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Deep Foundations for High-Rise Buildings in Hong Kong

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Abstract

Hong Kong is a renowned small city with densely placed skyscrapers. It is no surprise that heavy duty or even mega foundations are built over the years to support these structures. To cope with the fast construction pace, several heavy deep foundation types have been widely adopted with some prescribed design rules.
This Paper has selected two commonly adopted but distinctive foundation types, namely large diameter bored piles and percussive steel H-piles to illustrate the special design and construction considerations related to these pile types in related to local context. The supervision requirement in related to foundation works for which again may be unique in Hong Kong will also be highlighted. A case history is also discussed in the later part of the Paper to illustrate the application of one of these foundations and to highlight the importance of considering foundation design and basement excavation method in a holistic manner.

Keywords: Deep foundation, High-rise buildings, Large diameter bored pile

1. Introduction

The development of foundations in the last three decades, especially the deep foundations, in Hong Kong can be found in Lui et al. (2007) in which the earlier version of heavy duty foundations, such as hand-dug caissons, had been discussed. A brief account of the design and construction of mega foundations in Hong Kong had also been addressed recently by Lee & Sze (2007).

To support the heavy structures, the commonly adopted heavy duty foundations, in descending order of bearing capacity, are listed as follows:

1. Large diameter deep shafts - machine-dug shafts to allow footings/raft to be built directly on top of bedrock to carry significant loads. Usually for super-high rise developments with deep basements which are close to or beyond the surface of bedrock level. Large ones usually comprised diaphragm wall segments arranged in a form of circular cofferdam and upto 61 m internal diameter cofferdam had been built for this kind of purpose.
2. Large diameter bored piles - usually defined as greater than 750 mm in diameter and is usually installed by machine boring to the required level with reinforcement cage and concrete filling subsequently. The boring operation is carried out under water or in a suitable fluid such as bentonite and no dewatering for the excavation should be permitted.
3. Barrettes - usually ranged from 0.8 to 1.5 m thick, 2.8 m to 6 m width. Installed by machine excavation into a bentonite slurry filled trench down to the founding level, inserting the reinforcement cage and concreting the excavated trench by tremie method.
4. Pre-bored Rock-socketed H-piles - installed by inserting steel H-piles into pre-bored holes (typically 0.6 m in diameter) sunk into bedrock, and subsequently grouting the holes with cementitious materials.
5. Percussive steel H-piles and tubular piles - steel sections installed by pitching into the ground to achieve a final “set” which is usually terminated into decomposed rocks. The sections are lengthened by on-spot welding.

The types of foundation adopted for some skyscrapers in Hong Kong are illustrated in Table 1.

This Paper discusses two commonly adopted foundation types, namely large diameter bored piles and percussive steel H-piles, in view of their distinctive structural forms, installation methods and acceptance criteria, with an aim to illustrate the special features of the deep foundation design, construction and supervision in local context. A case history will then be discussed in the later part of the Paper to illustrate the importance of a holistic design consideration for basement excavation and foundation works in order to enable cost effective solutions in overall sense to be applied.

2. Large Diameter End-bearing Bored Piles

Large diameter end-bearing bored piles are usually preferred for the capacity in supporting high-rise or super

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Table 1. Summary of foundation types adopted for selected skyscrapers

Development	Height	Foundation Type
International Commerce Centre	484m	Shaft grouted barrettes
Two international Finance Centre	416m	Raft on rock with local replacement barrettes
Central Plaza	374m	Large diameter mechanical-dug caissons
Nina Tower	319m	Large diameter end-bearing bored piles
One Island East	298m	Raft on rock
Cheung Kong Centre	283m	Large diameter mechanical-dug caissons
The Cullinan	270m	Large diameter end-bearing bored piles
Azura	211m	Percussive steel H-piles

Figure 1. Overview of constructing large diameter bored pile foundations.

high-rise developments as well as the easiness to accommodate large sized steel stanchions to facilitate a top-down construction of deep basements. The use of top-down basement construction is usually associated with tall buildings such that valuable time can be gained by simultaneous construction of the basement excavation and the superstructure. An overview of a site using large diameter bored piles is shown in Fig. 1.

The urban area of Hong Kong is of igneous rock formation beneath the superficial deposits and a tropical weathering soil profiles. The engineering bedrock, usually defined as Moderately Decomposed Rock with a minimum Total Core Recovery of 85% is generally achievable with common modern piling techniques. Therefore bored piles are normally designed as end-bearing piles founded onto rock.

The commonly adopted shaft diameters range from 1.5 m to 3.0 m although in a few cases 3.3 m shaft diameter bored piles had been used in recent years. The typical, but also the maximum, concrete grade used is 45 MPa (28-day cube strength). Due to the presence of high groundwater table in many places of the territory, concrete is normally placed through a tremie method into the pile bore. A tremie factor of 0.8 is therefore needed to derive the structure capacity. To fully utilise the structural capacity and obtain a maximum benefit from the geotechnical capacity from end-bearing, forming an enlarged base (bell-out) into rock of upto 1.5 times the shaft diameter is allowed. This may not be a common design and practice in other cities.

With respect to the geotechnical capacity, although there were initiatives to attempt to improve the long adopted presumed bearing values stated in the Code of Practice for Foundations (BD 2004) (CoP) through full-scale testing, such as Hill et al. (2000), the higher bearing stresses can only be applied in project specific manner. For general design purpose, the design values cannot exceed those stated in the CoP, as shown in Table 2, for various grades

Table 2. Presumed Allowable Bearing Pressure under Foundations

Category of Rock	Brief Description	Total Core Recovery, TCR	Min. Uniaxial compression strength, UCS (MPa)	Allowable capacity (kPa)
1(a)	Fresh strong to very strong rock of material weathering grade I and no weathered joints.	100	75	10,000
1(b)	Fresh to slightly decomposed strong rock of material weathering grade II or better.	95	50	7,500
1(c)	Slightly to moderately decomposed moderately strong rock of material weathering grade III or better.	85	25	5,000
1(d)	Moderately decomposed, moderately strong to moderately weak rock of material weathering grade better than IV.	50	n/a	3,000
2	Highly to completely decomposed, moderately weak to weak rock of material weathering grade V or better, with SPT N-value ≥ 200	n/a	n/a	1,000

Table 3. Presumed allowable rock socket friction

Category of rock	Presumed allowable rock socket friction (kPa)	
	Under compression or transient tension	Under permanent tension
1(c) or better	700	350
1(d)	300	150

of founding materials. Adopting these values, the settlement of the beneath the foundations is usually ignored and the elastic shortening of the foundations is treated as the only component in estimating the building settlements.

Out of these categories, Category 1(c) is the most common founding criterion for end-bearing piles in balancing the weathering condition of rocks and construction risk in case more competent rock grade cannot be verified upon completion of the piles. Table 3, again as extracted from the CoP, shows the presumed allowable side friction between rock and concrete for rock socketed piles. If one wishes to combine the rock socket capacity with end-bearing capacity, the socket length cannot exceed 2 times the socket diameter to ensure strain compatibility.

For a 3 m shaft diameter bored pile with a bell-out and socket founded into Category 1(c) rock, the allowable pile capacity can be as high as approximately 120MN. This demands compression steel to be added to cope with the high shaft stress.

3. Site Supervision Requirements

The foundation industry in Hong Kong was in a turmoil time after the short pile scandals had been discovered in late 1990s which had resulted in large extent of investigations over different selected sites. These incidents had triggered a reform in the site supervision practice of foundation works and resulted in unique system comparing to other places within the region.

It is stipulated by the Regulations that the engineering consultant who performs the design shall also be responsible for the supervision of the construction works. Under the Buildings Ordinance, the Registered Structural Engineer (RSE) holds the design responsibility of the foundation works. If the design and construction involved significant geotechnical content, for example building foundation in the vicinity of the subway lines, a Registered Geotechnical Engineer (RGE) is also get involved. It is therefore in many circumstances the site supervisors are representing the RSE and RGE categories. The grade, qualification, number and frequency of inspection of the Technical Competent Persons (TCPs) required for the supervision were prescribed in the Code of Practice for Site Supervision (BD 2009) and these are largely depending on the scale of works, sensitivity of the site as well as the complexity.

It is also a statutory requirement that the foundation works shall be implemented by a Registered Specialist

Figure 2. Koden (Sonar) Testing.

Figure 3. Reservation pipe within bored piles.

Contractor and the corresponding TCPs from the Contractor shall also be resided on site to supervise the works being carried out.

For large diameter end-bearing bored piles, pre-drilling by sinking a borehole to determine the rockhead level at every pile location is mandatory. Variation of rockhead across the site is also considered to ensure the entire pile base will be founded minimum 300 mm into the designated grade of rock. To check the verticality, dimensions of the socket and bell-out formed, ultrasonic method such as Koden test, as shown in Fig. 2, is usually performed before the steel cage installation. Sonic logging through the reservation pipes, as shown in Fig. 3, in the completed pile is commonly adopted to check the concrete quality.

Interface coring through a reservation tube stopped about 1 m above the pile base, bigger pipe in Fig. 3, is mandatory to check the quality of the concrete/bedrock interface and formed one of the most important requirements. A sample of intact concrete/bedrock interface as retrieved from the completed pile is illustrated in Fig. 4.

Figure 4. Concrete/bedrock interface.

Full depth coring on the selected piles is also carried out to verify the quality and strength of the concrete.

4. Percussive Steel H-piles

The most common percussive steel H-piles applied in Hong Kong are Grade S450 305×305×180 kg/m and 305 ×305×223 kg/m universal bearing pile (UBP) sections. For the developments in urban areas, these piles are normally driven into the decomposed materials successively through reclamation fill, marine deposits and alluvial deposits, until a "final set" is achieved. The typical inferred founding levels have Standard Penetration Test 'N' values of 180 to 200 (blowcounts/300 mm). Pre-boring may sometimes be required in case need to penetrated through boulderly fill layer in the reclaimed area.

The stress in the steel section at working load is limited to 30% of the yield stress to avoid the risk of damage during the driving process. The design working stress due to combined axial load and bending may, however, be increased to 50% of the yield stress. Given the piles are placed in saturated manner with a typical spacing of 1.3 m × 1.3m c/c, as shown in Fig. 5, the group of piles are able to support a working pressure of around 1,800 kPa which is beyond the loading requirement of typical high-rise developments upto around 200 m in height. This makes the driven H-pile being a popular solution whenever it is applicable.

With respect to the geotechnical capacity, the piles are driven to a final set of 25 mm to 50 mm per 10 blows using drop hammer or hydraulic hammer, see Fig. 6, with a safety factor of 2.0 on the driving resistance.

Although it has been criticized for its incorrectness as well as its applicability in the local ground conditions, Hiley formula (Hiley, 1925) remains the traditional final set criterion for driven piles. Hammer weight of 16 to 18 ton with a 1.5 m drop height is not uncommon to set the piles and they could be "over-driven" in order to achieve the final set requirement.

In some occasions the piles may be driven to a level very

Figure 5. Snapshot of a site using percussive steel H-pile foundation.

Figure 6. Pile pitching using hydraulic hammer.

Figure 7. Final setting of pile.

close to the bedrock surface. In this case, it is more important to ensure the energy delivered from the hammer can achieve the minimum pile capacity requirement but on the other hand to avoid damaging the pile, the driving stress is generally limited to about 80% of the yield stress.

For driven piles, one of the critical elements to verify on site is the hammer weight and efficiency as assumed in the Hiley formula. Hammer weight is measured and certified by an independent laboratory. The efficiency is usually measured through high speed camera to check the stroke speed and the accelerometer mounted onto the pile to derive the energy transfer. The final set shall be counted in every 10 blows and is drawn on a graph paper for recording purpose by a skilled labour on spot, see Fig. 7.

In order to sustain the high driving stress, full penetration butt weld is adopted to extend the pile sections. All the weld joints shall be visually inspected with a minimum of 10% to be tested by means of non-destructive tests, such as ultrasonic test or magnetic particle inspection, prior to driving in the spliced sections of the piles. The steel section is painted with depth marks and hammer drop heights and blowcounts required for the pile to penetrate every 0.5 m penetrate are recorded into a logging sheet which forms part of the quality control process as well as the construction record.

Noise permit is required for pile driving and a maximum 3 hours per day is granted for urban sites. In general this has not severe impact on the construction programme given the limited size of the urban sites and the time required for other site activities, such as splicing and machine maneuvering.

Pile Dynamic Analyser (PDA) is widely used to monitor the driving stress at the pile, hammer performance, pile integrity and indicative pile capacity. The sampling rate is typical 10% of total number of piles.

Although there are researches demonstrated that dynamic testing using PDA accompanied by the CAPWAP (CAse Pile Wave Analysis Program) analysis can reasonably predict the ultimate static pile capacity, such as Fung et al. (2004), it is still a mandatory requirement to have static load test on 1% of the total number of the working piles upon completion of driving process. The selected piles shall be loaded to two times the working capacity through a two major loading cycles and a 72-hour hold is applied at the peak load in order to observe the creep settlement. A typical load test set up is shown in Fig. 8. The acceptance criteria on total and residual settlements follow the Davisson (1972) "offset" limits. A typical test result plot is shown in Fig. 9.

Figure 8. Load test set-up for driven piles.

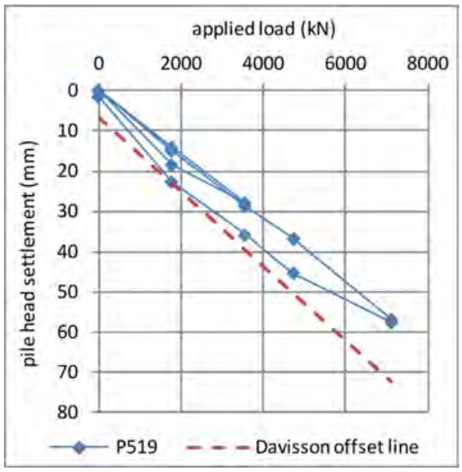

Figure 9. Load versus settlement curve.

5. Case Example - Residential Development at West Kowloon, Hong Kong

5.1. The site

The site, measured about 140 m by 80 m, is located at West Kowloon, Hong Kong. The site was reclaimed in early 1990s using a dredged method to the existing ground level of about +5.5mPD. The proposed development comprises the construction of five high-rise residential buildings sitting over a five-level podium shopping arcade and a three-level car-park basement structure.

In terms of constraints, the site is bounded by the surrounding development structures, as illustrated in Fig. 10, and various underground utilities along the main road. To the west, the proposed development has a 26 m set back zone named "Yellow Area" from the existing seawall facing Victoria Harbour.

5.2. Ground conditions

The soil stratigraphy comprised fill, lenses of marine deposits left in-place, alluvium, completely to highly decomposed granite and then granitic bedrock. The fill was

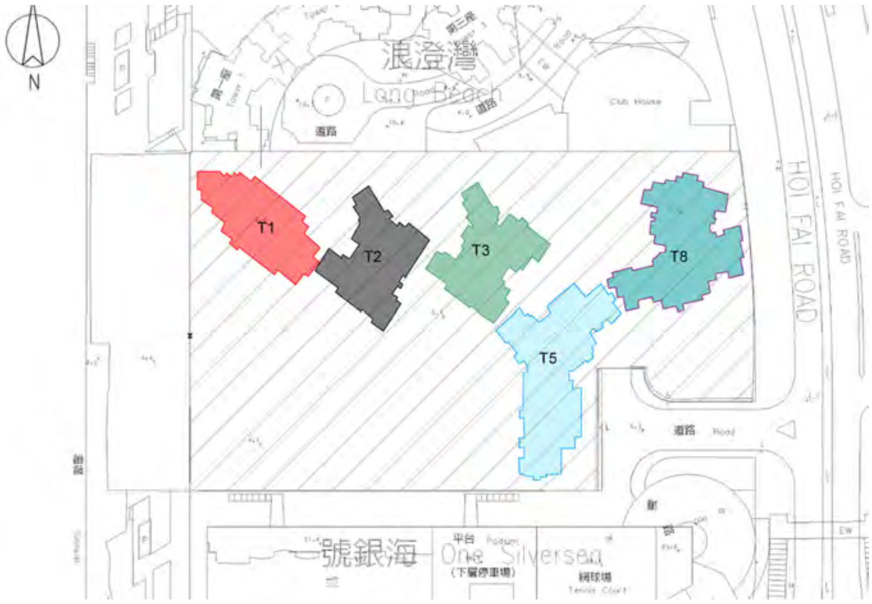

Figure 10. Site Layout with adjacent constraints.

generally a greyish brown, silty fine and medium sand. The SPT ‘N’ values ranged from 9 to 57 which indicated a loose to dense state, with the majority being medium dense sand. Owing to the dredged reclamation, the fill layer had a thickness of about 20 m and 28 m. The lenses of marine clay were generally of soft to firm, grey to dark grey, silty clay with occasional shell fragments while the marine sand/silt was medium dense, grey to dark grey, slightly clayey silty sand. The alluvial clay was firm, yellowish brown and pink, silty clay. The decomposed granite generally varied from medium dense completely decomposed granite at the top of stratum to very dense highly decomposed granite. The SPT ‘N’ values of decomposed granitic rock ranged from about 20 to greater than 200.

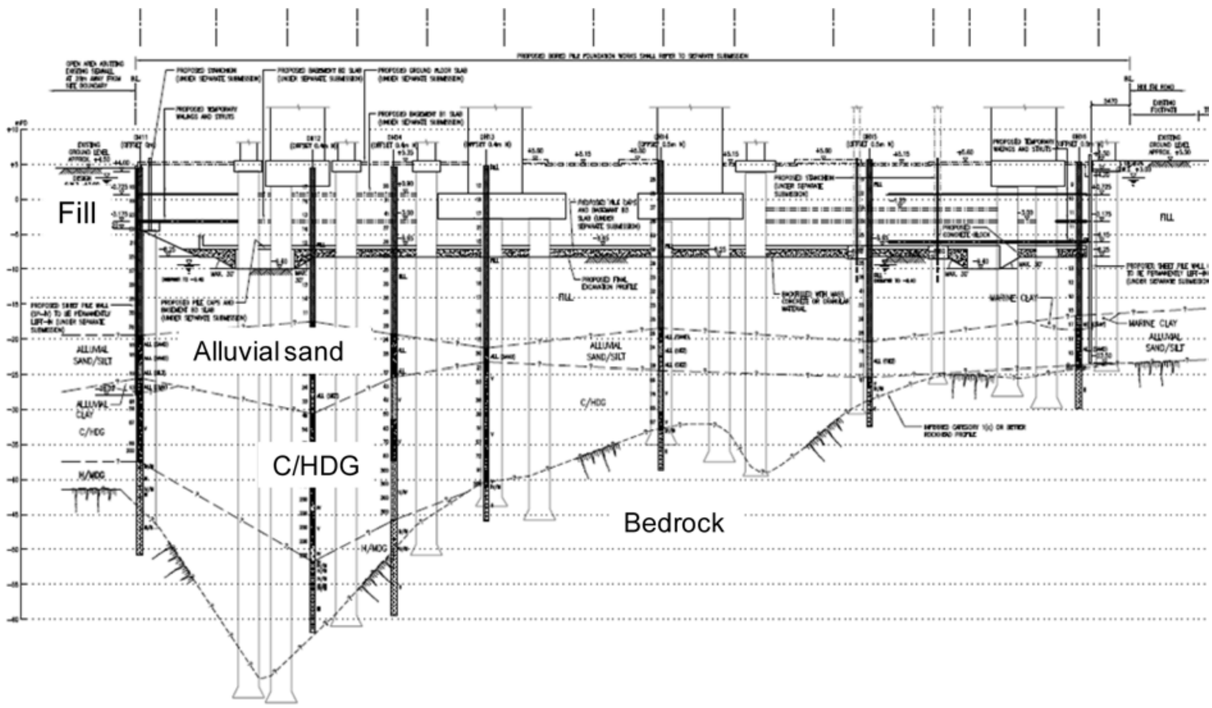

Figure 11. Typical Geological Section (W-E direction).

The rockhead level as defined as “Grade III or better rock” was found to be around 25 m at the eastern end and deeper than 85 m at the western end with a deep weathering zone revealed at north-western corner of the site. The groundwater table had direct connection with the sea and fluctuated within tidal range, which is around 2.5 m to 3.5 m below the existing ground level. A typical geological section along the west-east direction is presented in Fig. 11.

5.3. Evolution of the foundation design

In view of the loads from the towers, heavy duty foundations were demanded. Percussive steel H-piles and large diameter bored piles were on the top of the choices. The foundation design had been evolved with the basement excavation scheme. At the early stage of the project, a one-level basement structure was planned. A temporary sheet pile wall surrounding the basement box structure with island excavation method was considered to be appropriate and cost effective. With this regard, percussive steel H-pile foundation was considered to be more cost-effective. This is largely due to easiness of driving through the reclamation sand fill and no abortive length will be resulted by using a 4 m long follower.

However, when the project developed, the building plan was modified and demanded a three-level basement structure. This had resulted in an excavation depth of around 14 m, over the majority area of the site. In some areas, the abortive lengths of the H-pile above the pile cut-off levels could be even longer than the net length left in the ground. Another factor being the fluctuation of the steel price at the time of design had deterred the attractiveness of the steel H-pile option.

Most importantly, the project demanded a fast-track construction programme in order to enable an early start of the superstructure. To minimise the cost of the lateral supports and to achieve an earlier commencement of the podium and tower construction, a semi top-down basement construction method had been developed. Such change also demanded temporary supports to the basement and podium structures before the final excavation level is reached. These push-pull factors had resulted in a series of discussions among the Client, the Project Team as well as the Contractor, and the foundation scheme of large diameter end-bearing bored piles, with or without a rock socket, was finally adopted.

5.4. Foundation works

A total of 117 nos. large-diameter end-bearing bored piles, 1.8 m to 3.0 m, were adopted as the foundation to carry the vertical and lateral loads from the proposed tower and podium structures. In view of the geological condition, the foundation criteria of these piles were divided into three categories in order to optimise the foundation design, as shown in Table 4.

Founding on Category 1(b) rock was applied to piles located at eastern side of site at where the bedrock is generally shallower and more competent. In contrast, Category 1(d) rock as founding material was assigned to a few piles located near the western end of the site at where a depressed rockhead and the fault related feature of fracture rock were identified.

With rock socket plus end-bearing capacity of the piles, the design capacity of the pile is 114MN under static load. In case of transient load case under wind load condition, the capacity can be enhanced by 25% to 142MN.

One special feature of these piles was having the cut-off levels within the tower zone raised to higher elevations, at B1 floor instead of below B3 level. This enabled the construction of pile cap in earlier manner and commencing the tower construction without the need of heavy steel stanchions. The exposed bored piles within the basement were also adopted as the permanent columns without further structural treatment. To provide structural connection for the basement slabs and beams onto the bored piles, special steel collars, as shown in Fig. 12, were reserved in the bored piles to allow reinforcement connections to the external side of the collar, after exposed by trimming away the concrete cover.

At the podium zone, where the bored piles had a cut-off level at B3 level. Steel stanchions, typically comprising four latticed steel H-steel members of S450 305×305×223 kg/m UBP, was plunged into bored piles to support podium and basement slabs during the semi top-down construction of the basement. The stanchions were encased by concrete to form square-sized composite columns in a later stage. A general view of the stanchion prior to installation is shown in Fig. 13.

5.5. Sequence of works

An overview of the bored piling work at a corner of the site is shown in Fig. 14. The bored piles were installed

Table 4. Design End-bearing Pressure

Rock Category	Brief Description	Total Core Recovery, TCR (% over 1.5 m core run)	Min. Uniaxial compression strength, UCS (MPa)	Allowable capacity (kPa)
1(b)	Fresh to slightly decomposed strong rock of material weathering grade II or better.	95	50	7,500
1(c)	Slightly to moderately decomposed moderately strong rock of material weathering grade III or better.	85	25	5,000
1(d)	Moderately decomposed, moderately strong to moderately weak rock of material weathering grade better than IV.	50	n/a	3,000

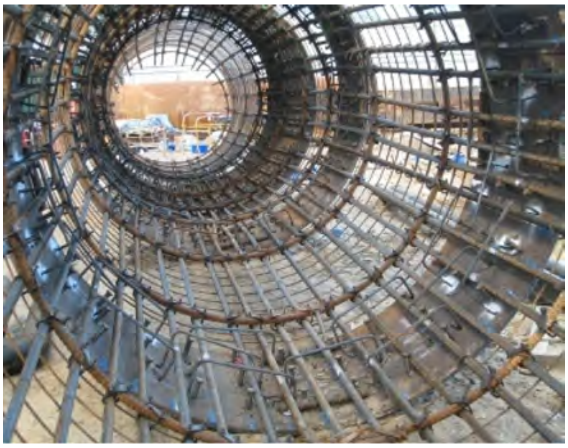

Figure 12. Steel Collar in the Bored Pile.

Figure 13. Stanchion installation into Bored Pile.

Figure 14. Overview of the bored piling works.

with conventional piling technique in Hong Kong, with full length temporary steel casing to support pile bore through the soils. Hammer grab was used to excavate through the superficial deposits and decomposed materials. The temporary steel casing with cutting teeth at the toe was advanced simultaneously by oscillator or rotator as the excavation proceeded.

Reverse Circulation Drill (RCD) drillbit, as shown in Fig. 15, was used to form the socket into rock of designated grade. Water was used as the flushing medium to lift the cuttings from the pile bore to the filtering tank of the circulation system. The bell-out was formed by a special expandable RCD bell-out bit to the designed dimension, as shown in Fig. 16. Due to the presence of high groundwater table near the seashore, concreting was inevitably carried out by a typical tremie method.

A typical cross-section of the development along North-south direction is shown in Fig. 17. After installation of the bored pile foundation and the peripheral temporary sheet pile wall, the ground level was reduced to +3.2mPD to enable most of the ground floor slab to be cast. The pile caps for two towers near the eastern and western site boundaries could also be built with a soffit level of around +2mPD, as indicated in Fig. 18, to facilitate the podium construction in due course. In order to cast the pile caps for the inner towers, local excavation to B1 level would be carried out as illustrated in Fig. 19.

From this stage, the podium and the tower structure can be commenced with concurrent further basement excavation. At lower levels, the middle portion of the basement

Figure 15. Large diameter RCD drillbit.

Figure 16. bell-out drill bit.

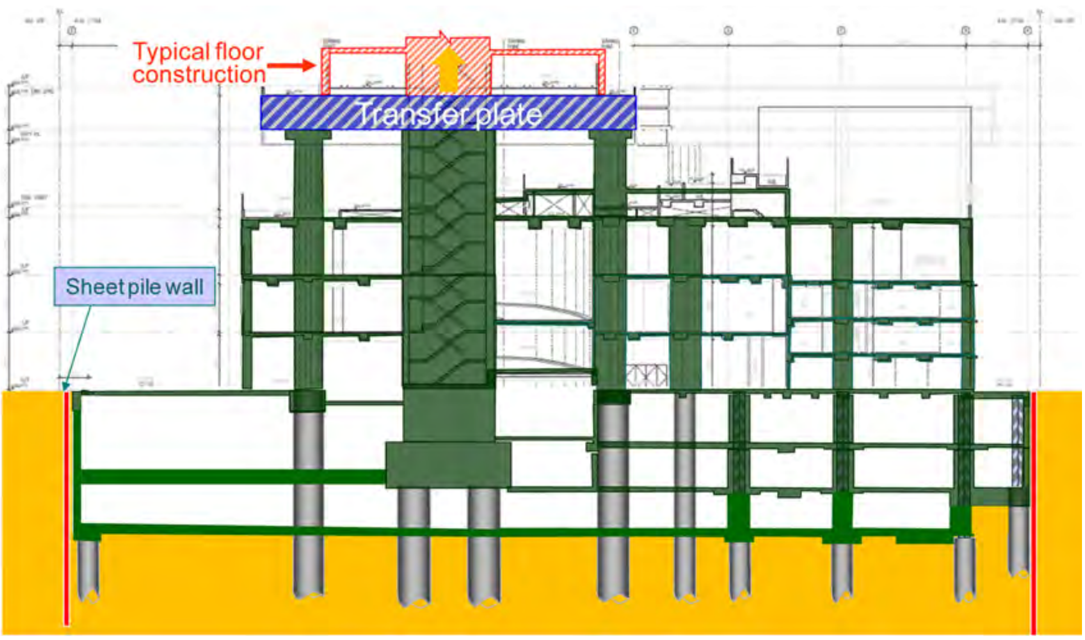

Figure 17. Typical Cross-section along N-S direction.

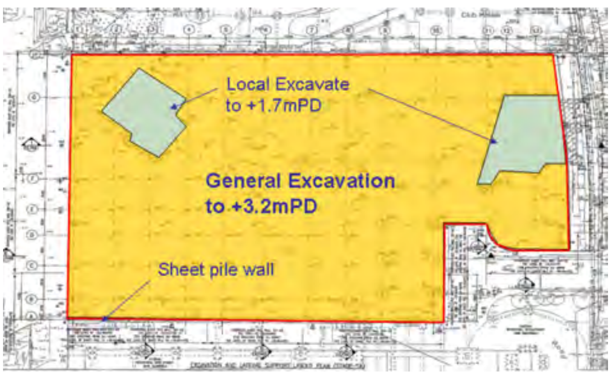

Figure 18. General Excavation near Ground Level.

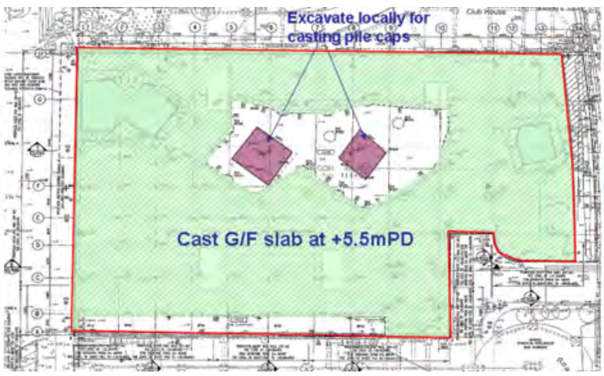

Figure 19. Local Excavation for Inner Pile Caps.

Figure 20. Snapshot of Basement Excavation.

Figure 21. Welding of bracket for beam/slab reinforcement connection.

slabs was cast to allow steel props to be installed near the edge of the basement to provide lateral support to the sheet pile wall, these struts were preloaded to control the wall deformation and hence the excavation incurred ground movements. A snapshot during the basement excavation is shown in Fig. 20. The concrete cover of the bored pile piles was trimmed to expose the collar at each basement level. Steel brackets were then welded onto collar, as shown in Fig. 21, to allow a connection from the steel reinforcement of the basement slabs and beams.

This project is a good demonstration of the collaborative and interactive efforts among the Client, the Architect, the Designer as well as the Contractor in deriving the optimised foundation and excavation design together with construction method and sequence in achieving the common goals.

6. Conclusion

Large diameter bored pile and driven steel H-pile were selected to illustrate the special features of the foundation design and construction supervision requirements in Hong Kong. A case history of development adopting large diameter bored pile is also shared to illustrate the holistic approach in deriving the most optimum foundation solution in conjunction with deep basement excavation and a fast track construction of the superstructures.

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