

The Establishment of a Safe Method of Offshore Pile Driving in Hong Kong

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ABSTRACT

Large diameter driven steel tubular piles have been used as the foundations for the recently completed Hong Kong Offshore LNG Terminal located in the southern waters of Hong Kong to the east of Soko Islands. A large number of PDA tests have been conducted for assessing the pile capacity of the offshore piles and gauging the development of pile resistance with time. This has provided a good opportunity to better understand the behaviour of offshore piles in Hong Kong. Analyses of the PDA test data are presented to explore the relationship of pile capacity predicted by the Case method and CAPWAP method and also variation of energy transfer and development of pile resistance over time after the end of initial driving. A simpler approach for describing the set-up curve of pile capacity is also proposed.

1 INTRODUCTION

CLP Power Hong Kong Limited (CLP) and The Hongkong Electric Co., Ltd. (HKE) have jointly developed the Hong Kong Offshore LNG Terminal (hereafter called HKOLNGT or the Terminal) which is an offshore liquefied natural gas (LNG) facility 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 Terminal comprise 6 pile groups of mooring dolphins, MD1 to MD6, each with 4 raking piles; 3 pile groups of breasting dolphins, BD1 to BD3, each with 8 vertical piles; and two pile groups of fireboat mooring dolphins, FD1 and FD2, located adjacent to MD1 and each with 3 vertical piles. The piles for MD1 to MD6 and BD1 to BD3 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 project was completed in 2023. Figure 1 shows a photograph of the completed foundation of the Terminal and Figure 2 the completed facility. Some backgrounds of the HKOLNGT project have already been presented in Lee et al (2022) and Shea et al (2022).

Pile Dynamic Analyzer (PDA) tests based on equipment developed by Pile Dynamics Inc (PDI) had been conducted to measure the pile capacity and to gauge the increase in capacity of the piles over time (i.e. the set-up effect which is also known as the aging effect). An agreement was reached with the Building Authority that no full-scale loading tests were to be used to verify the pile capacities and the factors of safety, due to safety reason, as per international practice. Instead, to meet the statutory requirements of Hong Kong for proof testing of completed piles, the number of PDA tests conducted for this project were unusually large as compared with a similar project in other parts of the world. The testing requirements did cause some difficulties to the project team in the planning, construction and testing of pile foundations within a very tight construction programme which was severely constrained by the need to avoid the peak calving season of the Finless Porpoise in the area that would last a total of 6 months within the year between January and June. On the positive side, the project has provided a wealth of data on PDA testing of offshore piles for understanding



the behaviour of driven offshore tubular piles and such knowledge will be useful for similar foundation projects in future in Hong Kong.



Figure 1: Photograph of the completed foundations of HKOLNGT (Lee et al, 2022)

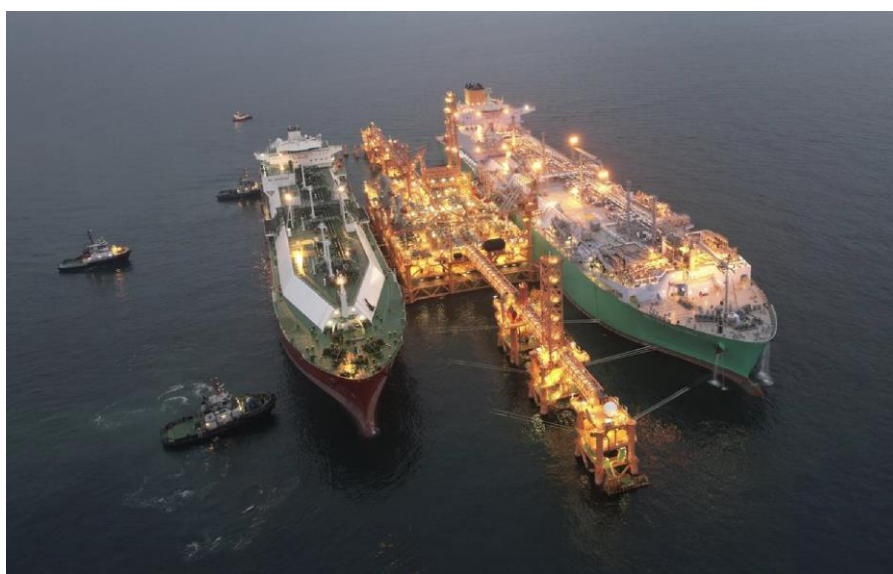


Figure 2: Photograph of the completed HKOLNGT in operation

Some discussions on PDA testing of the piles for the Terminal have been presented earlier in Lee et al (2022) and Shea et al (2002). This paper aims to supplement these two earlier papers by presenting further analyses of the PDA test data in an attempt to gain better insight into the behaviours of driven tubular offshore piles. Only the results of PDA testing of the piles for the mooring and breasting dolphins will be presented in this paper.

2 PILE FOUNDATION AND PDA TESTING

The soil profile along the Terminal consists of marine deposit, underlain in sequence by upper alluvium (clay/silt), interbedded alluvium (plastic clay/sand and silts), alluvial sand (thick dense sand) and lower alluvium (comprising clays, silts and sands). Residual soils and the bedrock were encountered at depths of approximately 85m and deeper than 95m below the seabed respectively. Figure 3 shows the soil profile along the Terminal.

The piles for MD1 to MD6 and BD1 to BD3 are all tubular piles with an outer diameter of 1.83m, with typical thicknesses of 45mm and locally thickened to 50mm as necessary at areas with higher predicted bending moment. The piles were all driven with hydraulic hammers to found at the target founding levels located within the soil layer of dense to very dense alluvial sand denoted by ALs in Figure 3.

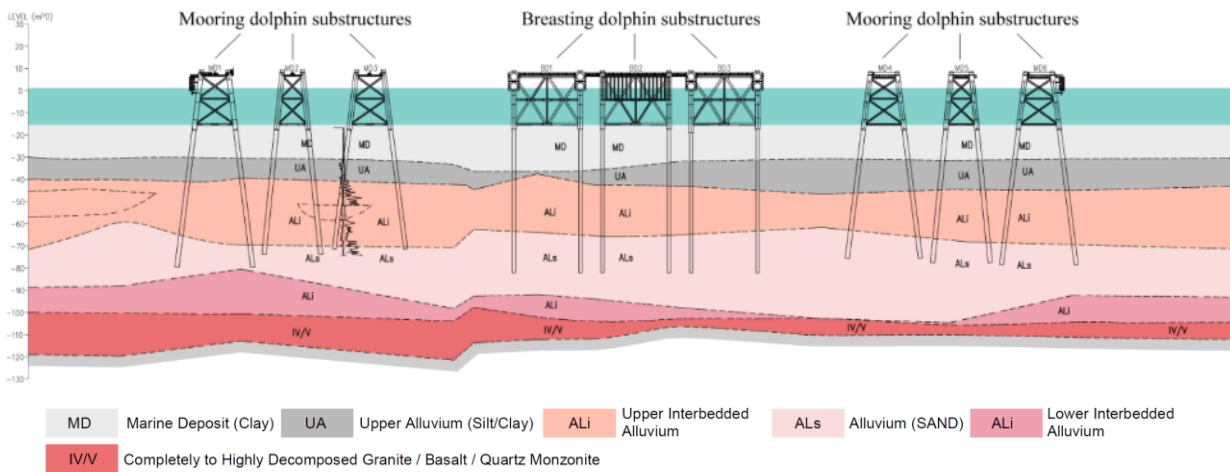


Figure 3: Soil profile along the Terminal

Two sizes of hydraulic hammers were used for the project, namely, MHU800S and MHU1200S. The MHU800S hammer had a nominal ram weight W of 444.51 kN and a drop height h of 1.84m, giving a rated energy of $W \times h = 820$ kJ. The larger MHU1200S hammer had a nominal ram weight of 648.4 kN and a drop height of 1.85m, giving a rated energy of 1200 kJ. Figure 4 shows the offshore pile of a mooring dolphin being driven with a hydraulic hammer.

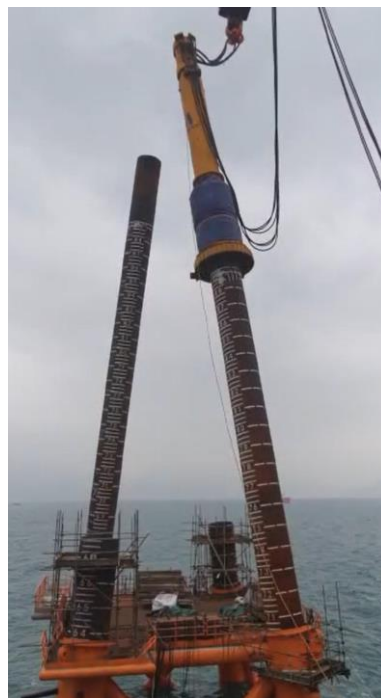


Figure 4: Driving of steel tubular pile by hydraulic hammer

The PDA tests were carried out for each pile at end-of-driving (EOD) and on selected piles at restrike to monitor the increase in pile capacity over time after EOD. In PDA testing, the restrike test is given the abbreviation of BOR to denote beginning-of-restrike. The PDA tests at BOR can help to establish the set-up

effect of the piles. The smaller hammer MHU800S was used for initial PDA testing at EOD for MD2 to MD6. For the remaining PDA tests, the larger MHU1200S hammer was used at EOD or BOR.

There are two commonly used methods developed by researchers at the Case Institute of Technology (now Case Western Reserve University) including the Case method and the Case Pile Wave Analysis Program (CAPWAP) (Hussein & Goble 2004) for predicting the capacity of a driven pile. Further discussions of these two methods can be obtained from Turner (1997). The two pile capacities predicted by PDA testing will hereafter be referred as the Case capacity and CAPWAP capacity respectively. The CAPWAP method involves a more complicated soil-pile interaction model. The CAPWAP capacity so obtained is usually regarded as more accurate than the Case capacity.

The predicted Case capacity is dependent on a parameter called the damping factor, J_c . In Hong Kong, the Case capacity is usually presented for a range of J_c values from 0 to 0.9 in increments of 0.1 in a PDA test report. The appropriate value of J_c depends on the soil types and other factors. The designer/contractor should adopt a suitable value of J_c based on local experience, judgement or calibration with CAPWAP capacity on selected piles when predicting the pile capacity using the Case method.

The PDA tests for this project were conducted in a conventional way by a foundation testing company accredited under the Hong Kong Laboratory Accreditation Scheme using PDI test equipment. The information contained in the PDA test reports for this project is similar to that of land piling in Hong Kong.

Measured parameters or predicted pile capacities obtained from a PDA test can be classified as “quick” or “late” results for ease of discussion. Quick results are quantities that are produced by on-board processing of the data measured by the PDA equipment. The quick results can be obtained immediately after the PDA test by reading off the output shown on the monitor of the PDA equipment or its printout. Examples of the quick results include the maximum energy transferred from the hammer to the pile after impact and the Case capacity for different damping factors.

Late results are quantities which require further post-processing of the PDA test data and cannot be made available immediately on site after PDA testing. An example of late results is the CAPWAP capacity obtained by a running a software developed by PDI using the field data obtained from PDA testing.

PDI uses special notations for the quick results obtained from the PDA equipment, including the following that will be discussed in this paper.

Quantity	Abbreviation
Maximum compressive stress	<i>CSX</i>
Maximum energy transferred from the hammer to the pile	<i>EMX</i>
The maximum driving force measured at pile top	<i>FMX</i>
Pile capacity predicted by the Case method	<i>RMX</i>

Very often, only the results of *CSX* but not *FMX* are presented in the formal PDA test result. The result of *FMX* can easily be obtained by the product of $CSX \times A$ where A is the cross-sectional area of the pile. PDI does not use any special notation for the pile capacity predicted by CAPWAP method. In this paper, the CAPWAP capacity will be denoted by *RCW* for ease of reference. Another parameter that is commonly used in PDA testing is the energy transfer ratio, X , defined as $X = EMX / \text{rated energy}$. The energy transfer ratio X can be interpreted as the energy transferred to the pile after impact expressed as a proportion of the rated energy.

3 THE IMPORTANCE OF EARLY PREDICTION OF PILE CAPACITY

As discussed by Lee et al (2020), the sea state due to weather conditions often dictates the method of construction and hence the foundation design. Idling is extremely costly and a major safety hazard for offshore foundation works. The capacity of an offshore pile is usually assessed by the CAPWAP method and the results of CAPWAP analysis are often only available a few days after PDA testing. To reduce the idling time, it will be extremely useful to the piling contractor if tools are available for rapidly assessing whether the installed piles are likely to achieve the required capacity such that they can make an earlier decision of relocating the piling equipment for installation of another offshore pile.

For land piling, there are published correlations between the CAPWAP capacity (*RCW*) and the peak/maximum driving force (*FMX*) in the literature. Chow et al (1989) observed a linear relationship

between the RCW and FMX and their data covers a range of pile types including precast reinforced concrete piles, prestressed concrete piles, steel H-piles and steel pipe piles driven to a small set value of less than 25mm per 10 blows by diesel, hydraulic or drop hammers. The scattering of data reported by Chow et al (1989) is fairly large, with the ratio of RCW/FMX falling generally between 0.8 and 1.3 and having a mean value of 1.04. For steel H-piles driven with hydraulic hammers in Hong Kong, Fung et al (2013) observed that the mean value of the ratio RCW/FMX decreases from 1.2 for friction piles to 1.0 for end-bearing piles.

It is worth investigating whether FMX will be a useful predictor for RCW for offshore piles. Figure 5 shows the data of RCW plotted against FMX for the offshore piles of the HKOLNGT project. The data points in Figure 5 lie entirely below the equality line. Given the large scattering of results, FMX is therefore not a useful predictor for the CAPWAP capacity.

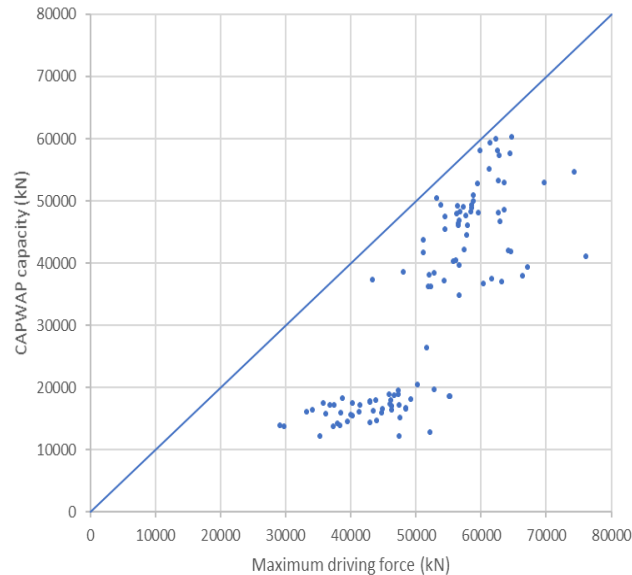


Figure 5: Correlations of CAPWAP capacity (RCW) with maximum driving force (FMX)

Although the Case method is generally regarded to be less accurate than CAPWAP analysis for estimation of pile capacity, one may explore whether there is a good correlation that can be established between the pile capacities obtained with the two methods. If a good correlation does exist between RCW and RMX , the correlation can be established initially using early results and then constantly updated using subsequent results for progressively more accurate prediction of the CAPWAP capacity. The value of J_c to be selected for establishing the correlation can be easily obtained by calibration with the early results of CAPWAP analysis. In doing so, the $RCW-RMX$ correlation can be used for early prediction of the RCW based on the quick results of RMX .

For land piling, a good correlation can often be established between RCW and RMX based on a suitably selected value of J_c . Figure 6 shows an example of a very good linear correlation between RCW and RMX observed for steel H-piles driven with hydraulic hammers to final set for a project in Hong Kong based on the commonly used value of 0.6 for J_c . The R^2 value, which is a measure of goodness-of-fit for a linear regression, is as high as 0.9962 which signifies an extremely good linear correlation for the land piling project.

A review of the PDA test data indicates that a good linear correlation also exists for the offshore piles of the HKOLNGT project when J_c is within the range of 0 to 0.3 with R^2 value exceeding 0.978 as illustrated in Figure 7(a) & (b) for the correlations corresponding to $J_c = 0$ and 0.2. The value of R^2 begins to drop and the scattering of data points becomes larger as J_c further increases from 0.4 to 0.9 as depicted by Figure 7(c) & (d). In view of these observations, the correlation between RCW and RMX can be used as a tool for quick prediction of the pile capacity when a value of J_c within a suitable range is adopted for the Case method.

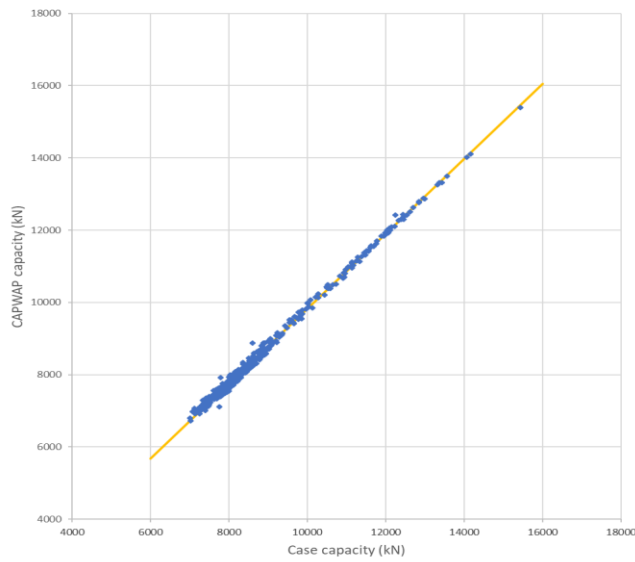


Figure 6: Example of a correlation between RCW and RMX (based on $J_c = 0.6$) for H-piles

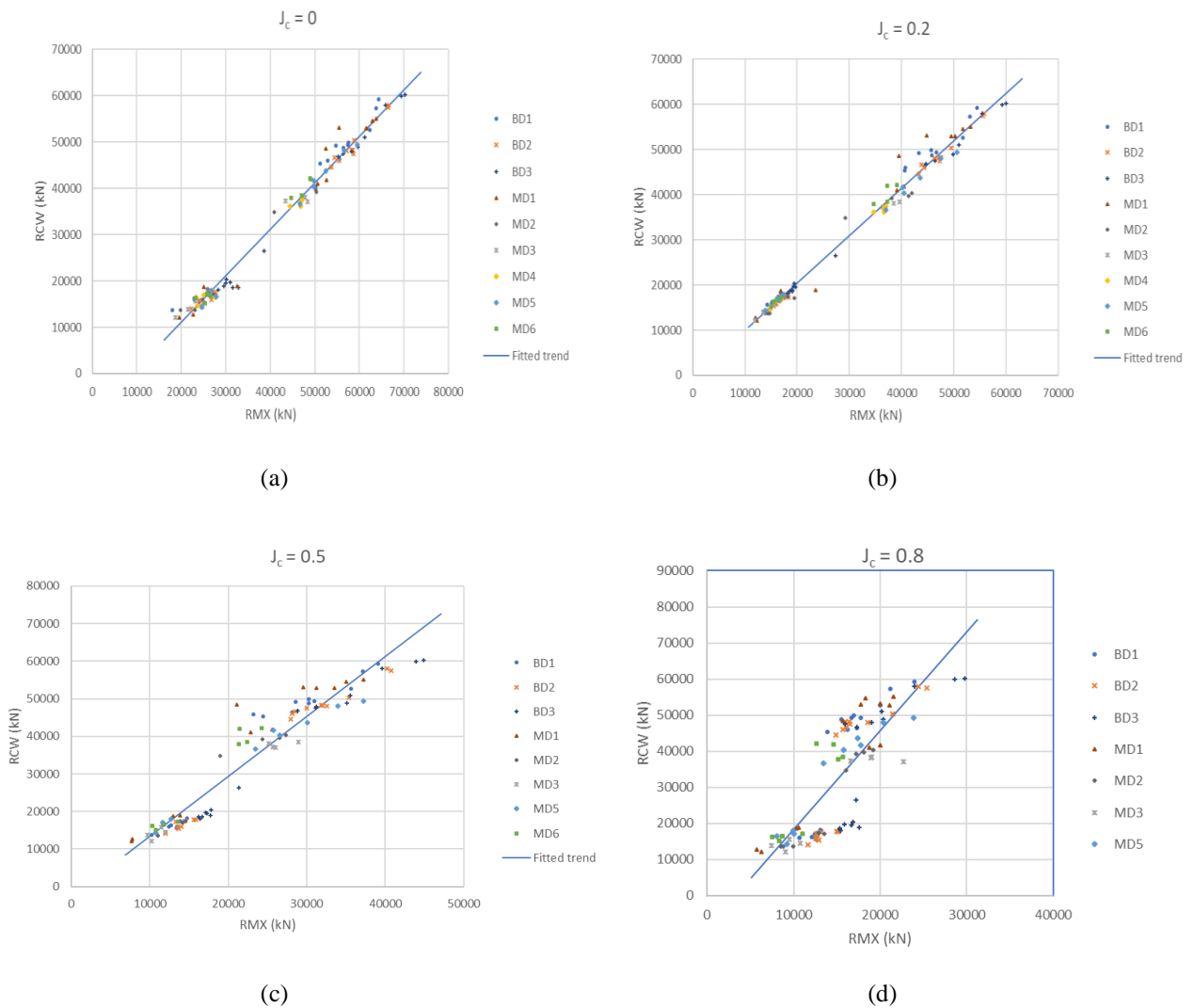


Figure 7: Correlation between RCW and RMX for HKOLNGT project

4 TRANSFER OF ENERGY TO PILE DURING DRIVING

For driven steel H-piles in Hong Kong driven to final set, Li (2003) and Li et al (2003a, 2003b) observed that the energy transfer ratio tends to be relatively constant and independent of pile length. The observations of energy transfer to the offshore piles for the HKOLNGT project are quite different, however.

Figure 8 shows the energy transfer ratio X and CAPWAP capacity RCW plotted against time after pile driving for a particular offshore pile for this project. It can be observed that both quantities tend to increase with time after EOD.

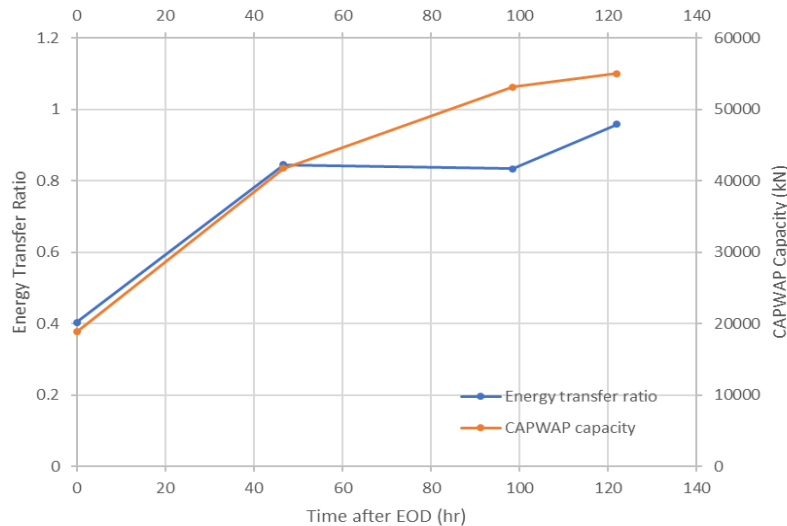


Figure 8: Energy transfer ratio and CAPWAP capacity versus time after EOD for a pile in MD1

Based on the observation in Figure 8, one would expect a positive correlation between X and RCW as confirmed by the graphical plot in Figure 9 for all piles of MD1 to MD6 and BD1 to BD3.

As discussed in Lee et al (2022), the Hiley formula which is commonly used for land piling in Hong Kong and enshrined in the current Code of Practice for Foundations 2017 published by the Buildings Department is not suitable for offshore piling works. The results of Figures 9 and 10 can be used to further explain this point.

According to the derivations presented in Li et al (2003a, 2003b), the energy transfer ratio based on the Hiley formula can be approximated closely by the product of hammer efficiency α and the efficiency of hammer blow η . α is a measure of the energy loss in the hammer before impacting the pile and it is usually relatively constant for a given hammer type. The quantity η is a function of the weight of pile cushion W_c , the pile weight and hence the pile length L , and the coefficient of restitution e which governs the velocity of the hammer and the pile after impact.

In the current foundation practice, the parameter e is often assumed constant for a given hammer type and pile type. During restrike test, the change of pile length is small and the pile length can therefore be assumed constant for practical purposes. If α , e , L and W_c are all constant or approximately constant based on the above observations, one should expect the energy transfer ratio X to be constant with time. This conclusion is not supported by the observations in Figures 8 and 9 for the offshore piles of the HKOLNGT project. The change of X with time or pile capacity clearly imply that the parameter e in the Hiley formula is not a constant and it changes with time or pile capacity.

For an offshore foundation project, it is difficult to know *a-priori* a suitable value of e to be used for the site and even more difficult to establish its variation with pile capacity. The recording of the pile movement versus hammer blow using the conventional method of sticking a piece of paper on the pile and tracing the record using a pencil is a practically impossible task and outright dangerous when operating in rough sea environments. In summary, the Hiley formula and likely other pile driving formulas are not a practical tool for assessing the pile capacity of offshore piles.

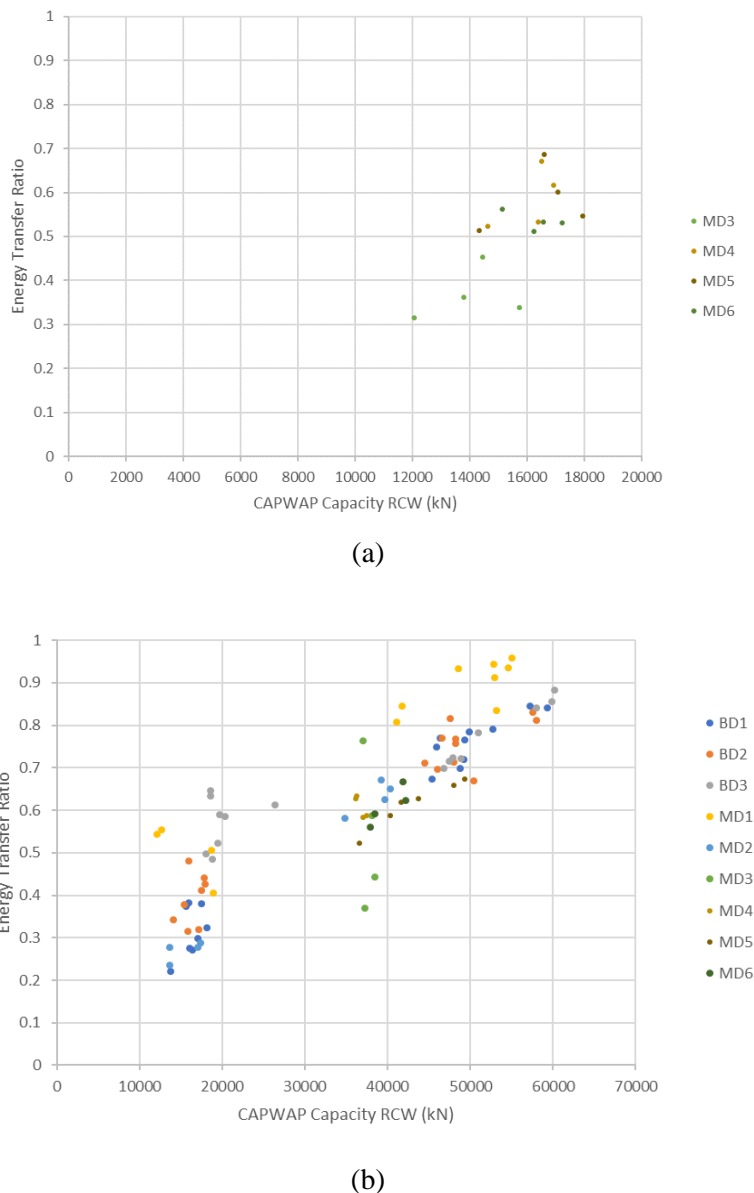


Figure 9: Energy transfer ratio versus CAPWAP capacity for piles driven with hammer with rated energy of (a) 1200 kJ and (b) 800 kJ

5 DEVELOPMENT OF PILE RESISTANCE OVER TIME

It is well established that large diameter driven tubular piles will exhibit the set-up effect. Different mechanisms which attempt to explain the set-up effect have been put forward by various researchers. Schmertmann (1991) discussed aging of soils as a contributing factor for the set-up effect and proposed that drained creep movements associated with aging would lead to the increase in soil resistance and stiffness with time. Jardin et al (2006) believe that the dominant process is relaxation of the circumferential arching effect with time caused by creep movement, resulting in progressive increase in radial effective stress and shaft resistance acting on the pile. Bowman & Soga (2003, 2005) attribute the set-up effect to kinematically restrained dilation of soils close to the pile shaft and soil aging.

The real mechanism for set-up is likely to be complex process affected by a multitude of factors. This, coupled with variability of soil properties along the pile and variation of soil profiles across the site, will often give rise to scattering of data for the set-up curve. Despite the data scatter, significant and rapid set-up effects had been evidently observed for the offshore piles for the HKOLNGT project as discussed by Shea et al. (2022). The discussions will be augmented by additional data presented in this paper.

While there is an increase in total pile capacity with time, the rates of increase of shaft resistance and toe resistance are different as typified by the pile resistance predicted by CAPWAP analysis for pile P4 in MD1 presented in Figure 10. The shaft resistance tends to be developed more rapidly and over time the shaft resistance occupies a dominant proportion of the total capacity. More data to show the variation of portion of toe resistance relative to the total pile capacity over time (all predicted by CAPWAP analysis) are presented in Figure 11 for individual groups of BDs and MDs.

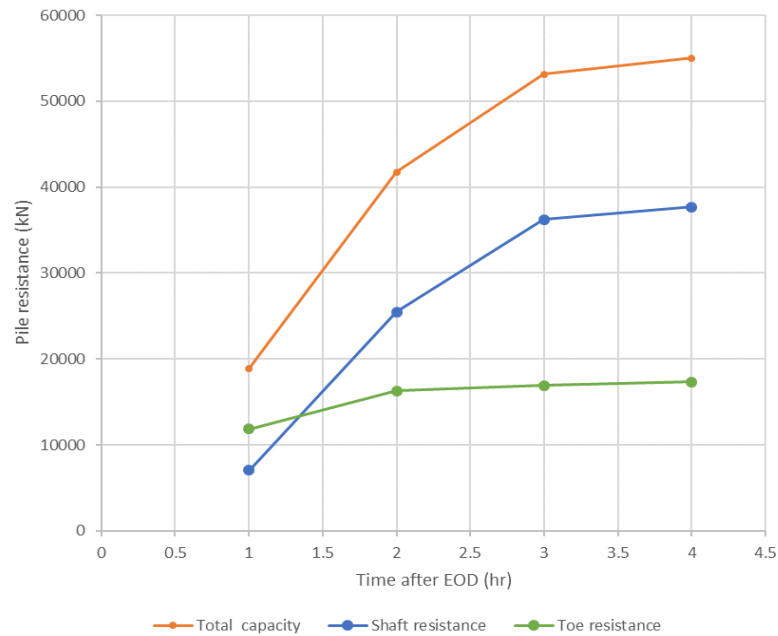


Figure 10: Change with pile resistance with time for pile P4 of MD1

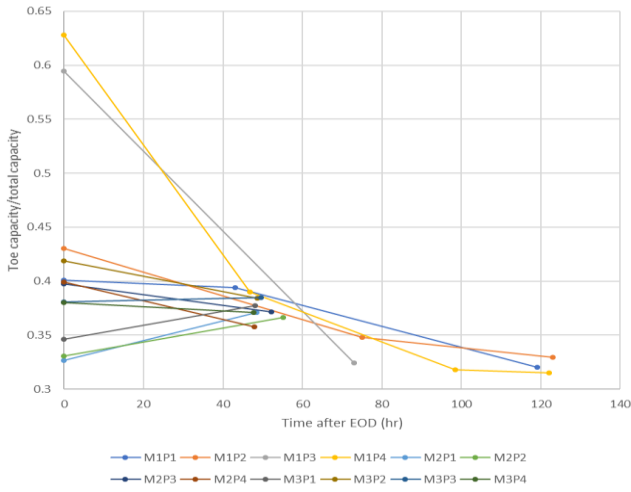
The offshore piles for the HKOLNGP project are founded on alluvial sands. As the shaft resistance increases with time due to set-up effect, the energy that can be transferred to the pile toe by the hammer impact with the same energy is expected to be progressively smaller. The displacement of the pile toe may not be sufficient to mobilize the full resistance of the toe. This may perhaps explain why the proportion of toe resistance tends to decrease with time as indicated in Figure 11 for many of the piles.

The change of pile resistance or pile capacity with time is called the set-up curve. The ratio of pile capacity increase is defined by $r = R/R_o$ where R is the pile capacity at time t and R_o the pile capacity at EOD. It is common in the literature to describe the set-up curve for r using a logarithm relationship, but it has an inherent limitation because the logarithm function gives no upper limit on r . This implies that the pile capacity can continue to increase with time, something which is physically impossible. In a recent paper by Shea et al. (2022), an alternative approach is suggested in which a hyperbolic function has been adopted for describing the set-up curve of the average shaft resistance, but the set-up effect of the toe resistance is ignored when predicting r .

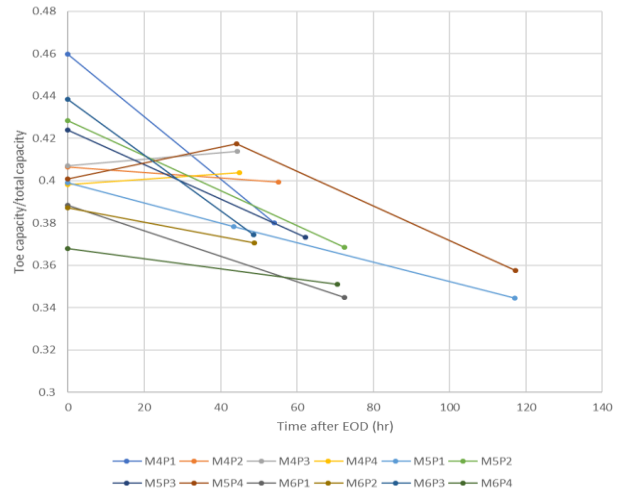
A simpler approach, which is a variation to the methodology by Shea et al. (2022), is to use the hyperbolic function to directly describe the set-up curve for r . Theoretically, $r = 1$ at EOD. A suitable hyperbolic function for describing the set-up curve of r will then be as follows.

$$r = 1 + t / (a + b \times t) \quad (1)$$

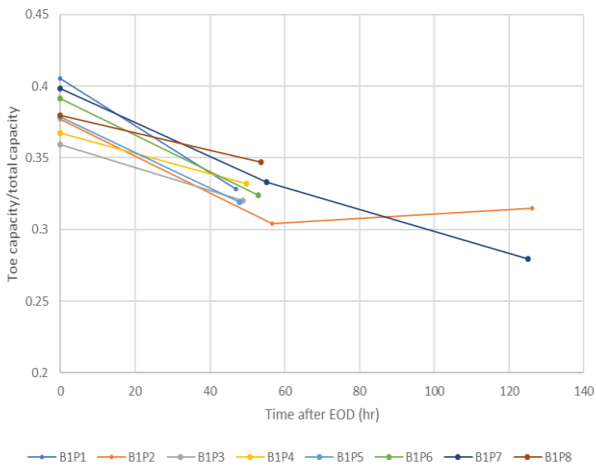
a and b are constants.



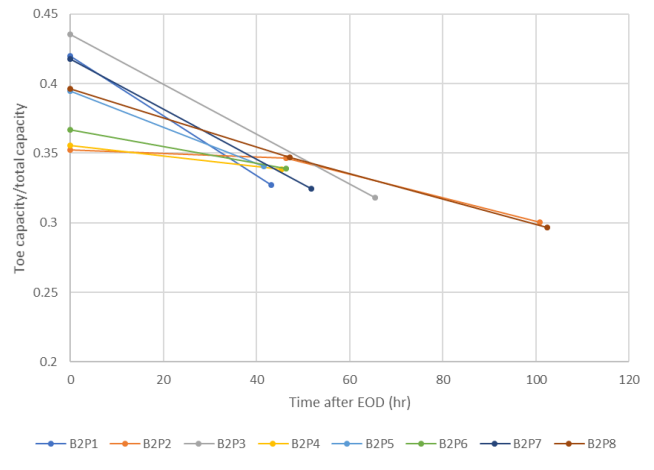
(a)



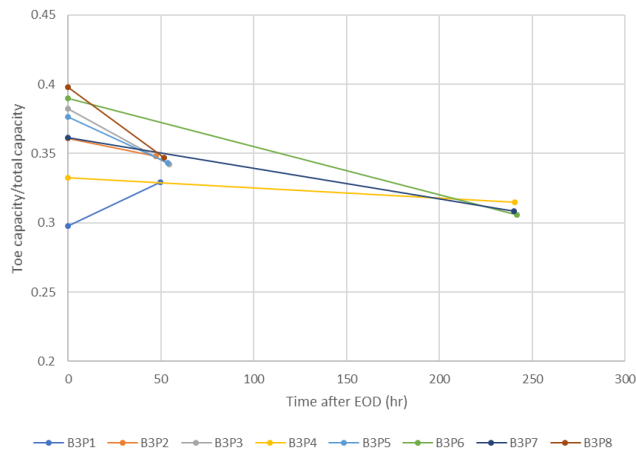
(b)



(c)



(d)



(e)

Figure 11: Ratio of toe capacity / total capacity versus time after EOD for (a) MD1 to MD3, (b) MD4 to MD6, (c) BD1, (d) BD2 and (e) BD3

Eq.1 gives an asymptotic upper limit of $1 + 1/b$ for the value of r and it can be re-arranged to give:

$$t/(r-1) = a + b \times t \quad (2)$$

By plotting $t/(r-1)$ against t , one should expect a linear relationship. The constants a and b can be obtained easily by least-squared fitting. It should be noted that the exercise of least-squared fitting used here is different from the conventional linear regression analysis of two variables x and y related by $y = a + b x$ in which y is not be a further function of x . In Eq.2, the expression in the left-hand side is itself a function of t and regression analysis will lose its statistical meaning when used to obtain the coefficients a and b . The method of least-squared fitting is only used as a numerical tool for fitting a curve to the data by estimating a and b . Further discussion on this point is given in Li (2007). The left-hand side of Eq.2 contains the multiplier of $1/(r-1)$ to the time t . This multiplier is larger when r is smaller. This implies that the exercise of least-squared fitting gives a larger weighting to smaller values of r . The fitted curve will therefore be biased towards the data points with lower values of r , a result which is conservative. Figure 12 shows the results of least-squared fitting using Eq.2 for the HKOLNGT project, with R^2 value equal to 0.8.

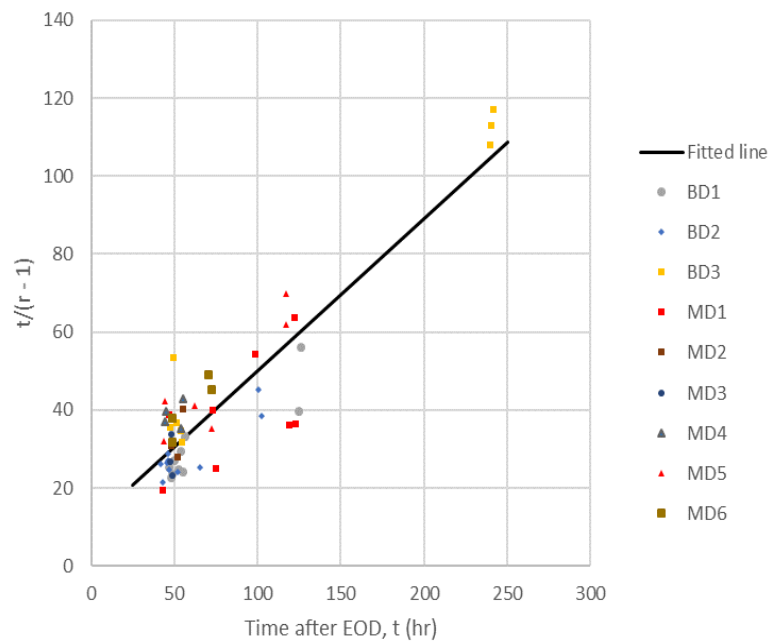


Figure 12: Plotting of $t/(r-1)$ versus time t after EOD

Figure 13 shows the data points of r and the fitted curve plotted against time. It can be observed that the fitted curve does tend to be biased towards data points with lower values of r as discussed above.

If a more conservative design line is preferred, the linear relationship in Figure 12 may be obtained manually by fitting a straight line closer to the upper envelop of the observed data. This will yield a more conservative set-up curve closer to the lower envelop of observed data in the r vs t plot in Figure 13.

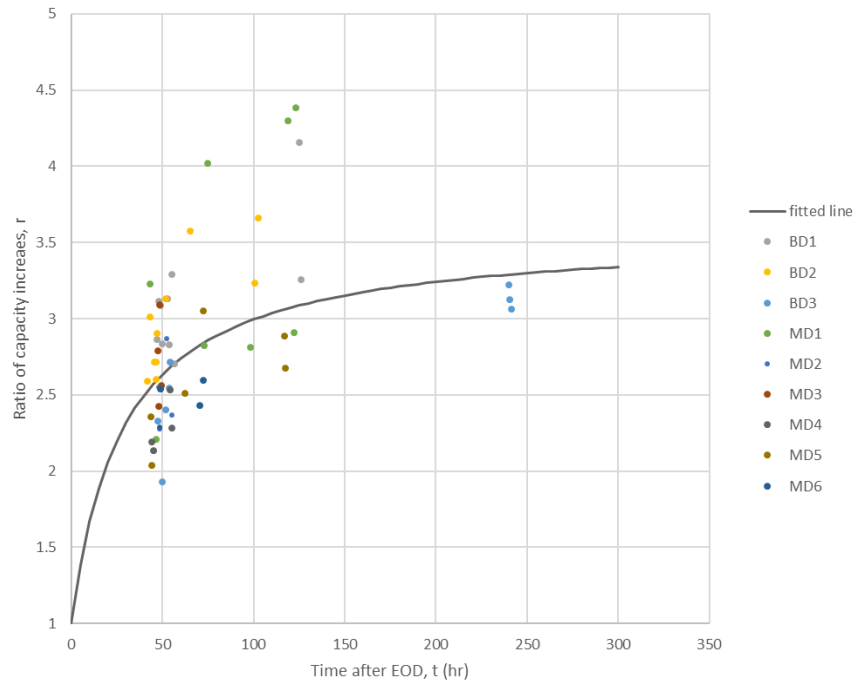


Figure 13: Ratio of capacity increase versus time after EOD (based on CAPWAP capacity)

As discussed earlier in Section 3, there exists a linear relationship between the pile capacity estimated using the Case method and the CAPWAP method with a suitable value of J_c . Based on this observation, the set-up curve can be obtained directly using the Case capacity. Figure 14 compares the set-up curves of r obtained using the CAPWAP capacity and Case capacity based on $J_c = 0.2$ and the same procedures discussed earlier based on the least-square method.

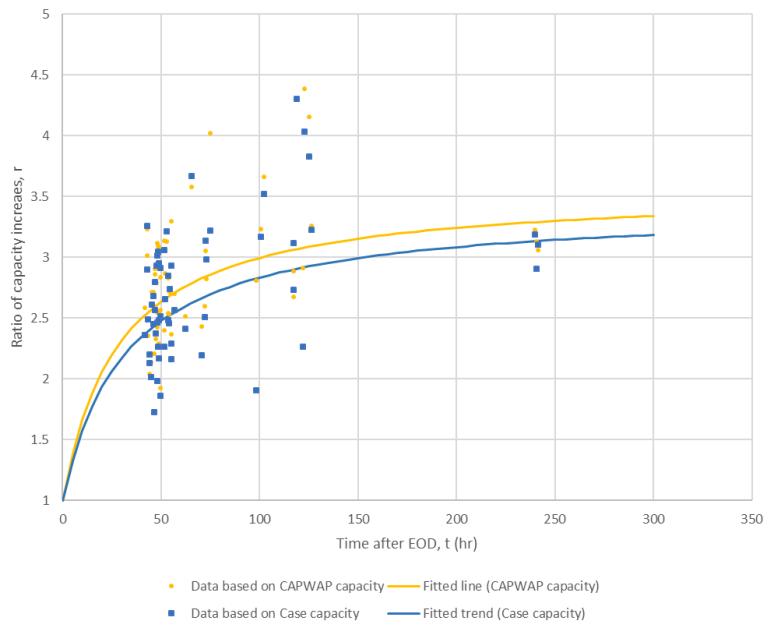


Figure 14: Comparison of set-up curves of r based on CAPWAP capacity and Case capacity

Figure 14 indicates that the set-up curves obtained from results of CAPWAP capacity and Case capacity are quite similar to each other. Based on this observation, a simpler approach for assessing the pile can be

proposed in which the pile capacity at EOD is estimated using the CAPWAP capacity for calibration of the J_c value and the prediction of subsequent pile capacity over time can be made with the help of the set-up curve obtained using the results of Case capacity corresponding to a suitable value of J_c .

To implement the simplified procedure, CAPWAP analyses at EOD are carried out for a small percentage of piles completed early in the project. A suitable value of J_c for the Case method can then be obtained by calibration with the CAPWAP analysis based on results of these early PDA tests. As described earlier, a linear relationship exists between the pile capacity predicted by the Case method and CAPWAP analysis for a range of J_c value. As long as the selected value of J_c is within this suitable range, the Case method can be used in lieu of CAPWAP analysis for obtaining a reasonably good prediction of the pile capacity. The subsequent estimation of pile capacity with time and the determination of set-up curve can then be based on the Case method. Figure 15 summarizes details of the proposed simplified procedures.

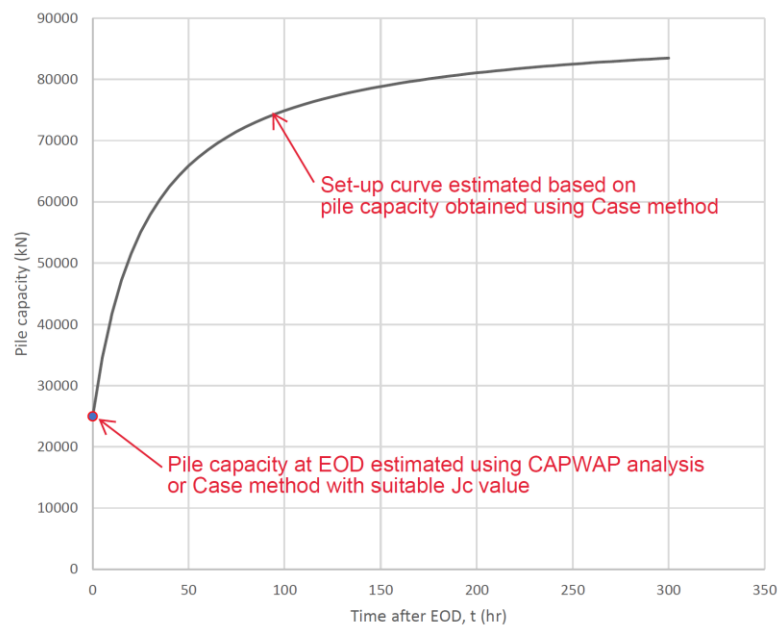


Figure 15: The estimation of pile capacity with time based on the simplified procedures

6 CONCLUSIONS

The HKOLNGT project has provided a wealth of valuable data for understanding the performance of large diameter offshore piles in Hong Kong. More results of PDA testing for the project are presented in this paper to supplement the discussions presented earlier by Shea et al. (2022) and Lee et al. (2022).

It is observed that there exists a good correlation between the pile capacity predicted by the Case method and the CAPWAP method if a value of J_c within the suitable range is used in obtaining the Case capacity. Such a relationship may be used as a quick tool for early predicting the CAPWAP capacity.

The data on energy transfer ratio re-affirms that the Hiley formula is not a viable tool for assessing the capacity of offshore driven piles. The PDA test method have been established as an accurate and practical tool for assessment of offshore pile capacity.

The PDA test data reveals that the development rates of shaft resistance and toe resistance are different and this should be considered when evaluating the static capacity of the piles.

A simpler approach based on the hyperbolic function is proposed for describing the set-up curves of the ratio of pile capacity increase, r . It is further observed that the set-up curves for r obtained from the results of CAPWAP capacity and Case capacity are reasonably close to each other. When planning the installation of offshore piles, one can use of the set-up curve based on the results of Case capacity directly without having to wait for the results of CAPWAP analysis.

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REFERENCES

- 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.
- Chow, Y.K., Yu, C.L., Wong, K.S. and Lee, S.L. 1989. Relation between peak driving force and the bearing capacity of driven pile. *Geotechnical Engineering*, 20: 103-109.
- Fung, W.K., Wong, C.T. and Wong, M.K. 2013. A study on capacity predictions for driven piles. *HKIE Transactions*, 11(3): 10-16.
- Hussein, M. & Goble G. G., 2004. A brief history of the application of stress-wave theory to piles. *Current practices and future trends in deep foundations*, Geotechnical Special Publication No. 125, ASCE, 186-201.
- Jardine, R.J., Standing, J.R. and Chow, F.C. 2006. Some observations of the effects of time on the capacity of piles driven in sand. *Geotechnique*, 56(4): 227-244.
- Lee, D., Hung, K.T., Lee, S. and Li, V. 2022. A critical review of the current practice of design and construction of offshore foundations in Hong Kong. *Proc. HKIE Geotechnical Division Annual Seminar*. 38-53.
- Li, K.S. 2003. Discussion on “On the application of Hiley formula in driving long piles”. *Geotechnique*, 53(3): 373-374.
- Li, V. 2007. Analysis of geotechnical data. *Bridging Research and Practice – the VLA Experience*, 121-156.
- Li, K.S., Lam, J. and Ho, N.C.L. 2003a. Chapter 3 - driven piles. *Design and construction of driven and jacked Piles*, Centre for Research & Professional Development, 51-71.
- Li, K.S., Chan, S.T. and Lam, J. 2003b. An alternative pile driving formula – a preliminary study. *Proc. HKIE Geotechnical Division Annual Seminar*, 179-189.
- Schmertmann, J.H. 1991. The mechanical aging of soils. *J. of Geotechnical Engineering*, ASCE, 117(9): 1288-1330.
- 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*. 175-187.
- Turner, M.J. 1997. *Integrity testing in piling practice*, CIRIA.