A Critical Review of the Current Practice of Design and Construction of Offshore Foundations in Hong Kong

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doi: https://doi.org/10.21467/proceedings.133.4

ABSTRACT

Large diameter driven tubular piles have recently been used as the foundation system for the Hong Kong Offshore LNG Terminal located in the southern waters of Hong Kong SAR, to the east of the Soko Islands. At present, there are limited guidelines in local codes or guides for the design of offshore foundations in Hong Kong. It is observed that the current practice of regulatory control in Hong Kong will often cause great difficulties in planning and construction of foundation works. Moreover, it is of paramount importance to have experience in offshore pile installation, which is severely lacking in local industry, in order to produce safe and efficient foundation designs to handle the much more hostile site conditions. Some suggestions for revising the current practice are suggested to bring it more in line with accepted international practices for offshore foundations.

Keywords: Offshore Piling

1 Introduction

To support the HKSAR Government's Climate Action Plan 2050 on the increasing use of natural gas in Hong Kong to reduce carbon emission, CLP Power Hong Kong Limited (CLP) and The Hongkong Electric Co., Ltd. (HKE), are jointly developing an offshore liquefied natural gas (LNG) facility called the Hong Kong Offshore LNG Terminal (HKOLNGT) to receive and convert LNG into gas for supply to the gas receiving stations at CLP's power station at Black Point and HKE's power station at Lamma Island for power generation.

The foundations for the HKOLNGT comprise 6 pile groups each with 4 raking piles for the mooring dolphins, named MD1 to MD6; 3 pile groups each with 8 vertical piles for the breasting dolphins, named BD1 to BD3, and two pile groups each with 3 vertical piles located adjacent to MD1 for the fireboat mooring dolphins, named FD1 and FD2. The piles for MD1 to MD6 and BD1 to BD6 are 1.83m outer diameter open-end driven steel tubular piles and those of the FD1 and FD2 are similar piles but with a smaller outer diameter of 1.26m. There are a total of 54 piles for the Terminal. The foundation works for the HKOLNGT have recently been completed. Figure 1 shows a photograph of the completed foundation of the Terminal. Details of the design and installation of the foundations for HKOLNGT are presented in a companion paper by Shea et al (2022) published in the proceedings of this seminar.

The design and installation of the foundations for HKOLGNT are subject to the regulatory control of the Buildings Department (BD). There are difficulties faced in fulfilling some of the regulatory requirements for the foundation works in the project. This paper aims to present a critical review of the current practice of design and construction of offshore foundations in Hong Kong and suggest some changes that can be made to reduce these difficulties. Although the suggestions made in this paper are mainly related to the foundation type used for HKOLNGT, the ideas may also be applicable generally to other types of offshore foundations.

Proceedings DOI: 10.21467/proceedings.133; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-957605-1-0

Figure 1: Photograph of the completed foundations of HKOLNGT

2 Current Government Control on Design and Construction of Foundations

The design and construction of foundation for private development projects in Hong Kong, including those of power supply companies, are subject to the control of the Buildings Ordinance. The designs of foundation for such projects require approval by the BD. In addition, consent for constructing the foundation works needs to be applied for and granted by the BD before such works can be commenced.

The BD implements a central processing system for foundation submissions. For offshore foundations, the BD will usually refer the design submissions to relevant government departments such as the Geotechnical Engineering Office (GEO) and Port Works Division (PWD) of the Civil Engineering and Development Department (CEDD) for comments. The BD will consider comments from these departments in addition to the guidelines promulgated by its own department before granting approval of the foundation plans.

In Hong Kong, the design of foundations for private development projects usually follows the guidelines of the Code of Practice for Foundations (CoPF) (BD 2017). The GEO Publication No. 1/2006 (GEO 2006), which supersedes the earlier GEO Publication No. 1/1996 (GEO 1996) is also commonly used as a guide for foundation design, particularly for design submissions that also require acceptance by the GEO. The two GEO publications are hereafter named GEO-2006 and GEO-1996 for ease of reference.

The CoPF and GEO-2006 give guidelines only for the design of more common foundation types including footings and pile foundations such as bored piles founding on rock, driven steel piles, socketed H-piles and mini-piles. Offshore foundations often involve driven large diameter tubular piles. There is virtually no guideline in CoPF and GEO-2006 for such a foundation type and it is strongly recommended not to simply adapt these for use in offshore foundation designs. The BD implements a system of recognized pile types. At present, there are 13 recognized pile types on the approved list (BD, 2022). Currently, there is only one recognized pile type, of Reference Number BD-RP018, that is related to driven pipe piles. According to BD (2022), this pile type covers "Driven Steel Bearing Piles including H-piles and Pipe Piles (sections of yield strength not more than 355 MPa to BD EN 10025-2 or equivalent)". Unfortunately, this recognized pile type does not cover large diameter driven tubular piles commonly used for offshore foundations.

The CoPF gives the following guidelines for the design of driven piles.

"For driven piles, the ultimate bearing capacity of driven piles may be assessed by any one or more of the following methods:
(a) a dynamic formula based on the data obtained from test driving the pile on site;
(b) a static formula based on design parameters of the supporting soil obtained from suitable tests; or
(c) loading test of the pile on site.

Proceedings DOI: 10.21467/proceedings.133
ISBN: 978-81-957605-1-0
Series: AIJR Proceedings
ISSN: 2582-3922

A suitable factor of safety should be adopted when deriving the allowable bearing capacity of the piles. In general, a factor of safety not less than 3 should be used for a static formula and those formulae for which lower factors of safety have not been established. In no cases should the factor of safety be less than 2.”

All the above three methods are normally required by the BD for assessing and confirming the capacity of a non-recognized pile type. For driven tubular piles, this will usually mean that the required pile length to attain the design capacity of the piles needs to be assessed by soil mechanics principles with a factor of safety (FoS) of 3 and that final set tables need to be developed using a suitable pile driving formula for ascertaining that the target FoS can be achieved at final set. In addition, one or more trial piles may be required to be installed and subjected to a static loading test to verify the design capacity with a FoS of 3. The trial piles may be selected from the working piles or they can be purposely constructed piles to be abandoned after loading test.

According to the current practice, approval of and/or consent for the working piles or remaining working piles not selected as trial piles may not be granted until the results of trial pile(s) have satisfactorily confirmed the design pile capacity or principles of the foundation design.

Based on past experience, it will usually take 5 months or more before the design and consent of the trial piles of a non-recognized pile type can both be obtained from the BD. Once the installation of trial piles has been completed, works on site may need to be suspended until approval and/or consent for the remaining piles have been granted by the BD depending on the conditions stated in the approved foundation plans or approval letters.

Similar to the CoPF, the GEO-1996 and GEO-2006 also stipulate higher FoS for piling design unless trial piles have been used to increase the confidence of the design method. GEO-1996 recommends that the minimum FoS should be 3 for compression and lateral resistance and 3.5 for tension capacity if the method of determining pile capacity is based on theoretical or semi-empirical method not verified by load tests on trial piles. The corresponding FoS can be reduced to 2 and 2.5 if the design method is verified by a sufficient number of load tests on trial piles. In GEO-2006, the recommended FoS are reduced to 3 throughout for pile designs not verified by trial piles and 2 throughout when there are sufficient load tests on trial piles.

3 Difficulties Faced in Design of Offshore Foundations

In the preceding section, an overview of the current practice regarding regulatory control of design and construction of larger diameter tubular piles has been presented. Such practices, when applied to offshore foundations, will impose extreme difficulties on the design and construction as explained below.

3.1 Dynamic Formula

In Hong Kong, the pile driving formula developed by Hiley (1922) and enshrined in the CoPF is essentially the only pile driving formula that will be accepted by the BD for developing the final set tables. The Hiley formula which has served the industry well in times of uncertainty is long overdue for retirement. As discussed by Li et al. (2003a), the Hiley formula predicts that the energy transmitted to a driven pile after hammer impact will decrease with pile length. However, there are abundant data to indicate that the energy transferred to a driven pile after impact will remain relatively constant and independent of pile length for a given pile type, pile driving hammer and ground condition (e.g. Li et al. 2003a). The Hiley formula is therefore flawed, or at least problematic for long piles.

The Hiley formula contains three input parameters, namely the hammer efficiency α, the coefficient of restitution e, and the elastic compression of pile cushion C_c. Usually, the formula is not sensitive to the magnitude of C_c, but highly dependent on α and *e*. The parameter *e* is not a fundamental parameter and essentially an artifact of the theoretical model. One has to rely on past experience of similar pile types and hammer types for the selection of a suitable design value of *e*. For offshore piles, there are rarely sufficient past experience for the choice of a suitable site-specific design value of *e* for meaningful application of the Hiley formula for prediction of pile capacity.

3.2 Static Formula for Assessing of Pile Capacity

There is little guideline in the CoPF on assessing the static capacity of piles except for some presumed allowable bearing pressure for soils and rocks. The GEO-2006 does discuss some textbook methods on assessment of the static capacity of piles. For shaft resistance, the suggested methods are largely confined to the conventional approaches based on the so-called α-method for clayey soils and β-method for sands. For end-bearing resistance of a solid pile, the bearing capacity factor can be obtained from a design chart in GEO-2006. Limiting values are suggested in the GEO-2006 for both the shaft and end bearing resistance.

When a foundation design is subject to the scrutiny of regulatory authorities, it is not surprising that reasonably conservative values and assumptions need to be adopted for estimating the static capacity of piles. For instance, the design strength profiles should be reasonably close to the lower bound envelope of test results, soil layers with interbedding layers of sands, silts and clays should be treated as purely a clay layer using undrained parameters, design values of adhesion factor α and shaft resistance factor β should be sufficiently conservative and perhaps close to the recommended lower bound values, and shaft and end-bearing resistance to be capped at the limiting values such as those suggested in GEO-2006 or even lower values. Given these various sources of conservatism, the end results are usually that the pile length required to achieve the required static capacity with a FoS of 3 may become exceedingly long, making installation of offshore piles more difficult as more site welding will be necessary for splicing of longer piles and heavier hammer will be required for installing the longer and thicker piles.

The situation may become worse if the estimated pile length to achieve the calculated ultimate pile capacity turns out to be a requirement of the approval. If the design static length is obtained from conservative design assumptions and parameters or when a stiffer stratum is encountered earlier than expected due to local variation of ground conditions, the required minimum pile length may not be achievable during construction. This will trigger new design submissions for justifying the adequacy of a shorter pile and, if necessary, re-design of the foundation. Worse still, preboring may be required for the purpose of achieved the specified minimum pile length. All these problems will no doubt cause severe interruption of and delay in pile installation.

3.3 Multiple Approvals and Consents

As discussed above, trial piles are usually required for non-recognized pile types. If the design and installation of trial piles need to be separate from working piles, foundation works on site need to be suspended for months after the construction and testing of trial pile until approval and consent for the working piles have been obtained.

3.4 Loading Tests

Except for mono-piles, stability of offshore piles installed in deep waters is typically maintained by pile jackets or steel frames. To ensure safety of the pile foundation and the pile jacket under adverse or extreme weather and wave impact, it is always desirous to connect the piles to the pile jacket by welding and to also seal the gap between the pile and the pile jacket if necessary as soon as practicable after the satisfactory completion of pile installation. This will make static loading test of a working pile a difficult task.

Even if the welded connection of the working pile selected for loading test can be temporarily removed to free up the pile for loading test, the pile jacket may not be sufficiently strong to act as the supporting flame for the kentledge. It may not be feasible nor environmentally friendly to design the pile jacket to also serve as a supporting frame for static loading test to be conducted for any possible working piles, including edge piles, to be selected by the BD for loading test. Also, the layout of the working piles may be such that they will not be adequate in supporting a kentledge load in excess of three times the design working load of the test pile.

If a static loading test is to be carried out for the trial pile or a working pile, a separate temporary supporting frame similar to a pile jacket and perhaps also new reaction piles may need to be constructed for the purpose of static loading test. Such supporting frames and reaction piles cannot be commenced until the location of test pile(s) to be selected by the BD for loading test is known after completion of all working piles. This will make the task of conducting a static loading test much more difficult as the presence of installed pile jackets and working piles will impose severe limitations in maneuvering the marine vessels for such works. Moreover, reaction piles and temporary supporting frame may need to be removed after static loading test as they may affect the intended operation of the offshore facility. Perhaps most importantly, creating a large set up of kentledge for pile testing is inherently very risky for offshore environment as when adverse weather arrives such as strong winds and waves, the monsoons or the typhoons, complete evacuation would need to take place in good time.

For the above reasons, static loading tests are not practical for offshore foundation works and are therefore seldom used in international practice because of safety, the long delay they may cause to an offshore project and the high costs involved.

3.5 Suspension of Works

As discussed earlier, the design and construction of offshore foundation often require multiple approvals and consents for different stages of works. Sometimes, when conditions are imposed in the approved foundation plans and/or approval letters, such conditions may need to be complied with before the next stage of construction can be started. For instance, if a condition that working piles cannot be started after satisfactory completion of the trial pile(s) has been imposed, installation of working piles will need to be severely delayed. As will be explained later, idling is extremely costly and unsafe for offshore foundation works. There is a great need for simplifying the regulatory control procedures to make offshore works a less difficult task.

3.6 Understanding of Construction in Offshore

Designers of offshore foundation must also be experienced in dealing with the various constraints and difficulties in construction. This is indeed why typical foundations codes for land works cannot be easily applied to works in offshore. The sea state due to the weather conditions often dictates the method of construction and hence the design. Typically, it is essential to estimate the window of opportunities to carry out the piling works using the right type of Principle Installation Vessel (PIV). This often means that the designer will focus on how to ensure the installation time spent at offshore site is as short as possible. The preference will therefore be for large diameter driven piles to reduce the installation time. The piles would be thicker than those used on land to fully utilize the capacities from the friction and end bearing of the long piles. The need for splicing would also be kept to a minimum and hence single segment of pile of >50m long is quite common and usually limited by the size of the transportation vessels. For similar reasons, it is also not preferred to have pile lengths that need to be determined on site, for example, driving to a set table. The designers would also need to take into account during the design stage the type of PIVs that are likely to be used for installation in order to tackle the sea state such as wind, wave and in particular where it might be susceptible to long period swells. For the more heavy-duty offshore piling works, the PIVs may need to be secured well in advance and this, in turns, could also affect the tender strategy and the design process.

4 International Practice

The international practice for offshore foundations is no doubt influenced by the difficulties and high costs in carrying out both ground investigation and foundation works in deep waters. The tubular piles and pile jackets are usually pre-fabricated in whole or in parts in fabrication yards and shipped to site for installation.

In addition to boreholes that are sunk for obtaining soil samples for confirming the soil types of founding soils and laboratory testing for measurement of soil parameters, cone penetration test (CPT) soundings can be used more economically to supplement the boreholes for delineating variation of the soil profile and for inferring the soil properties.

The information obtained from ground investigation and CPT tests will be used for estimating the variation of pile resistance with pile length. This exercise is useful in planning the lengths of individual segments of tubular piles to be fabricated. It is equally important in assisting the contractor in selecting a suitable hammer for pile driving and evaluating of the drivability of piles, something which are commonly performed with a popular program GRLweap developed by Pile Dynamic, Inc. (PDI).

The estimated pile length required to achieve the target capacity is seldom used as a rigid design requirement unless there are other design considerations such as tension capacity which dictates the design pile length. Designers usually rely on a dynamic pile testing method for estimating the pile capacity of installed piles, and not counting fully on the calculated pile length needed to achieve the target static capacity. The piling testing equipment Pile Driving Analyzer (PDA) and the program CAPWAP which predicts the pile capacity based on data obtained from a PDA test, both developed by PDI, are popular tools that can be used for monitoring the pile capacity during driving, at end of driving (EOD) or after installation. Static loading tests are rarely used for determining the static capacity of offshore piles.

The design guidelines published by the American Petroleum Institute (API) are some of popular design standards adopted worldwide for design of offshore foundations. In the code API-RP 2A-WSD developed by API (2014), it is recommended that the FoS for pile design should be determined in accordance with the risk level of the structure. FoS of 1.5 or 2.0 have been recommended as general guidelines for the *design environmental condition* and *operating environmental condition* respectively, which can be treated as equivalent to the *Normal* and *Extreme Conditions* in Port Works Design Manual (PWDM), Part 1 (CEO 2002). The recommended FoS for pile design in API-RP 2A-WSD are shown in Table 1.

Table 1: Pile Factors of Safety for Different Load Conditions (from Table 9.1 of API-RP 2A-WSD)

Condition Number	Load Condition	Factors of Safety
1	Design environmental conditions with appropriate drilling loads	1.5
2	Operating environmental conditions during drilling operations	2.0
3	Design environmental conditions with appropriate producing loads	1.5
4	Operating environmental conditions during producing operations	2.0
5	Design environmental conditions with minimum loads (for pullout)	1.5

The design environment conditions in Table 1 are recommended to be determined based on the design life of the structures, likelihood, and consequence of its failure following API design philosophy. In general, 100-year oceanographic design criteria should be adopted for structures that are manned during the event or whose failure will result in a high consequence. For structures that are unmanned or evacuated during a storm event, with a short design life of say 20 years or when loss or severe damage

Proceedings DOI: 10.21467/proceedings.133
ISBN: 978-81-957605-1-0

Series: AIJR Proceedings
ISSN: 2582-3922

will not result in a high risk to life, a reduced factor can be allowed. The operating environment conditions generally refers to a 1-year to 10-year storm for the Gulf of Mexico, though the design conditions for a specific project will depend on the site-specific metocean condition and project-specific requirements.

In contrast, design load conditions for offshore works in Hong Kong usually follows the guidelines in Section 5.10.2 of the PWDM, Part 1 (CEO 2002). A 100-year return period for wave, current and water levels and 50-year return period for wind are generally required for the extreme condition, which is consistent with recommendations in API-RP 2A-WSD. For the normal condition, a design 2-year storm event can be adopted in the absence of more meaningful wave information. It should be noted that this recommendation should be consistent with the definition of normal condition in PWDM and it refers to the "wave condition at no.3 or within a first few hours of hoisting of no.8". The applicability of 2-year storm event as the *Normal Condition* should be reviewed for future offshore development for which the effect of climate change over the structure's design life may need to be considered in the choice of design return period.

The recommended FoS in Section 3.5.2 of PWDM Part 2 (CEO 2004) does not distinguish the Normal and Extreme Conditions and are based on the older GEO-1996 which requires a higher design FoS for piling design than GEO-2006 for tension piles.

As discussed earlier, large diameter driven steel tubular piles are regarded by the BD as a non-recognized pile type for which a design FoS of 3 and loading tests on trial piles may also be required. This, coupled with a similar requirement in PWDM Part 2, will mean that the design requirements for offshore pile foundations are much more stringent than international practice in terms of proof testing and design FoS.

The α-method for clay and β-method for sands are both discussed in GEO-2006 and in the main text of API standard API RP GEO (API 2011), although the recommended values of β and limiting shaft friction values are different. In international practices, the pile capacity of offshore piles are more commonly estimated directly from CPT results. Further discussions in this respect are given in Shea et al. (2022).

5 Behaviour of Offshore Piles

It is well established that large diameter driven tubular piles will exhibit increase in capacity with time, a phenomenon usually called the set-up effect. The set-up effect can be attributed to kinematically restrained dilation of soils close to the pile shaft and soil ageing (Bowman & Soga 2003, 2005). Set-up effects can be significant for large diameter tubular piles. Sze et al. (2014) reported a case study in which significant pile resistance increase had been observed during re-strike after the installation of closed-end tubular piles were temporarily suspended for extension of the pile before continuing the pile installation.

The set-up effect can be characterized by the ratio of $r = R_t/R_{EOD}$, where R_t and R_{EOD} are the pile capacities at time t after installation and at EOD respectively. In the literature, the set-up curve which describes the variation of r with time is commonly modelled as a logarithmic function. This relationship is theoretically deficient as it predicts an unbounded limit for r. An alternative relationship based on a hyperbolic function which caps the ratio r at a limiting value at large time t is suggested by Shea et al. (2022) and found to give a good fit to the data obtained from the HKOLNGT project.

Sometimes, foundation contractors will take advantage of set-up effect and stop pile driving before reaching the target FoS at EOD, allowing the required FoS to be attained due to set-up effect before the deck structure is built above the pile foundations.

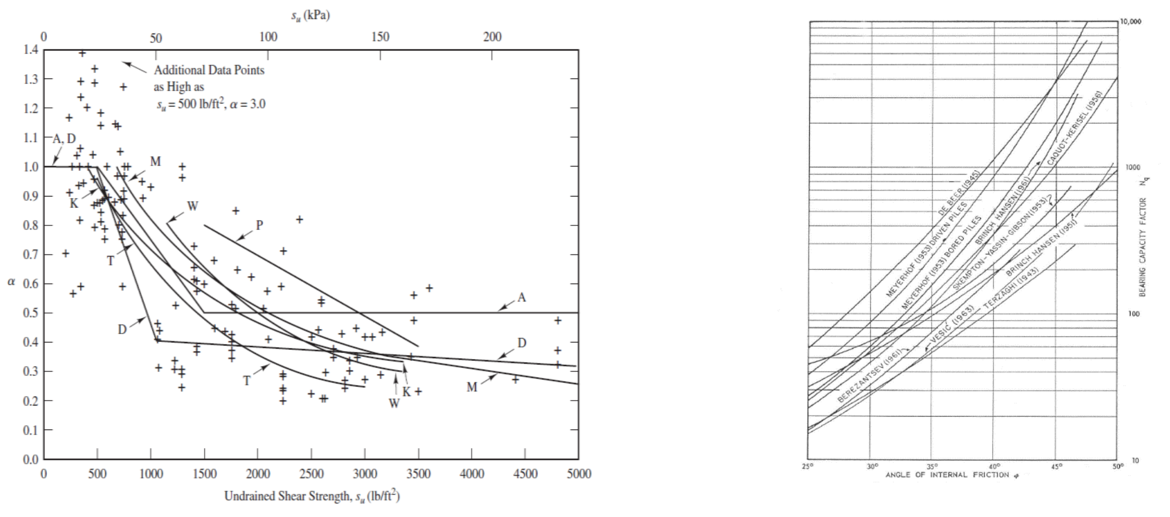
The set-up effect also has implications on planning the driving operation. To enable the design pile length to be reached with the minimum of pile driving energy, the installation of piles should be completed with as little interruption as possible to avoid increased pile resistance that will develop during interruptions.

The set-up effect may be different for the toe resistance and shaft resistance and may also vary along the pile length. The effect tends to be more significant for the shaft resistance than the toe resistance. Care should therefore be taken when back-analyzing the pile resistance obtained from CAPWAP analyses or instrumented piles. A higher mobilization ratio can often be attained for the toe resistance in the initial periods after pile installation when the shaft resistance is still low due to its slower rate of set-up. With time, a higher shaft resistance will be developed. For the same pile driving energy, the pile toe displacement that can be mobilized will be reduced and it may not be able to fully mobilize the toe resistance during the PDA test, giving a wrong impression that the toe resistance has dropped with time. When assessing the pile capacity, one should take account of all the estimated toe and shaft resistances measured at different times. The total capacity should be better assessed by summing the maximum measured toe resistance and shaft resistance although they may not occur at the same time (Hussein et al. 2002).

6 Uncertainty of Foundation Design

As remarked by Li et al. (2003b), the current practice of calculating the static capacity of piles is fraught with problems because the conventional, simple textbook theories described in most design guidelines, including GEO-2006, often fail to give accurate prediction of pile capacity. This can be illustrated using the data in Figure 2(a) which presents the data and design lines marked with A, D, K, M, P T and W recommended by various researchers for adhesion factor of clay and Figure 2(b) which shows the bearing capacity factor for the toe resistance of a solid pile proposed by different renowned researchers. It can be observed from Figure 2 that there is a high degree of uncertainty in soil mechanics theories and it is justifiable to adopt a higher factor of safety of 3 or higher when predicting the geotechnical pile capacity purely on the basis of theoretical or semi-empirical methods.

The technology of dynamic pile testing, such as PDA tests and CAPWAP analyses, has now become very mature after almost 50 years of development. The pile capacity predicted by such techniques are proven to be much more reliable than that estimated by conventional soil mechanics theories. Figure 3 shows the result published by Likins & Rausche (2004) for a correlation between pile capacities predicted by CAPWAP analyses (denoted by CW) and static loading test (denoted by SLT) based on a database of 303 results. The data cover results for a large range of piles including H-piles, bored piles, reinforced concrete piles, prestressed concrete piles, open-end and closed-end tubular piles, and auger piles. The results give a ratio of CW/SLT with a mean value of 0.98 and a coefficient of variation (COV) of16.9%. The CAPWAP analyses can therefore give an essentially unbiased and reasonably accurate prediction of the static capacity of piles.



(a) (b)

Figure 2:(a) Adhesion factor α for clay (after Coduto et al, 2016) and (b) bearing capacity factor N_q for toe resistance of pile (after Vesic, 1967)

Proceedings DOI: 10.21467/proceedings.133
ISBN: 978-81-957605-1-0

Series: AIJR Proceedings
ISSN: 2582-3922

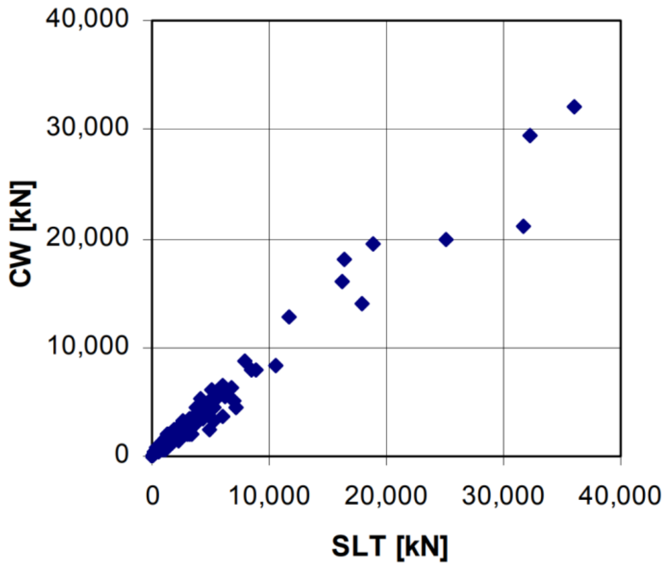


Figure 3: Comparison of pile capacity measured by CAPWAP analysis (CW) versus static loading test (SLT) (after Likins & Rausche 2004)

The reliability of the method for estimating the pile capacity has a significant bearing of the required FoS for piling design. This can be discussed by way of a simple analysis. Consider a group of n piles with a similar design and installed in similar ground conditions. One can assume that the failure probability p of each pile is the same. The system failure probability of the pile group, defined as the failure probability of one or more piles within the group (denoted by P_S), is given by:

$$P_S = 1 - (1 - p)^n \quad \textbf{(1)}$$

Consider two design approaches. In the first approach, the pile capacity is predicted using theoretical method with a target FoS of 3. The distribution of the actual FoS of pile under this design approach is denoted by R_1. As the design FoS is 3, it is convenient to assume that R_1 is a normally distributed random variable with a mean value of 3.0. Given the high uncertainty of predicting the pile capacity using a theoretical approach, it is reasonable to adopt a higher COV of, say, 30% for R_1, giving a standard deviation of $0.3 \times 3 = 0.9$ for R_1.

In the second design approach, PDA tests are conducted and CAPWAP analyses performed for all piles and each pile will achieve a FoS of 2.0 at EOD. The actual FoS of pile designed based on the second approach is denoted by R_2. Again, it is also assumed for convenience that R_2 is a normally distributed random variable, but now with a smaller mean value of 2. As CAPWAP analysis is a proven reliable tool for predicting the actual pile capacity, it is reasonable to adopt a smaller COV of 17% for R_2 based on the study by Likins & Rausche (2004). This gives a standard deviation of 0.17 x 2 = 0.34 for R_2.

A pile will fail if its FoS fall below a value of 1.0. The failure probability of a single pile, p, can then be evaluated using the cumulative distribution function of a normal distribution. For the first design approach, the value of p is given by p = Prob ($R_1 < 1$) = 0.013. For the second approach, the failure probability of a single pile is p = Prob ($R_2 < 1$) = 1.64×10^{-3}.

Suppose there are 40 piles in the pile group. Assuming that a loading test has been conducted successfully for a working pile as trial pile before commencement of foundation works and another working pile after completion of works, the pile capacities of these two tested piles are confirmed to be satisfactory by the loading tests. However, there is still a chance that one or more of the remaining 38 piles may fail. Taking $p = 0.013$ and $n = 38$, Eq.1 gives a system failure probability of $P_S = 0.395$ for the pile group designed using the first approach.

For the second design approach, all the 40 piles have been subjected to PDA tests and confirmed to have a CAPWAP capacity with FoS higher than 2.0. There is still a chance that any of the 40 pile may fail when subjected to a static loading test. The system failure property will then be evaluated based on $p = 1.64 \times 10^{-3}$ and $n = 40$, giving a result of $P_S = 0.063$.

It can be observed from the above simple analysis that the system failure probability is much lower for the second design approach despite the use of a lower FoS. Although the above analyses are over-simplified, it serves to illustrate the main point that, from a system reliability point of view, it is much more preferable to adopt a lower FoS for design coupled with the use of a reliable testing technique for indirect verification of the pile capacity for all or a significant proportion of the piles than to adopt a less reliable method of design but with a more reliable load testing method implemented for just a few piles.

The information that one or more piles have passed the static loading tests or PDA tests is useful in updating the probability distribution using the well-known Bayesian method (see Ang & Tang, 2007) to produce a more accurate prediction of failure probability. For the first approach, there is only limited information based on the results of a few static loading test and it will not produce a much more reliable posterior probability distribution after updating. For the second design approach, PDA tests are to be carried out for all piles and the posterior probability distribution so obtained based on such vast information of successfully completed PDA tests will lead to a much more accurate and smaller predicted failure probability. The contrast between the two design approaches will become much larger in actuality when considering the updating of probability distribution based on proof testing results and it will give a much stronger theoretical support to the notion that the second design approach is the much more preferred option.

Given the higher reliability of the PDA test, it will be overly conservative to require offshore piles to achieve a high FoS of 3 for the CAPWAP capacity when the second approach is adopted for pile installation and proof testing. If such a high FoS is stipulated, stronger tubular sections will be required to withstand the higher driving stress and the piles will have to be driven to deeper levels to achieve a higher geotechnical capacity. This is not a satisfactory situation when there is a global trend towards more sustainable construction and the aim to reduce the installation time in the risky offshore environment.

7 Difficulties Encountered in the HKOLNGT Project

The foundation system for the HKOLNGT project is the first of its kind in Hong Kong. It was anticipated from the outset that the BD would treat the larger diameter driven tubular piles for this project as a non-recognized pile type. It was also expected that the design of large-scale pile jacket for holding the piles during installation and maintaining stability of the pile under permanent conditions would also be something novel and the BD might take a longer period of time for reviewing the design before approval. For this reason, the design of the foundation works for the HKOLNGT project were divided into a few smaller packages to ensure smoother and hopefully more timely approval by the BD. The first submission package covered only the design of foundation of 4 piles and the associated pile jacket for mooring dolphin MD2, which is located on the northern side of the Terminal.

As expected, the proposed pile foundation system for the HKOLNGT was categorized as a non-recognized pile type and the design approval required a review by the Structural Engineering Committee (SEC) of the BD before approval. The review by SEC could not be initiated until comments from other concerned government departments or offices, including the GEO and PWD, had been received by the BD and there were no major objections from such parties in approving the design. In the event, it took about 5 months before approval of the foundation plans for MD2 could be obtained. At the time of submission, it was proposed that PDA tests and CAPWAP analyses would be conducted for all the piles of MD2 as an alternative to dynamic formula for pile driving and also as an alternative to static loading test of pile. It was initially hoped that a design FoS of 2.0 could be adopted in line with international practice for design of offshore foundations. In the event, the following requirements would need to be fulfilled for the foundation works after approval.

- PDA with CAPWAP analyses to be conducted for all the piles of MD2.
- Unless a FoS of 3 can be achieved for the CAPWAP capacity at EOD, restrike PDA tests should be carried until a FoS of at least 3 is attained.
- The piles have to reach the minimum pile length required to achieve the design static capacity, with a FoS of 3
- Back-analyses should be carried out using CAPWAP results to verify the design assumptions and soil parameters used for evaluating the static capacity.
- A performance review of the foundation works should be carried out upon completion of the foundation works for MD2.

The same requirements were also imposed on later submissions of the foundation works of other mooring dolphins and breasting dolphins.

Although trial pile and static loading test of working pile(s) are not required in the approved foundation plans, the need for achieving a CAPWAP capacity with a FoS higher than 3 for all piles is in essence a replacement for static loading test and arguably an equally stringent requirement for this project due to significant increase in weather risk with the prolonged installation.

One of the key constraints for the piling works on this jetty was to avoid the peak occurrence season of the Finless Porpoise that lasts a total of 6 months within the year. This was stated in the original Environmental Permit (EP) to be between December and May (both months inclusive) and later adjusted to be from January to June under a variation to the EP.

Due to the lengthy procedure required to secure approval and consent for the foundations, the first offshore installation of mooring dolphin MD1 could only be started in early December 2020. However, it was considered extremely important to complete at least one jacket and the associated 4 piles before the end of December so that during the non-piling period, the installation data could be analyzed in detail to gain more confidence in completing the rest of the piling works in the following year. The installation and subsequent PDA tests took approximately 15 days to complete just in time for the suspension of works at the end of December 2020. The installation of the foundations for MD1 was found to be slower than the contractor’s experience in carrying out similar foundations in similar geology internationally by some 40%. This is largely attributed to a higher FoS adopted for this project and a longer waiting time for the set-up effect to develop to enable a CAPWAP capacity with FoS higher than 3 to be attained for all piles.

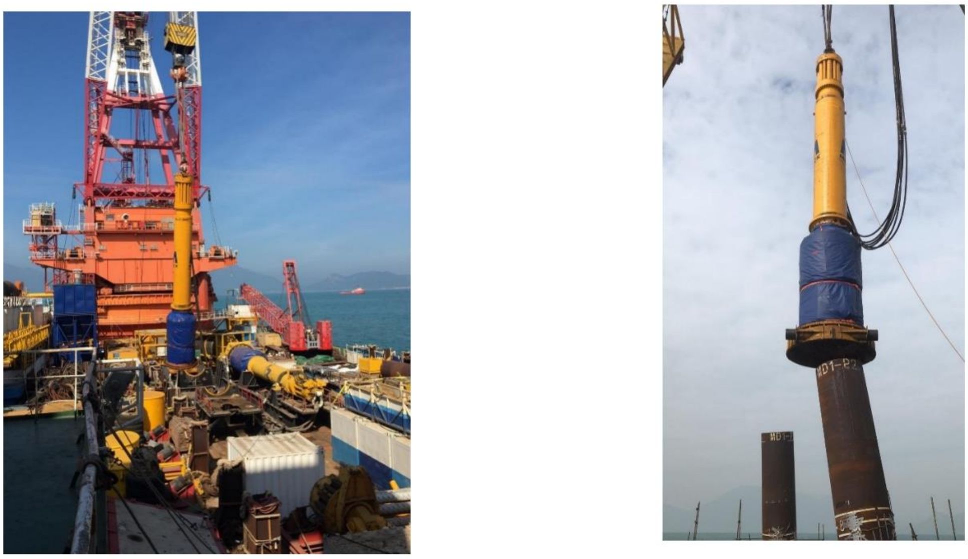
An idling time of nearly 5 days waiting for proof load test is rare in offshore installation practice due to the aim to achieve safe construction by limiting the offshore works duration as well as the expensive installation vessels and sizable crew and technical people onboard normally required for offshore installation works. Luckily, the development of set-up effect for this site has been consistent and fast enough to enable the pile installation for MD1 to be completed before the end of piling window with only a few days to spare. Otherwise, the partially completed piles would need to be temporarily fixed onto the pile jacket by welding and the piling works could only be resumed half a year later when the new piling window begins the following year.

The significance of being able to complete MD1 within 2020 cannot be overstated. During the peak porpoise activity season, the project team was able to make good use of the data collected on the behaviour of the pile / soil interactions and made suitable amends to the design to be in a much better position to complete the remaining piling and testing works within 2021. Further discussions on the observed pile capacity set-up for this project are presented in the work of Shea et al. (2022).

Like all other offshore works, the offshore lifting, installation and piling operations for this project were heavily controlled by the forecasted and prevailing weather conditions and sea states at the time.

Figure 4 shows examples of instances when the offshore construction works have been particularly challenging during the installation of MD1. Lifting of the heavy piling hammer from the congested vessel deck could be difficult under seemingly good weather often due to the long period wave from afar. Heaving, pitching and rolling motions of the crane vessel and/or high winds could potentially cause the piling hammer to swing making it difficult to slot its sleeve over the raking piles. Lifting operations were therefore suspended for 1-2 days until an improved weather window became available. This highlights the construction difficulties unique to large-scale marine construction compared to conventional land-based projects.

For reasons discussed earlier, it is always desirable to reduce the idling time as far as possible to enable the piling works to be completed as quickly as feasible while the metocean conditions are good. The duration of the jacket installation work cycle, including jacket lowering, piling, proof testing, welding and grouting, should be reduced as far as practical so that there is certainty that the majority of the installation can be completed within a seven-day forecast of reasonable weather. It is important to note that once the jacket is lowered on the seabed and the piling works have commenced, the work cycle cannot be interrupted. In the event of adverse weather conditions such as strong wind from monsoon or hoisting of typhoon signal No. 3 or above, the installation vessel will need to evacuate from site and take shelter because it would be unsafe for it to remain in the open sea under such conditions. Hence, it is of paramount importance to limit the installation cycle to around 7 days when the weather is 'forecastable', so that the jacket substructure can be well-secured to the seabed by completed piles to ensure the site safety.



(a) (b)

Figure 4: Difficulties of installation caused by weather (a) heavy piling hammer needs to be lifted from congested deck and (b) difficulty to slot piling hammer into raking piles.

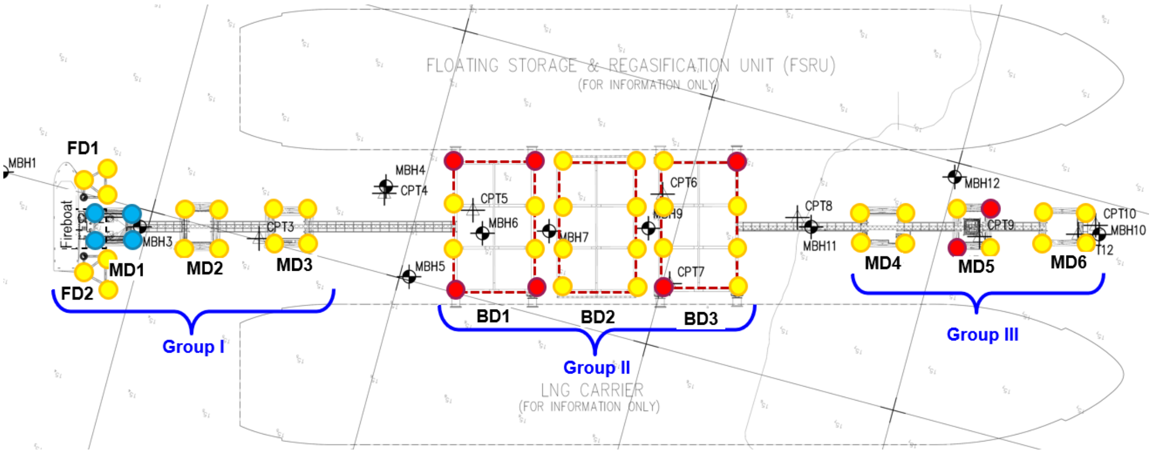
Soon after resuming piling works in the summer of 2021, with due consideration of the duration needed for installing and testing MD1, the early optimism of being able to complete the remaining piling works in 2021 was quickly eroding away with the arrivals of typhoons at poor timing. As explained by Shea et al. (2022), the offshore construction sequence and vessel maneuverability for this project are limited by the anchorage spread arrangement, making it difficult/infeasible for the installation vessel to readily return to the previous location(s) due to interference between anchorage lines and the completed mooring/breasting dolphins. Also, it will not be possible to mobilize one additional installation vessel to speed up the foundation works. Faced with this big difficulty, the project team decided to put forward the following proposal to the BD to relax the proof testing requirement so as to speed up the construction programme.

Proceedings DOI: 10.21467/proceedings.133
ISBN: 978-81-957605-1-0

Series: AIJR Proceedings
ISSN: 2582-3922

- Only some instead of all piles will be selected for restrike PDA tests to achieve a FoS of 3.
- The set-up curve is constantly updated as more information on CAPWAP capacities of installed piles becomes available.
- For the remaining piles not selected for achieving a CAPWAP capacity with FoS higher than 3, the longer-term pile capacity can be inferred from the updated set-up curve. The pile capacities of all such remaining piles inferred from the set-up curve should attain a FoS higher than 3 when reporting completion of foundation works to the BD.

The above proposal, if accepted, will save a lot of time in having to wait for achieving a FoS higher than 3 during restrike tests for all piles. A second SEC meeting was held by the BD to consider the above proposal. Figure 5 shows the relaxed proof testing regime by PDA tests for the project finally accepted by the BD.



- Completed MD1 piles with restrike PDA tests to FoS = 3, in addition to tests at EOD
- Selected for restrike PDA tests, in addition to test at EOD, to test to FoS = 2 and 3 by PDA at time of testing (Tentative locations shown)
- Selected for restrike PDA tests, in addition to test at EOD, to test to FoS = 2 by PDA at the time of testing and FoS =3 by set-up evaluation

Figure 5: Optimised Testing Proposal for Proof Load Tests at Remaining Dolphins

The piles are grouped into Group 1 to 3 according to similarity in geological conditions as shown in Figure 5. For Group 1 piles, the 4 piles of MD1 completed earlier have already achieved CAPWAP capacities with a FoS higher than 3. No more pile will be selected from this group for restrike PDA tests to achieve this higher FoS. For Group 2 piles, 4 piles have been selected for restrike PDA tests until a FoS higher than 3. For Group 3 piles, the number of selected piles is reduced to 2. With the revised proof testing arrangement, it was possible to complete the foundation works largely within the original construction programme.

8 Conclusions

The following recommendations are made after reviewing the current practice of design and regulatory control of offshore foundations in Hong Kong.

a. PDA tests with CAPWAP analysis are proven reliable techniques for predicting the pile capacity and can be used as a convenient alternative to pile driving formula for final setting of piles and as replacement for static loading test for verifying the geotechnical capacity of piles. For this reason, the requirement of trial piles should be dropped for offshore piles and the requirement of static loading test for working piles can be waived without jeopardizing safety.

b. From a system reliability point of view, it is much better to design piles with a lower FoS with more extensive PDA testing than to use a less reliable design method with a higher FoS and static loading test for a just a few piles. The current practice should be critically reviewed and revised to cater for the special conditions of offshore foundations.

c. If pile installation and acceptance are based on PDA tests, it will no longer be necessary to rely systematically on theoretical or semi-empirical methods for predicting the geotechnical capacity of piles. A FoS of 3, which is intended to cover the higher uncertainty of such theoretical methods, is considered not necessary and extremely conservative for offshore foundations installed with PDA testing. Lower FoS as suggested in API codes are considered reasonable and in line with international practice.
d. If the pile capacity predicted by theoretical methods is not reliable, it is unreasonable to require the installed piles to achieve the minimum pile length corresponding to the calculated static capacity. PDA tests can give a much more reliable indicator as to whether the installed pile length is sufficient to achieve the required capacity.
e. For offshore foundation projects, it is important that the installation of piles can be completed quickly and with as little interruption as possible to reduce the risks of damage to unfinished substructure during adverse weather and ocean conditions. Imposed conditions that may cause interruptions to foundation works should be kept to the minimum when approving the foundation plans.

9 Declarations

9.1 Acknowledgements

This paper is published with the permission of CLP Power Hong Kong Ltd. and Hongkong Electric Co. Ltd. The assistance from Mr. Victor Shea in preparing this paper is gratefully acknowledged.

9.2 Publisher's Note

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References

Ang, A.H-S. and Tang, W.H. 2007. Probability Concepts in Engineering: Emphasis on Applications to Civil and Environmental Engineering, 2nd Edition. John Wiley & Sons.
API. 2011. RP2 GEO: Geotechnical and Foundation Design Considerations. American Petroleum Institute.
API. 2014. Planning, Designing and Constructing Fixed Offshore Platforms - Working Stress Design. API Recommended Practice 2A-WSD. American Petroleum Institute.
Bowman, E.T. and Soga, K. 2003. Creep, ageing and microstructural change in dense granular materials. Soils and Foundations, 43(4), 107-117.
Bowman, E.T. and Soga, K. 2005. Mechanisms of setup of displacement piles in sand: laboratory creep tests. Canadian Geotechnical Journal, 42, 1391-1407.
Buildings Department (BD). 2022. List of recognized types of piles (downloaded from https://www.bd.gov.hk/doc/en/resources/pre-accepted-materials/CDBRPT.pdf 12 April 2022).
Civil Engineering Office (CEO). 2002. Port Works Design Manual Part 1 - General Design Considerations for Marine Works. Civil Engineering Office, Civil Engineering Department, Hong Kong SAR.
Civil Engineering Office (CEO). 2004. Port Works Design Manual Part 2 - Guide to Design of Piers and Dolphins. Civil Engineering Office, Civil Engineering Department, Hong Kong SAR.
Coduto, D.P., Kitch, W.A. and Yeung, M-C. R. 2016. Foundation Design Principles and Practices, 3rd Edition. Pearson Education, Inc.
Geotechnical Engineering Office (GEO). 1996. GEO Publication No. 1/1996: Pile Design and Construction.
Geotechnical Engineering Office (GEO). 2006. GEO Publication No. 1/2006: Foundation Design and Construction.
Hiley, A. 1922. The efficiency of the hammer blow. Engineering, 673-674, 711-714, 745.
Hussein, M.H., Sharp, M.R. and Knight, W.F. 2002. The use of superposition for evaluating pile capacity. Geotechnical Special Publication No. 116, ASCE, 6-21.
Li, K.S., Chan, S.T. and Lam, J. 2003a. An alternative pile driving formula – a preliminary study. Proc. HKIE Geotechnical Division Annual Seminar, 179-189.
Li, K.S., Lee, P.K.K. and Lam, J. 2003b. Chapter 1: Introduction. Design and Construction of Driven and Jacked Piles, (Editor: K.S. Li). Centre for Research & Professional Development.
Likins, G. and Rausche, F. 2004. Correlation of CAPWAP with static load tests. Proc. 7th International Conf. on Application of Stresswave Theory to Piles, 153-165.
Sze, J.W.C., Li, J.C.Y. and Lau, C.K. 2014. Foundation design for a residential development in adverse ground condition at Designated Area of Northshore Lantau. Proc. HKIE Geotechnical Division Annual Seminar, 143-149.
Shea, V., Li, D., Shum,D and Chu, F. 2022. Large diameter open-end steel piled foundations for the Hong Kong Offshore LNG Terminal – design and installation. Proc. HKIE Geotechnical Division Annual Seminar.
Vesic, A.S. 1967. Ultimate loads and settlements of deep foundation in sand. Proc. Symposium on Bearing Capacity and Settlement of Foundations, (Editor: A.S. Vesic), 53-68.