Installation of Prestressed Spun High Strength Concrete Piles by Hydraulic Jacking

Albert T. Yeung
University of Hong Kong, Hong Kong Special Administrative Region, China

ABSTRACT

The technique of hydraulic jacking has been applied to install prestressed spun high strength concrete PHC) piles in Macau. It should be noted that PHC piles are significantly cheaper than steel H-piles of comparable load-carrying capacities. PHC piles also have a lower carbon footprint than steel H-piles. The Macau experience will be presented in detail in this paper to introduce this pile installation technique, and to demonstrate how this technique can reduce material and construction costs, reduce construction time, increase environmental friendliness, improve site quality control and reduce construction risk. The limitations of the technique will also be presented. Moreover, the engineering performance of PHC piles installed by this technique deduced from full-scale maintained pile load tests will be presented. Lastly, the obstacles to the introduction of this cost-effective, efficient and environmentally friendly pile installation technique to Hong Kong will be discussed.

1 INTRODUCTION

Pile foundations are often required to support tall buildings and heavy infrastructures necessary to accommodate the rapid economic and population growth of Hong Kong. The common types of piles being used in Hong Kong include large-diameter bored piles, barrettes, steel H-piles, prestressed spun high strength concrete pipe piles (PHC piles) and mini-piles. The construction of large-diameter bored piles, barrettes and mini-piles requires excavation, installation of a reinforcement cage and *in-situ* concreting or grouting. The construction process is thus quite involved. Prefabricated piles, such as steel H-piles and PHC piles, are typically installed by preboring or percussion. The construction of a prebored socketed steel H-pile requires preboring, insertion of a steel H-pile, grouting and removal of casing. PHC piles are seldom installed by preboring in Hong Kong. Again, the construction process is quite involved. Installation of these prefabricated piles by percussion is most economical if the geological conditions are favorable. However, the construction method inevitably induces vibration, noise and air pollution problems despite of the stringent environmental requirements promulgated by the Hong Kong SAR Government. The limits on pile driving hours promulgated by the noise permit system operated by the Environmental Protection Department may reduce the adverse noise impact to sensitive receivers. The use of hydraulic hammer may alleviate the air pollution problem. However, the vibration problem remains. From a geotechnical standpoint, the founding conditions of a driven pile are not fully revealed. Although every driven pile is accepted using the Hiley formula in Hong Kong, there is no guarantee on its engineering performance, in particular its load-carrying capacity and the load-settlement characteristics. In fact, the engineering performance of a driven pile has to be evaluated by a pile integrity test, a pile dynamic analysis and/or a full-scale pile load test. Because of cost and time implications, these tests cannot be applied to every pile in a project. The energy impacted on a pile by the pile integrity test is probably inadequate to penetrate the full length of the pile. Therefore, the test is probably inappropriate for the evaluation of the founding conditions of the pile. Typically, pile dynamic analyses are performed on approximately 10% of the piles installed and full-scale pile load tests are performed on 1% of the piles installed. Therefore, there is a significant possibility that defective piles are not identified. The technique of hydraulic jacking can rectify most of these environmental problems and quality control problems. In this paper, the background of jacked piles is given. The experience of installing PHC piles by hydraulic jacking in Macau is also presented.

2 JACKED PILES

The technique of jacked piles was developed in the U.S., primarily for underpinning of existing structures (White 1975). The technique was later developed in China, Japan, Singapore, Malaysia and Australia as a pile installation method (Lam & Li 2003; Li 2011; Li et al. 2003). On February 16, 2007, the International Press-in Association, an academic organization with support from Giken Seisakusho Co., Ltd. of Japan, was established in Cambridge, England to explicate the underground phenomena and mechanisms encountered by the press-in technology in close collaboration with various technical fields such as civil, construction, environmental, geotechnical, instrumentation and mechanical engineering. Research awards are being granted to researchers worldwide to develop a better understanding of the technology. However, the progress on wide application of the technique in Hong Kong is extremely slow (Li & Lam 2011). Although the technique has been adopted for the successful installation of steel H-piles in a few public projects, the Buildings Department, i.e. BD, has approved only one private project at Fung Yuen, Tai Po using thirty-one (31) jacked steel H-piles to date (Li et al. 2011; Yeung & Li 2012). Moreover, the procedures approved for the quality control of the installed piles are extremely stringent, making the installation technique not very efficient or cost-effective. The approved design load-carrying capacity of these steel H-piles is similar to that of driven steel H-piles even the piles are not driven, rendering the installation method economically less attractive (Li & Lam 2011).

The installation technique has been applied to install PHC piles in Macau. It should be noted that the material cost of PHC piles is significantly cheaper than that of steel H-piles of comparable load-carrying capacities. PHC piles also have a lower carbon footprint than steel H-piles The Macau experience will be presented in detail in this paper to introduce this pile installation technique, and to demonstrate how this technique can reduce material and construction costs, reduce construction time, increase environmental friendliness, improve site quality control and reduce construction risk. The limitations of the technique will also be presented. Moreover, the engineering performance of PHC piles installed by this technique deduced from full-scale maintained pile load tests will be presented. Lastly, the obstacles to the introduction of this cost-effective, efficient and environmentally friendly pile installation technique to Hong Kong will be discussed.

3 STEEL H-PILES VERSUS HIGH STRENGTH CONCRETE PIPE PILES

Both steel H-piles and PHC piles are commonly used in Hong Kong while PHC piles are commonly used in Macau. A brief comparison of these two types of piles is given to facilitate further discussion.

3.1 Steel H-piles

Steel H-piles commonly used in Hong Kong are Grade 55C 305×305×149 kg/m, 305×305×180 kg/m or 305×305×223 kg/m and their design load-carrying capacities are 2,451 kN, 2,958 kN and 3,677 kN, respectively, as the design compressive stress of the steel H-piles is limited to 30% of the yield stress of steel to control the driving stress during percussion.

3.2 PHC piles

PHC piles are historically known as Daido piles in Hong Kong although the nomenclature may be technically incorrect. The original Daido piles were made in Japan where they are installed as replacement piles, as they are placed into prebored holes followed by grouting of the annular void space between the pile and the cylindrical vertical walls of the prebored hole. However, Daido piles are installed by percussion in Hong Kong. Since the installation method of Daido piles has been changed, construction problems, such as damage of pile shoe, crushing of concrete near the pile tip, damage of pile head, development of tensile cracks in the pile etc., occur in Hong Kong. Daido piles were later manufactured in Hong Kong and manufacturers of piles of lower quality from mainland China also enter the Hong Kong market, resulting in more construction problems unforeseen by the original Daido pile designers.

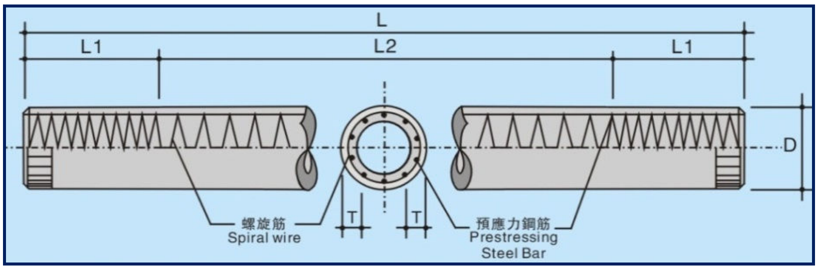
Although BD enlists approved manufacturers, the quality of piles is only evaluated during the application process for inclusion on the list but not on a regular basis afterwards. Any subsequent deterioration of manufacturing quality has never been monitored. The loop hole has been manipulated by some unethical mainland China pile manufacturers. Some of these enlisted manufacturers have already closed their business for years but they maintain their presence in the market as BD enlisted manufacturers, resulting in market monopoly by a few dominating market players who may not be able to produce high-quality PHC. As a result, PHC piles have become less popular for more than a decade in Hong Kong due to a series of unfortunate events in construction sites in Tin Shui Wai, Tung Chung etc. However, the use of PHC piles in Hong Kong has been rejuvenated recently.

Precast prestressed concrete piles are manufactured in different shapes and sizes. The most common type being used in Hong Kong and Macau is the tubular PHC pile as shown in Figure 1. They are manufactured by spinning wet concrete in a formwork with pre-tensioned wires installed. The compressive strength of the concrete and the tensile strength of the pre-tensioned wires are approximately 80 MPa and 1,420 MPa, respectively. The outer diameter of the pile D varies from 300 mm to 600 mm and the thickness T varies from 70 mm to 130 mm. The design load-carrying capacity of the pile is thus ranging from 900 kN to 3,500 kN.

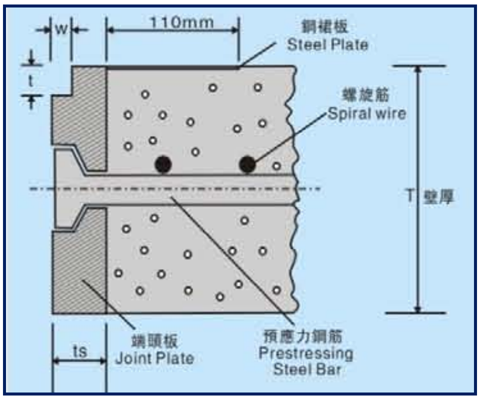
3.3 Material cost

An accurate comparison on the material costs of different types of piles can only be made on piles of similar design load-carrying capacities. The comparison is thus made on Grade 55C 305×305×223 kg/m steel H-pile and Type AB-130 PHC pile with D = 600 mm and T = 130 mm to Chinese Standard GB13476-2009. The design load-carrying capacities of the two types of piles are both approximately 3,500 kN.

The unit material costs of the steel H-pile and the PHC pile are approximately HK$1,200/m and HK$600/m, respectively. If the required lengths of the piles are similar, the cost/tonne of support load of the PHC pile is thus approximately a half that of the steel H-pile. The length required to achieve the same design load-carrying capacity for the PHC pile is in general shorter than that for the steel H-pile, as the side resistance developed along the length of the PHC pile is normally higher than that of the steel H-pile. The PHC pile is thus particularly useful in karst formation areas of Hong Kong to reduce foundation stress exerting on the marble rockhead. However, it should be noted that the masses per unit length of the PHC pile and the steel H-pile are 0.499 and 0.223 tonne/m, respectively. The transportation cost of the PHC pile is thus approximately twice that of the steel H-pile and the transportation logistics are more complicated.



(a) Pile details



(b) Joint details

Figure 1: Details of the PHC pile

3.4 Carbon footprint

Taking a carbon footprint of 0.76 tonne CO_2 per tonne of structural steel, the carbon footprint of the Grade 55C 305×305×223 kg/m steel H-pile is thus

$$0.76 \times 0.223 = 0.17 \text{ tonne of } CO_2 \text{ per m of steel H-pile} \tag{1}$$

Similarly, taking a carbon footprint of 0.155 tonne CO_2 per tonne of reinforced concrete, the carbon footprint of the Type AB-130 PHC pile of D = 600 mm and T = 130 mm is thus

$$0.155 \times 0.499 = 0.077 \text{ tonne of } CO_2 \text{ per m of PHC pile} \quad (2)$$

It is demonstrated that the use of more PHC piles can be a significant contribution by the construction industry towards a cleaner and more sustainable environment.

3.5 *Proximate availability of PHC piles*

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 the use of PHC piles than that of steel H-piles in terms of carbon footprint and transport distance of construction materials. Shortening of transport distance contributes directly to the reduction of transportation costs and indirectly to the reduction of fossil fuels and air pollution.

4 INSTALLATION OF PHC PILES BY HYDRAULIC JACKING

4.1 *Advantages and disadvantages*

As piles are jacked into the ground continuously by a hydraulic jacking system without percussion, no noise or vibration is thus generated. As a result, there is practically no limitation on the operation hours. The hydraulic system is powered by electricity and no black smoke resulting from incomplete combustion of diesel is generated. Most adverse impacts of pile installation on the nearby environment or sensitive receivers are thus eliminated. The technique makes it possible to install piles in close proximity of existing buildings or sensitive areas such as underground structures of the subway system. Piles are hydraulically jacked to the target 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. The daily production rate of jacked piles is considerably higher than that of driven piles, as there is no restriction on operation hour. As no tension is generated in the concrete pile during jacking, potential tensile damage to the pile induced by percussion is eliminated.

As the design load-carrying capacity of the pile is increased, the reaction required for jacking is increased proportionally. As a result, the dead weight of the pile jacking machine for the installation of piles of design load-carrying capacity of 3,500 kN is approximately 10,000 kN. It is very difficult to maneuver such a large and heavy pile jacking machine in construction sites of small footprints and/or steep terrain. As jacked piles are displacement piles, particularly for PHC piles, all the potential disadvantages of displacement piles have to be carefully considered and necessary precautions for proper installation of piles have to be taken.

4.2 *Pile jacking machine*

The pile jacking machine for the installation of PHC piles used in Macau as shown in Figure 2 is imported from mainland China together with the skilled laborers employed to operate the machine. The machine has a rated jacking capacity of approximately 10,000 kN. The pile jacking machine is equipped with a built-in crane for the lifting of PHC piles. It should be noted that the transportation of pile jacking machines to site is not an easy task. It takes seventeen (17) 70-tonne trucks to transport all the components of a single pile jacking machine to site for re-assembly. Moreover, the maneuverability of 70-ton trucks on a construction site is also limited by site conditions. Temporary access roads are often required to support these heavy trucks.

4.3 *Clamping device*

There is need for a specially designed clamp for the jacking of PHC piles. The design adopted in Macau is shown in Figure 3. It consists of several small clamps installed concentrically. The design enables the exertion of a uniform hoop stress on the pile so as to minimize the possibility of pile crushing. The stroke of each jacking operation is between 1.5 m to 2 m. Two simultaneous clamping devices are used in some pile jacking machines manufactured in mainland China for the installation of PHC piles to reduce the risk of pile crushing.

4.4 Termination criteria

The termination criteria to be adopted for the jacked pile should be such that the pile would satisfy the requirements of the static load test. The load-carrying capacity of most PHC piles in Macau is designed to the structural capacity of the PHC pile, i.e. 3,500 kN. Therefore, the ultimate load to be imposed on these piles in the static load tests would be 7,000 kN. The termination criteria for pile jacking adopted are: the pile is subjected to: (a) at least two cycles of sustained load of 2.2 times the design load-carrying capacity, i.e. 7,700 kN, for 30 seconds each to stabilize the pile settlement; and then (b) a sustained jacking load of 7,700 kN for 15 minutes and the rate of settlement does not exceed 5 mm/15 minutes. Unlike the jacking of steel H-piles, the criterion of settlement rate of less than 5 mm/15 minutes under the ultimate jacking load is normally satisfied during the first 15 minutes of sustained ultimate jacking load for most PHC piles, resulting in a much less tedious acceptance jacking process for PHC piles than that for steel H-piles.

Figure 2: Pile jacking machine for PHC piles

Figure 3: Clamping of PHC pile

4.5 Pile connections

Unlike driven piles, the pile jacking machine remains in place during the welding process, as the pile remains at the center of the machine and sticking approximately 1 m above ground. The welding process is thus always on the critical path of the pile jacking process. Gas metal arc welding using CO_2 as the shielding gas is used for connection of PHC piles in Macau. It is a welding process which joins metals by heating the metals to their melting point using an electric arc. The arc is between a continuous, consumable electrode wire and the metal being welded. The arc is shielded from contaminants in the atmosphere by a shielding gas, i.e. CO_2. A semi-automatic welding process is normally adopted, i.e. automatic electrode wire feeding by the equipment and manual handling of the welding gun by the welder. It is learnt from site experience that it takes approximately 15 minutes for two welders working simultaneously to complete the welding for a pile connection, an obvious expedient when compared to electric arc welding.

4.6 Results of the static load test

Every jacked pile has been preloaded to 2.2 times the design load-carrying capacity before the static load test. Therefore, the loading exerted on the pile during the static load test, i.e. 2 times the design load-carrying capacity, is practically a re-loading with the magnitude smaller than the maximum load that the pile has experienced. Using the same loading sequence and acceptance criteria adopted in the Hong Kong, all the test piles satisfy the requirements of the static load test. A typical load-settlement curve is shown in Figure 4.

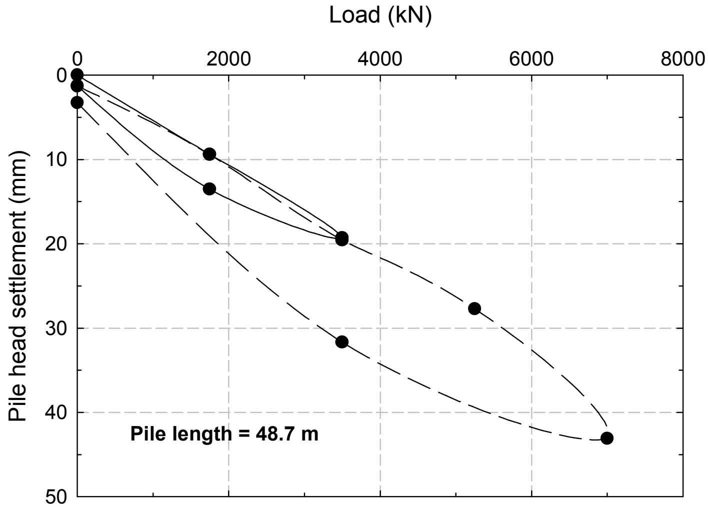


Figure 4: Load-settlement curve during static load test

5 OBSTACLES FOR THE IMPLEMENTATION OF THE TECHNOLOGY IN HONG KONG

As remarked by Li et al. (2000), the foundation construction equipment used in Hong Kong is the state-of-the-art but the construction technology adopted is very out-of-date. One of the major obstacles for the implementation of the hydraulic jacking of PHC piles in Hong Kong is probably the unnecessary, over-restrictive, bureaucratic and inappropriate government control. Jacked pile is still not a pile type recognized by BD. As a result, its design has to be approved on a project-by-project basis. The approval procedure is thus lengthy and the requirements are excessively restrictive, as demonstrated by the Fung Yuen Project (Li et al. 2011). In view of financial costs, developers and foundation designers will be reluctant to implement the technology.

The soil conditions in Hong Kong may make it difficult to install PHC piles of D = 600 mm and T = 130 mm. The typical size of PHC piles being used in Hong Kong is D = 500 mm and T = 125 mm, resulting in a design load-carrying capacity of 2,700 kN. The number of piles has to be increased by approximately 30% in comparison to Grade 55C 305×305×223 kg/m steel H-piles. However, the obstacle can be eliminated by the use of concrete of compressive strength of 105 MPa which is a mature technology in Japan.

Quality control and assurance of PHC piles is an important issue, 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 lot are from the same manufacturer as a result of the complicated transportation logistics. However, the problem can be easily solved by tracking each pile by the use of a RFID in conjunction with a GPS.

The supply of PHC piles in Hong Kong is practically a closed market as controlled by the listing system of BD. The system may function as a quality control and assurance system if the pile quality is being monitored regularly. Unfortunately this is not the situation now. Moreover, the increase in concrete strength or pile diameter may require another round of bureaucratic approval procedure which is a deterrent in the development of new technology or new material.

6 CONCLUSIONS

Installation of PHC piles by hydraulic jacking has been successfully implemented in Macau for many projects. It is evident from these successful case histories that there are no insurmountable technical obstacles. There are some solvable technical issues to be overcome for its implementation in Hong Kong. However, most obstacles arise from administrative issues imposed by the Hong Kong SAR Government. Therefore, it is a matter of the determination of the Hong Kong SAR Government to implement this cost-effective, efficient and environmentally friendly pile installation technique in Hong Kong.

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