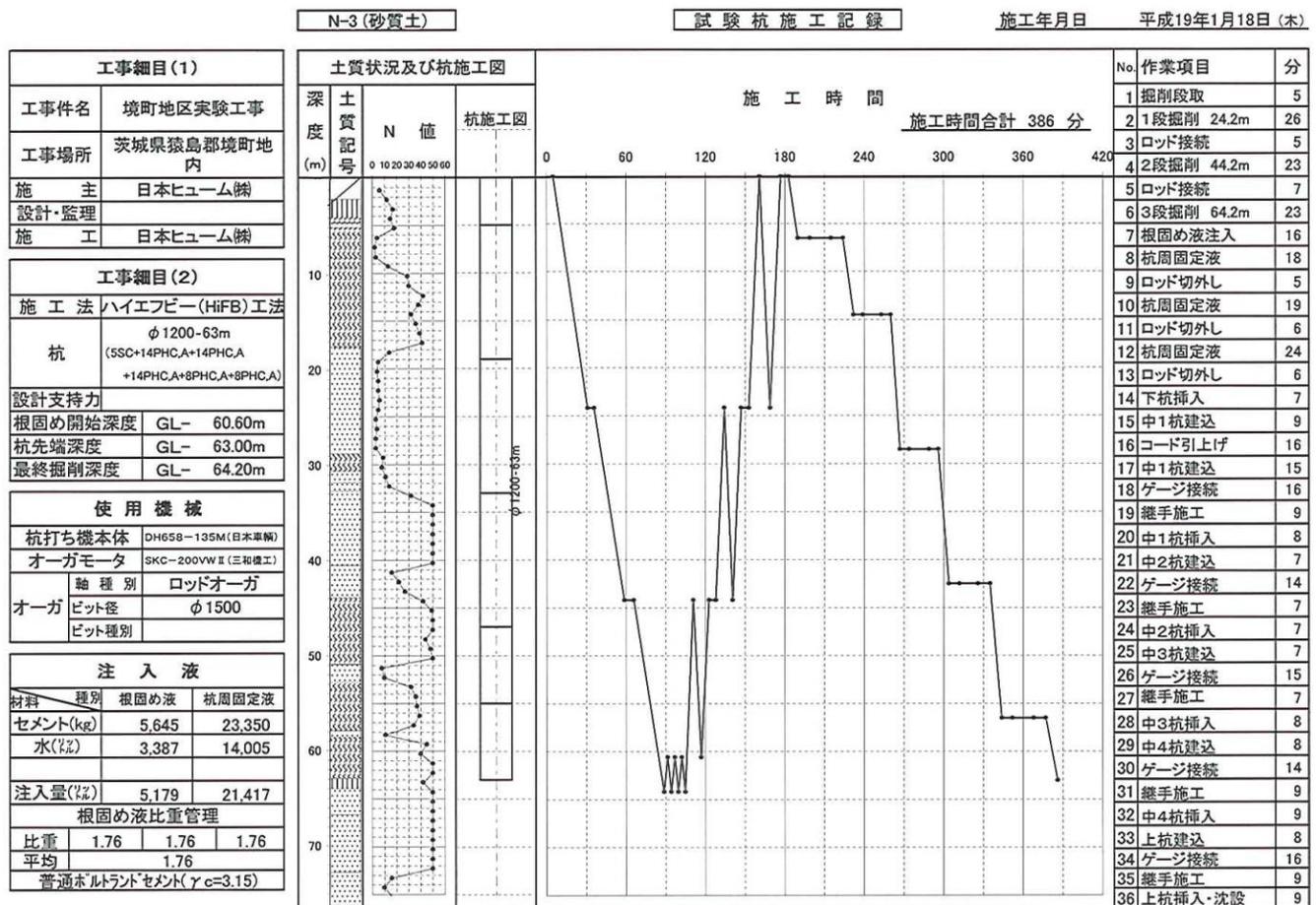


Figure 4 Typical construction records of a prebored PHC pile (in Japanese)

5 OBSTACLES TO INNOVATIONS

The obstacles to innovative technologies in geotechnical works in Hong Kong were identified and frankly voiced by Li and Lo (2012) as follows: (1) government over-control; (2) McDonaldization of university research and teaching; (3) McDonaldization of consulting services; (4) protection of self-interest; and (5) human psychological barrier to innovations. All these obstacles are probably equally applicable to innovations in all other disciplines of civil engineering.

At the time of writing, the prebored rock socketed PHC pile is already a pile type recognized by the BD of the HKSAR Government after a successful field test of the new pile type in 2006 (Cheung et al., 2012). The new pile type was later successfully adopted to support a church building in Hung Shui Kiu, Yuen Long (Cheung et al., 2012). The current non-technical obstacle is the human psychological barrier of the BD approving officer and that of the foundation designer for public works to this new pile type. However, the maximum design load-carrying capacity of the pile is currently limited to 5,104kN on the basis of the pile configuration used in the test pile program, which was a 500-mm diameter PHC pile with a bundle of 50-mm diameter high yield reinforcement bars in the central hollow space of the pile. In Macau, one hundred three (103) prebored rock socketed PHC piles were successfully constructed using 600-mm diameter PHC piles to support a new school building. The maximum design load-carrying capacity of the pile is 6,412kN which is very competitive to the Grade 55C 305×305×223kg/m steel H-pile. Therefore, the remaining hurdle is to overcome this unnecessary bureaucratic obstacle on the technical issue of allowable design load-carrying capacity.

Although the technology of jacking steel H-piles was introduced to Hong Kong approximately 17 years ago (Yeung, 2002, 2014; Li et al., 2003) and it has been employed by a number of public development projects (Chan et al., 2002; Li et al., 2003), it is still not a pile type generally recognized by the BD of the HKSAR Government. Its use for private development projects is being approved on a project by project basis. Jacked steel H-piles have been approved for use in only one private development project in Tai Po to date. The proposal of trying jacked PHC piles for the project was rejected by the BD on the ground that there was no such past experience in Hong Kong. However, thousands of 600-mm diameter PHC piles have been successfully installed by jacking for casino and resort projects in Macau (Yeung and Li, 2012; Yeung, 2014), not to mention even more were successfully completed in mainland China and many other Asian economies. Such ground of rejection is a classic example of unnecessary government bureaucratic over-control and government officers' lack of ability to think out of the box. If there is no trial on a new technology, there will be no approval. When there is no approval on the new technology, there will be no past experience. When there is no past experience of the new technology, there will be no trial on the new technology. This vicious and hopeless circle of arguments will never lead to any technological breakthrough. The implementation of the proven and environmentally friendly technology of jack piling is practically hindered by bureaucratic government procedures.

Prebored PHC piles have not been introduced to Hong Kong yet. However, obstacles for its implementation in Hong Kong are predictable from the terrible past experience of jacked PHC piles. Hopefully it will not take fifteen years to get the first project approved by the BD.

Quality control and assurance of PHC piles may be another obstacle, as there are too many manufacturers of variable quality in the market. It is not an easy task to confirm all the PHC piles in a particular shipment are from the same manufacturer due to the complicated transportation logistics. However, such problems can be easily solved by tracking each pile in real time by the use of a RFID embedded in the pile and a global positioning system (GPS) in conjunction with the internet. The tracking technology is readily available.

The supply of PHC piles in Hong Kong is practically a closed market as controlled by the listing system of the BD. The system may function as quality control and assurance measures if pile quality is being monitored regularly. Unfortunately, this is not the case. There are listed PHC pile manufacturers which have gone out of business for quite some time and the BD has no knowledge about it. Although there is a stringent application procedure to be listed, there is no regular monitoring of the performance of the manufacturers on the list. Poor manufacturers are giving PHC piles a bad reputation, rendering another unnecessary obstacle for the use of PHC piles in Hong Kong. The obstacle can be easily overcome if the BD has a quality monitoring and registration renewal system in place.

The increase in concrete strength or diameter for the PHC pile may require many rounds of bureaucratic approval procedures which may become a deterrent to the development of new technology and/or new high strength material.

6 CONCLUSION

The foundation is one of the most important structural components critically impacting the engineering performance of an infrastructure or a high-rise building. The pile foundation is the most common foundation type for heavy infrastructures and high-rise buildings in Hong Kong. The material cost of the PHC pile is considerably lower than that of the steel H-pile. Moreover, the carbon footprint of the PHC pile is smaller than that of the steel H-pile. If innovative techniques can be developed for efficient and quality installation of PHC piles, the use of PHC piles can be more efficient, economical and environmentally friendly than those of other pile types. Three different experience-proven innovative installation techniques have been presented in this paper. Moreover, obstacles to the implementation of these techniques in Hong Kong and solutions to overcome some of these obstacles are also presented. It is evident from many successful case histories that there are no insurmountable technical obstacles for the implementation of these innovative technologies in Hong

Kong, although there may be some solvable technical issues to be overcome. However, most obstacles arise from administrative blockades imposed by the HKSAR Government. Therefore, it is a matter of the determination of the HKSAR Government to implement these cost-effective, efficient, quality assured and environmentally friendly PHC pile installation techniques in Hong Kong.

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