Methods of Soft Ground Treatment and Rigid Bored Pile Foundation for Offshore Structures

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ABSTRACT: Indonesia is on a solid path of economic growth and development. The development of the country is on the way in all areas whether infrastructure, urban, industry, tourism and resources. Massive construction projects are required to facilitate such development. Indonesia's construction industry is faced with very special challenges due to its geographic and geological character. In a country which has 13,677 islands and where 7.9 km^2 out of a total territorial area of 9.8 mio km^2 is covered by water the significance of offshore construction is evident. Making things not easier, Indonesia is a place, due to its location, where natural disasters, especially earthquakes, are more common than in other countries. This requires the stabilization of soft ground to provide safety against liquefaction. Heavy structures need to be founded on solid foundation whether on- or offshore. The following presentation explains a technique of soft ground treatment and a technique for the construction of large diameter Bored Piles by referring to methods being used for 2 major projects which are part of the development of the Hong Kong Zhuhai Corridor. The projects need to be built both offshore in the open waters of the Pearl River Estuary between Hong Kong and Zhuhai (Mainland China).

1 INTRODUCTION

The Governments of the PRC and the Hong Kong Special Administrative Region of the PRC are in the process to build a fast lane connection between Hong Kong and the Mainland China / Zhuhai and Macau. Two key projects for this connection are the Hong Kong Boundary Crossing Facilities (HKBCF) and the Hong Kong Zhuhai Macau Bridge (HZMB). The HKBCF will serve as a transportation hub and provide clearance facilities for goods and passengers using the HZMB. The HKBCF will be placed on a man built island with a size of about 130 hectares. The reclamation site is located in the open waters close to the Hong Kong International Airport (HKIA). The Hong HZMB is a mega-size sea crossing with a total length in excess of 40 km. The bridge is being built in 2 packages, one, the longer package, starting from the PRC and the other from the HKGSAR. At the border the bridge packages will be linked. The location of the projects is shown in Fig. 1. The following presentation is split into 2 parts, part 1 explaining methods used for the soft ground treatment for the HKBCF and part 2 describing the principles and method used for the Bored Pile construction for the HZMB. The presentation is not intended to be looked at as case studies for the reason that the construction is still ongoing. The intention is to show to the audience possibilities and techniques which are available to construct structures offshore under very difficult conditions. The material presented for part 1, the soft ground treatment, is based on proposals which were made by Bauer-Betterground to Main Contractors during the tender stage. It is particularly noted that the HKBCF works were awarded to a Main Contractor who did not sub-contract the soft ground treatment to Bauer-Betterground however purchased the services of Betterground for the soft ground treatment. Methods shown hereafter are based on the proposals by Bauer-Betterground. Pictures and Figures presented herein for part 1 are given with the consent of Betterground. Part 2 deals with the Bored Pile Construction for the HKZMB. The project was awarded to Dragages-VSL-China Harbour JV. The Bored Pile construction as referred to hereafter was awarded to Bauer Hong Kong Limited.

Figure 1. Development of the Hong Kong Zhuhai Corridor

Figure 2. Artist impression of HKBCF

2 METHOD FOR SOFT GROUND TREATMENT PARTIALLY USED FOR THE HKBCF

2.1 *Understanding and Technical Appreciation of Some Challenges*

An Artist Impression of the HKBCF is shown in Fig. 2. The picture shows the strategic location of the island in very close proximity to the HKIA. The sub-ground conditions on which the artificial island is to be built consist of a thick layer of soft marine clay on top of alluvium. Due to environmental considerations it was not allowed to remove the marine clay and replace with sand. The Engineer's design therefore provided the installation of stone columns which are to be terminated in the alluvium below the marine clay. Minimum disturbance to the water from the installation process was a mandatory requirement. The installation method was specified to be dry bottom feed stone columns. The Stone Columns are to be placed below the 6,150 m long seawall and box culverts. On top of the Stone Columns Cellular Structures were foreseen to be installed filed with sand which together would form the rigid perimeter seawall necessary for the formation of the island. The principle areas in which Stone Columns were to be installed is shown in Fig. 3.

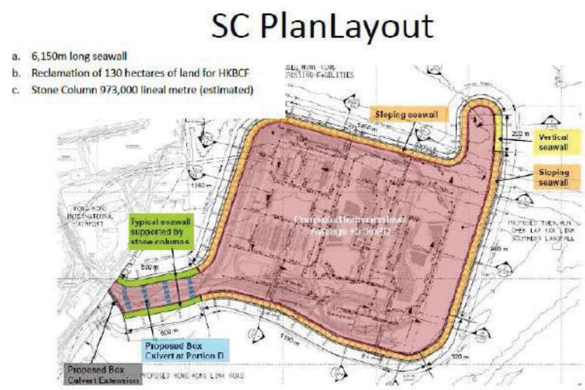


Figure 3. Areas for Stone Column Construction

2.2 *Objectives of the Stone Columns*

The ground treatment involving stone columns need to be carried out at various parts of the site. The objective of the stone columns is to satisfy one or a combination of the following purposes:

i) Provide support for the fill above and above and the Cellular Structures
ii) Serve as porous drains for lateral drainage, and
iii) Provide immediate improvement to strength

The Stone Columns attain a threefold effect:

1) Instant increase in shear strength
2) Reduction of total settlements
3) Acceleration of time settlement

A sequencing of work as suggested by Bauer-Betterground during the Tender is shown in Fig. 4. The plan was that the installation of the Stone Columns was running in advance to the installation of the Cellular Structures. A picture showing a Cellular Structure during installation is shown in Fig. 5.

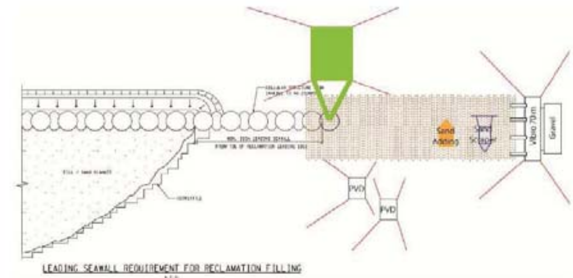


Figure 4. Proposed Work Sequence

Figure 5. Cellular Structure

2.3 *Key Issues Addressed*

The particular issues which have a material impact of the construction method for projects of this kind and addressed hereafter are:

- Environmental Issues
- Low Head Room Restrictions
- Low seabed level / Heave

2.3.1 *Environmental Issues*

The environmental issues can be grouped generally in the following three categories:

- Noise & Vibration
- Dust / Exhaust Emissions
- Water Pollution

For projects of such magnitude it is mandatory to prepare an environmental management plan for the project to cover the above topics and ensure that all construction activities comply with the relevant requirements and fulfill the environmental permits. The equipment employed for such projects need to be state of the art to comply with the first 2 categories. To minimize water pollution from the installation of the Stone Columns a sand blanket can be installed (best after laying a geotextile) on top of the soft clay prior to installation of the Stone Columns. Unavoidable remainder pollution can be prevented from escaping into the open sea by providing silt curtains around the installation units. Fig. 6 is showing a low headroom stone column installation unit working within a silt curtain.

Figure 6. Stone Column Installation within Silt Curtain

2.3.2 *Low Headroom Constraints*

In some areas of the site, the depth of the stone column treatment was larger than the height available for construction equipment (length of vibroprobe unit) to install the columns with conventional standard equipment. Such requirements existed to respect the flight path of the planes within close proximity to the HKIA. For such condition the equipment needed to be modified. Fig. 7 & 8 show the areas where Airport Height Restrictions need to be observed. Fig. 9 shows a normal Stone Column Dry Bottom Feed Operation with Standard Equipment and using a gravel pump for stone feed. From the picture it can be seen that the top part of the standard rig which does not enter the soil has a length of approximately 5 m. In addition to this un-effective length the rig needs to keep a safe distance from the crane boom top wheel of another 5 m. Hence in total 10 m of height are lost.

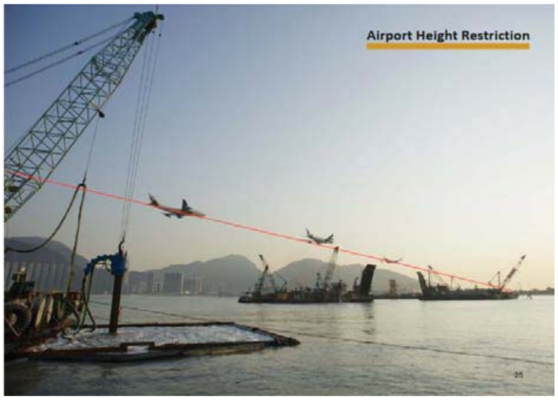


Figure 7. Airport Height Restriction

Figure 8. Area with low headroom requirement

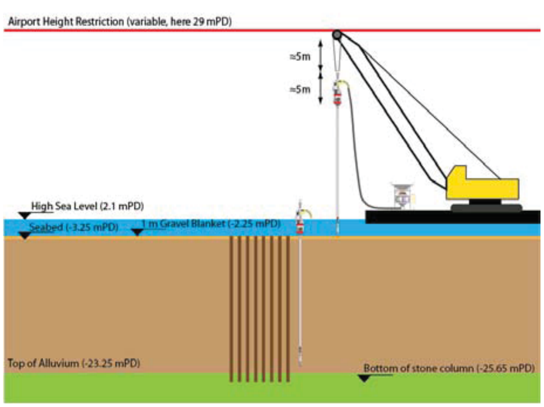


Figure 9. Stone Column set up without height restrictions

To accommodate the installation of the stone columns also for low headroom conditions the equipment was modified to shorten the unusable length to a minimum by introducing an "elephant trunk" on top of the vibroprobe. The vibroprobe with the "elephant trunk" is shown in Fig. 10 and Fig. 11.

Figure 10. Work installation for Marine Stone Column in Low Headroom Condition

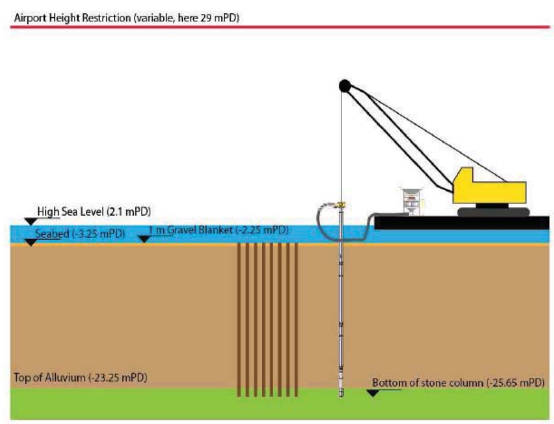


Figure 11. Sketch for Set-up with Height Restriction

The transport of the gravel is being done by a sophisticated system. The stones are placed by an excavator into a hopper on top of a sealed chamber from which the gravel is pumped by an airstream into a Receiver Tank on top of the Vibroprobe Unit. The Receiver Tank is sealed by a double lock to make sure that the entire stone feed system from pump to outlet remains pressurized at any time. The system is called the Pressure Chamber Injection System (PCIS). Fig. 12 shows the Gravel flow in the PCIS. The gravel flow tank on an offshoer project is shown in Fig. 13.

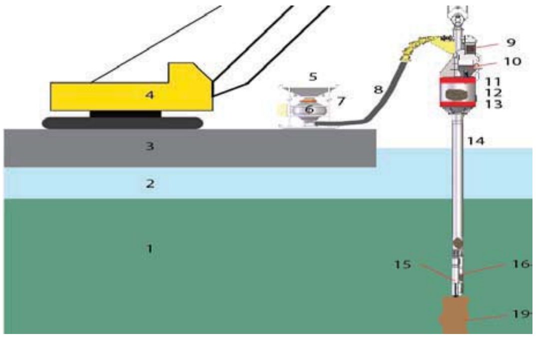


Figure 12. Gravel Flow in the PCIS

Figure 13. Gravel Flow tank in Operation

2.3.3 *Low Water Conditions/Heave*

As the stone columns are installed the gravel is more displaced than replaced. The consequence from this displacement in soft clay condition are so called volume constant deformations. The soft soil is being pushed somewhere by the added volume. A small part of the soft soil will drain (=Compact) but the majority will move either sideways or upwards creating some heave as shown in Fig. 14.

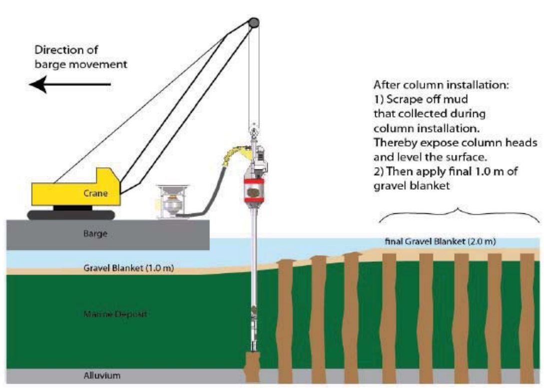


Figure 14. Sketch showing working direction in low water conditions with heave

The heave effect is very important to be considered in shallow water conditions to avoid that the barge may be grounded. In such conditions the work sequence has to move away from the areas in which stone columns have been installed. The stone supply must come from the back of the barge.

2.4 *Alternative Gravel Feed Methods from Gravel Pump*

The gravel feed system as described above is certainly of advantadge in low headroom conditions. In case that such restrictions do not exist the stone feed into the vibroprobe can be done from a stone barge with excavators into a skip bucket, pretty much the same as it is done on-shore. Fig. 15 and Fig. 16 illustrates examples of such a set up.

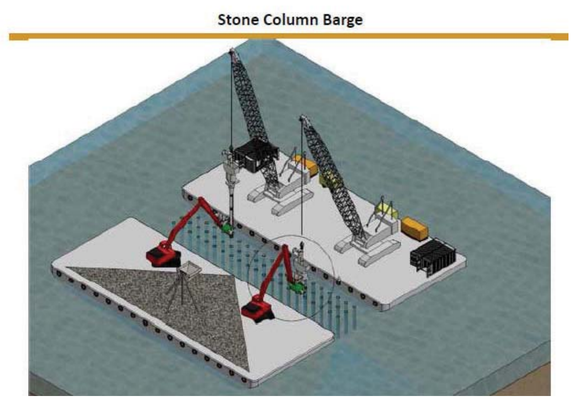


Figure 15. Stone Feed using Excavator and Skip Bucket

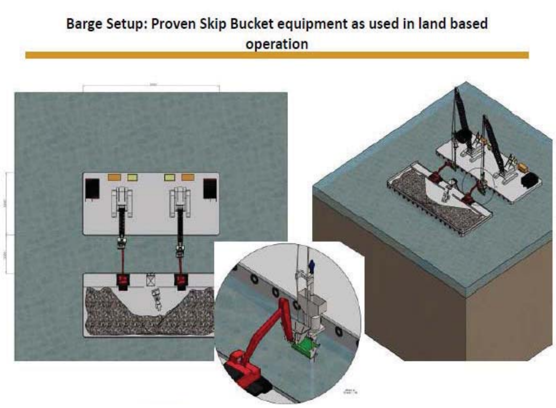


Figure 16. Skip Bucket Operation

3 LIQUIFACTION

3.1 *What is Liquifaction*

Liquefaction is the almost complete loss of shear strength in a water saturated granular soil, triggered by the sequence of events as listed below:

1) Earthquake shaking causes soil grains to rearrange.
2) As soil grains move closer to each other, the water between the grains does not drain quick enough.
3) Excess pore water pressure builds up, until it reaches the magnitude of the effective stresses in the soil.
4) With the effective stress thus reduced, the soil looses its shear strength (which in granular soil is a function of effective stress times tangent of friction angle).
5) Objects lighter than the liquefied soil (e.g. sewer pipes, tunnels) “pop up” and heavier objects “sink in”

3.2 *Information needed for Ground Improvement Design*

The following are the minimum basic information needed for ground improvement design:

1. Loads
2. Width and length of load bearing elements (footings, rafts, walls)
3. Cross sections and layout drawings of structures, wherever available, to identify the relevant cross section or detect stability issues.
4. Depth of groundwater table.
5. Depth of foundation level below existing ground,
6. Planned addition or removal of earth fill, if any. Earth is heavy and sometimes more heavy than the actual building. If we forget this, the settlement estimates can be far off the mark.
7. Soil stiffness profile (SPT, CPT, pressure meter, boreholes), favorably showing on a layout drawing where these soundings are in relation to the foundations under 2) above.
8. For settlement in soft clay and silt: Oedometer load and time settlement curves to evaluate soil settlement not only in their magnitude but also in time. Good laboratory data gives more confidence in the calculation assumptions than if we have to correlate soil stiffness from SPT or CPT alone)
9. Allowed time for construction (to evaluate the need for vertical drains, vacuum)
10. For projects where slope stability is an issue: Friction angle or undrained shear strength over depth from vane shear, CPT correlation, or lab shear tests.
11. For projects involving mitigation of earthquake induced settlements and lateral spreading: Moment Magnitude Mw of the earthquake and the Peak Ground Acceleration (PGA), the water table elevation and for lateral spreading evaluation the relevant cross sections for lateral spreading.

3.3 *Earthquake Frequency and Prediction*

Fig. 17 shows the earthquake with a magnitude > 5 which occurred between the years 2000 and 2008. It can be seen that Indonesia is located in an area with the highest frequency.

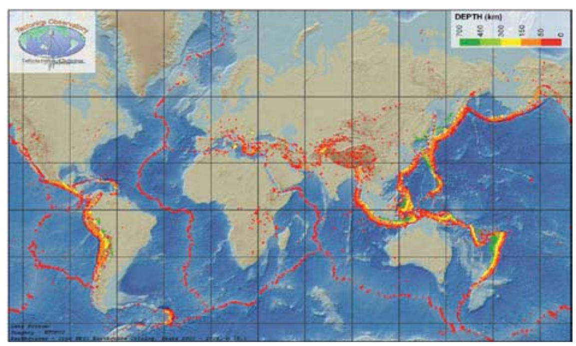


Figure 17. Earthquakes with Magnitude > 5 between 2000 and 2008

Globally a Magnitude 6 earthquake happens once a week, Magnitude 5≈ 10 times, 4 ≈ 100 times, 3 ≈ 1000 times. These quakes happen often in uninhabited locations and then generate little or no damage. The main damage by earthquakes originates from large quakes of a size that only happens a few times in a century. Per today we are not able to predict location, time, and magnitude of future earthquake events. This has to do with the fact that in contrast to weather phenomena, the phenomena generating earthquakes occur mainly underground, hidden from direct observation.

The best insight is gained from recording of annual movements on the fault lines and from recording the small-earthquake activity.

3.4 *Effects of Liquifaction*

The effects are devastating. Heavy structures do sink or topple, light structures like sewers pop up. As a result of the horizontal forces bending moments and shear stresses in piles, columns or frames do increase to an extent that stresses exceed the ultimate values and structures do collapse.

Figure 18. Niigata, Japan

Figure 19. Izmit, Turkey 1999

Figure 21. Sewer Pop Up

3.5 *Prevention of of Liquifaction*

In simple terms 3 steps can help to prevent liquifaction:

- Use seismological data and statistics to define the relevant design earthquake magnitude and acceleration. In other words: Agree on the size earthquake for which the soil shall be made safe against liquefaction.
- Find out through soil density sounding (preferably CPT) if the soil is loose enough to liquefy under the design earthquake.
- Increase the soil density of granular soils (e.g. with Vibro Compaction, Falling Weight Compaction) or reinforce non-granular (cohesive) soils with Stone Columns or other reinforcement techniques or Soil Mixing.

For soft soils stone columns are very effective to prevent liquefaction. The effect is two-fold.

- Stone Columns act as vertical drains, thus reducing the excess pore pressures that lead to liquefaction.
- The earthquake induced shear stress is distributed onto soil and column in a ratio proportional to the stiffness ratio between both materials.

Fig. 22 and Fig. 23 illustrate the above effects.

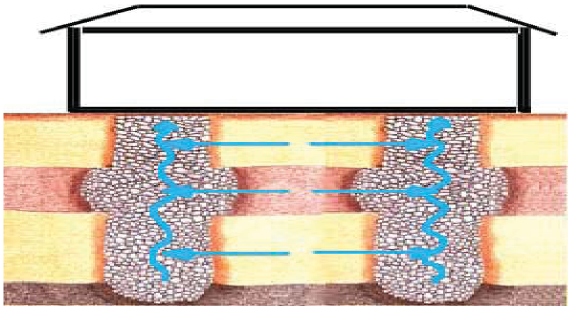


Figure 22. Drainage Effect of Stone Columns

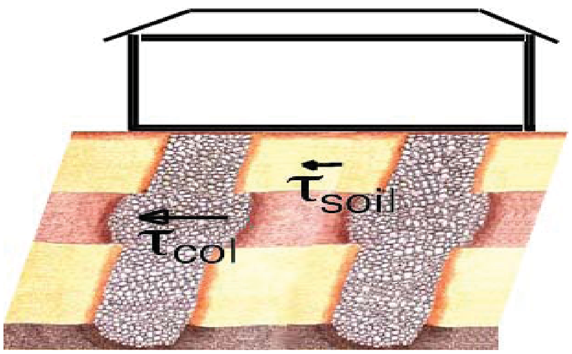


Figure 23. Distribution of Shear Stresses

4 BORED PILE FOUNDATION FOR OFF-SHORE STRUCTURES

4.1 *The Hong King Zhuhai Macau Bridge*

4.2 *The Project*

The Hong Kong–Zhuhai–Macau Bridge is an ongoing project. The bridge will link three major cities in the Pearl River Delta, Hong Kong, Zhuhai and Macau. The location of the bridge is shown in Fig. 24.

The construction of the entire link is divided in various packages which consist of bridge sections, tunnels and artificial islands to form finally the complete connection. An Artist Impression of the Key Structures is shown in Fig 25.

Figure 25. Artist Impression of Key Structures

One of the major packages, the bridge structure leading through the Hong Kong Airport Channel to the PRC border (known as section Scenic Hill and HKSAR), was awarded to the Dragages –VSL- China Harbour Joint Venture. The location of this package is shown in Fig. 26.

Figure 26. Bridge between Scenic Hill and HKSAR

The Joint Venture sub-contracted the construction of the Bored Piling Works for the area within the so-called deep water area to Bauer Hong Kong Ltd. The deep water section is shown in Fig. 27.

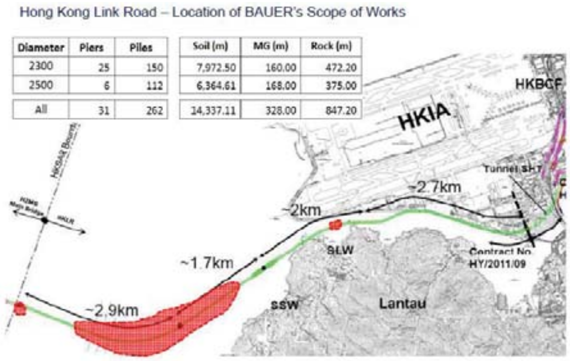


Figure 27. Deep Water Section

4.3 *The Geology*

The sub-ground condition consists of a thick layer of Marine Clay over Alluvium and Granite. The Granite is in the upper layers completely to highly decomposed before turning into moderately strong G III to G II rock. The Hong Kong Granite G III to G II rock has commonly unconfined compressive strength in the range of 90 MPa to > 200 MPa. The Geological Profile as anticipate in the early stages of the contract is shown in Fig. 28. Fig. 29 shows that the thickness of the Marine Clay increases towards the deep water section and the granite rock head level dips down into depth of – 80 m below seabed level.

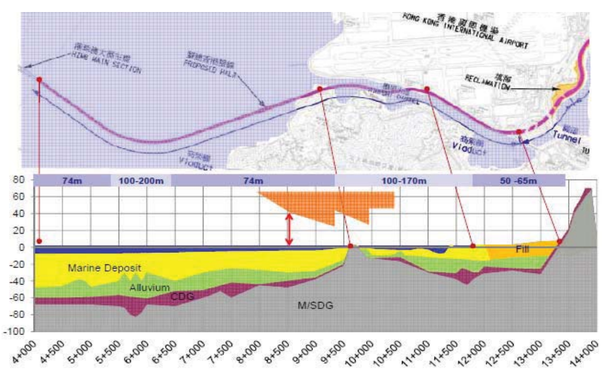
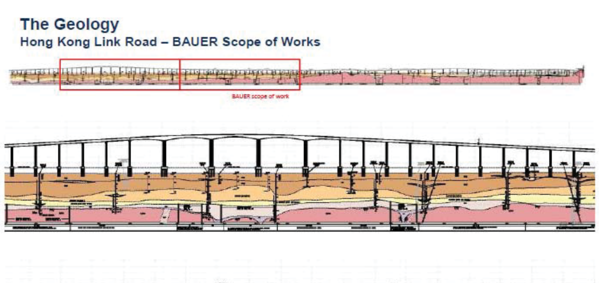


Figure 28. Geological Profile



The Engineer's requirement is that at every pile location a pre-drill is being done from which cores are being recovered and which are the basis of determining the founding level of the Bored Piles.

The detailed predrilling at every pile ensures that all piles are constructed in defined conditions and there is no risk of dealing with undetected fault structures or weathering grades.

Fig. 30 to Fig. 32 show the soil investigation carried out and the result of the predrilling as an example which is done for every pile location.

Figure 30. Soil Investigation at each Pile Location from Platforms or Barges

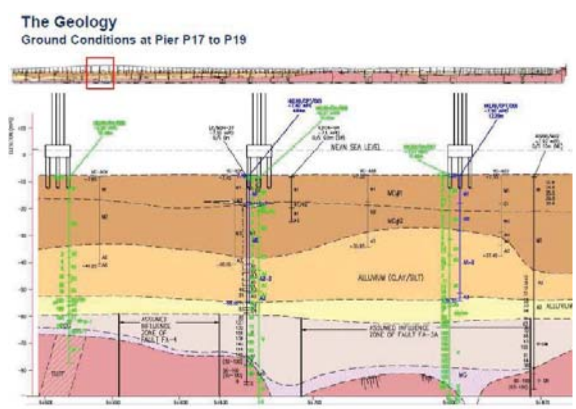


Figure 31. Precise Investigation of Ground Conditions at Pile Location

Figure 32. Rock Core Samples Retrieved from Predrilling

4.4 *Pile Design and Layout*

For the standard piers the bridge has a span of 75 m. The span for the navigation channel is 150 m, double of the standard span. Fig. 33, Fig. 34 and Fig. 35 show the typical pile cap arrangements. The Bored Piles have diameters of either 2300 mm or 2500 mm.

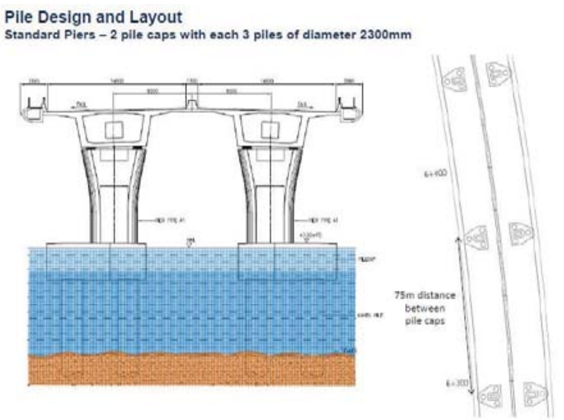


Figure 33. Pile Cap Arrangement for Standard Piers

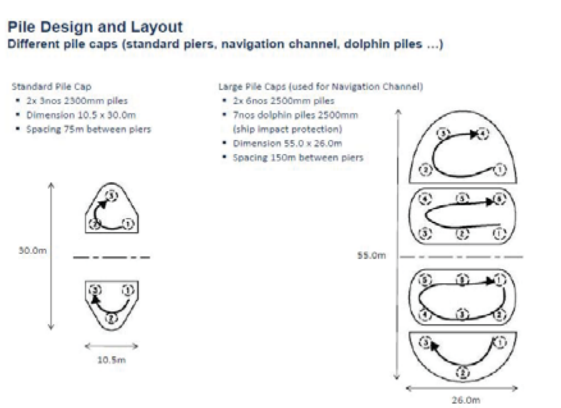


Figure 34. Pile Cap and Bored Piles for Standard Pier and Navigation Channel

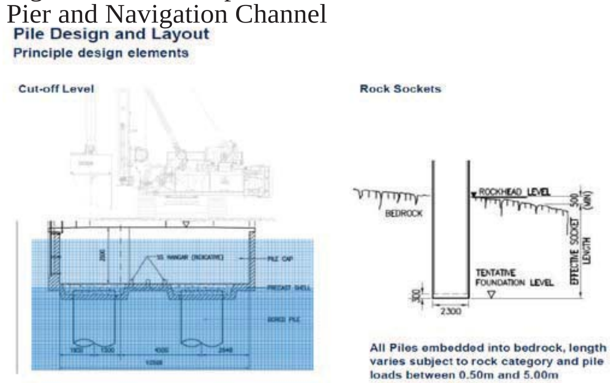


Figure 35. Typical Socket Detail

The Bored Piles were typically designed as end bearing piles whith rock socket friction. The socket length of the Bored Piles varied, depending on weathering grade, between 0.5m to 5.0 m per pile. The latest predrilling for some of the piers in the deep water section did not detect rock head until over 125 m depth. For end bearing piles the length of the piles could end up at 130 m. The construction of such piles is not impossible but may turn out to be time consuming and expensive. Considerations are taken to design the piles as friction piles possibly shaft grouted.

4.5 *Principle Working Method and Equipment Set Up*

Bauer Hong Kong selected to construct the Bored Piles using the Rotary Kelly Drilling Method (RKD). The method foresees the drilling using a top temporary (for offshore drilling permanent) casing through loose / soft layers and continues drilling under stabilization fluid. In this case Bentonite suspension was chosen for the stabilization fluid (Fig. 36). The advantage of this method over the conventional offshore drilling method of Reversed Circulation Drilling (RCD) is the construction speed. The faster production offers cost savings due to shorter construction time. For offshore projects time has a very big influence on cost due to the high cost of marine facilities. Additional and substantial cost savings do derive from the permanent casings which for RKD are drastically shorter than for the RCD Method. The necessity of having rigid platforms for the BG Drilling Rigs (either Jack Up Barges or Platforms) add construction cost. For the HKZMB the JV selected to construct platforms for the BG – Drilling Rigs.

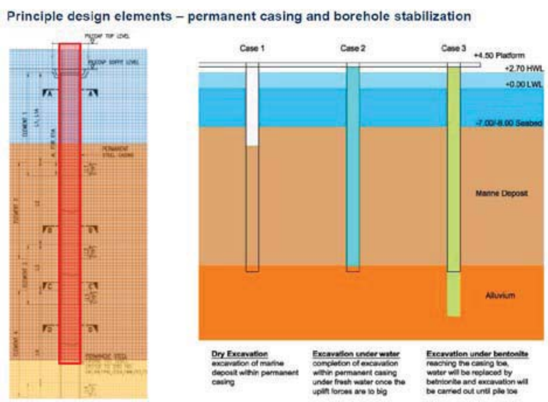


Figure 36. Steps of Borehole Stabilization

The additional cost for the platform can be reduced by using the permanent casings for the Bored Piles as bearing elements for the platform. The platform may be used for subsequent construction of caps and piers. In the specific case of the HKZMB the legs for the platform were installed separately from the permanent casings of the Bored Piles. The typical construction steps of erecting the piling platform and installing the permanent casing is shown in Fig. 37 and Fig. 38.

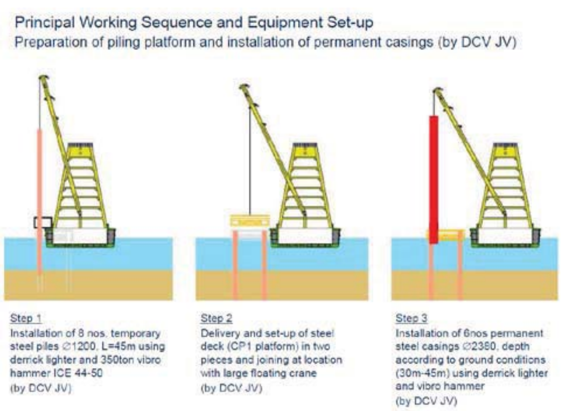


Figure 37. Erection of Piling Platform and Casing Installation

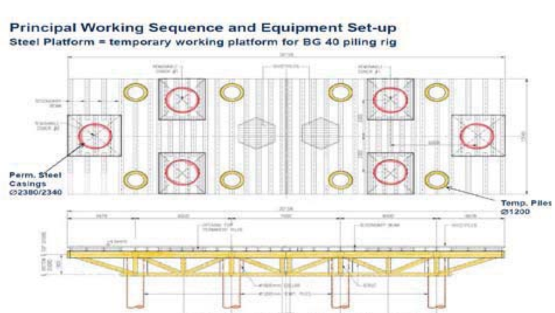


Figure 38. Layout + Section through Piling Platform with Casings

The Key element for off-shore piling is work panning and back-up facilities (Fig. 39). Every construction step need to be preplanned in detail and back up facilities need to be on stand bye to minimize expensive inefficiency on the water. Fig. 40 shows the Bauer Workshop set up and its distance to the workfront. In order to deliver parts from the workshop to the workfront it need 4 hours of boats ride.

Figure 39. Back Up Facilities


Figure 40. Aerial View of Bauer Site Workshop

Once the preparation work for piling has been completed the BG Drilling Rig type BG 40 is being mobilzed by a barge equiped with a movable ramp to the platform. For moving the BG 40 Drill Rig to the platform tidal levels and wave actions need to be considered carefully. Fig. 41 and Fig. 42 show the movement of BG 40 Rig on to the piling platform.

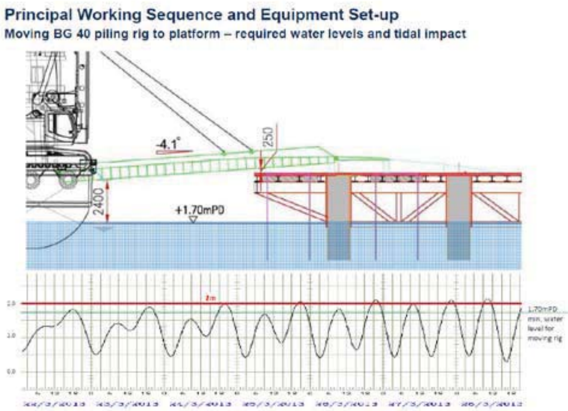


Figure 41. Sketch of Moving of BG 40 to Piling Platform

Figure 42. Actual Moving of BG 40 to Piling Platform

The set up for the pile drilling and installation work must include all facilities which are also needed onshore, such as

- Piling platform
- Space for Service Crane
- Space for Tools and Accessories
- Space for Slurry and Desanding
- Spoil Removal Facilities

A typical set up for a standard pier is shown in Fig. 43 and Fig. 44 as sketches.

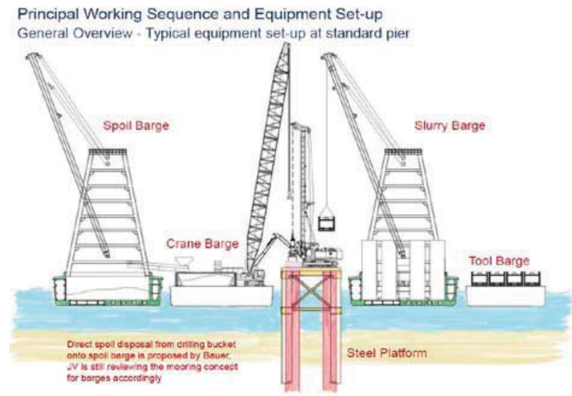


Figure 43. Sketch of Equipment Set Up

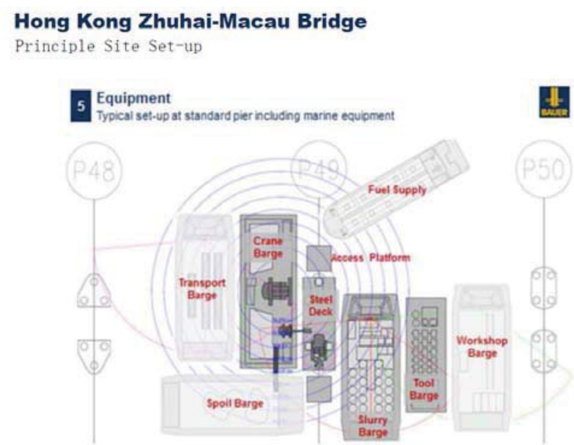


Figure 44. Sketch of Layout of Working Set Up

The actual site situation and working set up is shown in the Fig. 45 to Fig. 46 as aerial views and pictures from the site.

Figure 46. Tool Barge

Figure 47. Aerial View of Bridge Site

Figure 48. Picture of Barge Set Up

4.6 *Pile Drilling and Installation of Materials*

The Bored Pile Drilling offshore follows exactly the same sequence as onshore. The principle steps are as follows:

- Soil excavation with bucket or auger within casing
- Continue excavation under Stabilization Fluid
- Rock excavation using Core Barrells, Cross Cutter or other Tools
- Cleaning of Pile Toe with Cleaning Bucket
- Recycling of Stabilization Fluid
- Installation of Rebar Cage
- Concreting of Bored Pile using high slump self compacting tremie concrete

It is selfunderstood that all the above steps are done under a strict quality plan and suprvision by the Engineer. Prior to material installatin Koden Tests are carried out and the integrity of the piles is checked with sonic logging. The proper socketing is verified by interface coring at the pile toe through concrete into the rock.

As explained above the steps need a very detailed preplanning to arrange the timely sequencing of actions and availability of resources on site. The mobilization of the resources on the water is time consuming particularly when the concrete volume of 1 pile can be up to 500 m³ and the cage have weights up to 100 tonnes. The following Fig. 49 to Fig. 57 give site impressions of the steps above.

Figure 49. Drilling on Platform

Figure 50. Emptying Bucket into Spoil Bin

Figure 51. BG 40 Drilling on Platform

Figure 52. Recovered Granite Rock Core

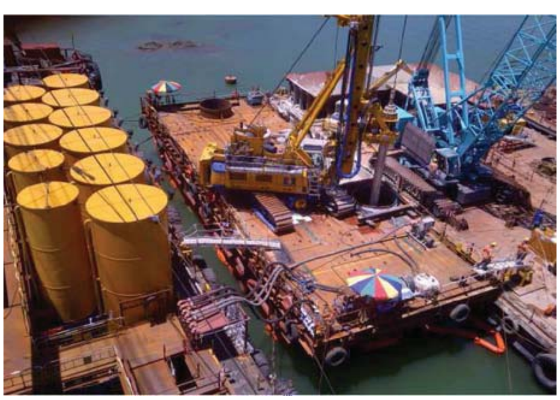


Figure 53. BG 40 Drilling with Bentonite

Figure 54. Bored Pile Inspection

Figure 55. Koden Verticality Test

Figure 56. Rebar Cage Installation with Sonic Pipes

Figure 57. Concreting of Bored Pile

The drilling performance of the Bored Piles is generally as fast as on land. Typically a Bored Pile with a length between 60 m to 80 m depth can be completed within 2 to 3 days drilling extended shifts (14 to 16 hours). The time consuming activities are the rock drilling and material installation. However, it is without doubt that the construction speed of the RKD is much faster by factors compared to the conventional RCD offshore drilling. It is this construction speed that makes the RKD also offshore the competetive solution for Bored Pile construction. A typical drilling performance chart is shown in Fig. 58.

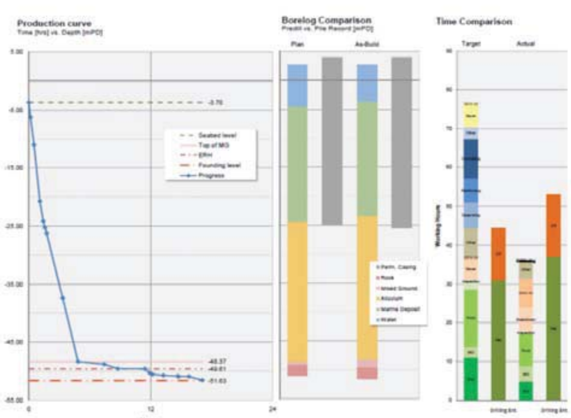


Figure 58. Typical Bauer Drilling Performance Chart

The presentation is concluded with adding a few site impression photos in Fig. 59 to Fig. 61 of this impressive Mega Project.

Figure 59. Aerial View of Airport Channel

Figure 60. Aerial View near Airport

Figure 61. Aerial View of Deep Sea Section

5 SUMMARY

The presentation intended to show methods and technical possibilities available in the market to improve soft ground offshore and construct large diameter Bored Piles efficiently offshore by referring to 2 Mega Projects presently under construction in the Hong Kong Zhuhai Corridor. The methods described are the Bauer RKD Method and the Bauer Betterground offshore Stone Columns. Both construction techniques deliver high quality products econimically by minimizing construction time. It is the first time that Bauer RKD Method is being used for Mega Offshore Project worldwide. Upon completion of the projects final conclusions will be drawn but the present experiences on site are all positive. The overall convincing performances surely still can be improved by all parties involved learning from each other to understand the needs and further optimize the entire process to fully gain the most out of the method. A short view on liquification awarness was offered in the light of the specific relevance for Indonesia.

6 APPRECIATION

We wish to thank the Organization Committee for giving us the opportunity to present this paper. Special thanks are extended to Prof. Dr. Masyhur Irsyam for inviting us to prepare this presentation. Special thanks also to our partner Betterground and Dr. Wilhelm Degen who have contributed substantially to the Section about Stone Columns and Liquifaction herein.

Bauer thanks also their Clients in Indonesia, Singapore, Hong Kong, Malaysia and throughout the world that we were given the trust to execute their difficult foundations. Particular thanks are being expressed to Dragages / China Harbour / VSL Joint Venture as our valued Clients for the project referred to in this paper.