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TECHNICAL NOTE

Innovative method for remote measurement of pile set and temporary compression of driven H-piles in Hong Kong

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The final set and temporary compression (also known as the elastic rebound) of pile and soil of a driven H-pile are conventionally measured manually by a worker standing next to a pile during pile driving. While this manual method is currently used in Hong Kong and many other countries, it may pose a potential hazard in occupational safety and health and its accuracy may be affected by ground vibrations and human limitations. The Pile Driving Monitor (PDM) is an innovative and non-contact mobile device that provides a better alternative method. It allows measurements to be taken remotely and accurately at a safe distance of 5–25 m from a pile. The Hong Kong Housing Authority (HKHA) [The specification library 2008 edition (SL). Housing Department, Government of the Hong Kong SAR; 2008] instituted a pilot study in a housing project on the use of PDM. A total of 120 sets of parallel measurements by manual and PDM methods were obtained and the results were found in good agreement. PDM advantages in occupational safety and health, measuring accuracy, reliability and efficiency were well demonstrated. The use of PDM method has been accepted by the Hong Kong Buildings Department on project basis.

Keywords: Pile Driving Monitor; final set; temporary compression; rebound; pile driving; driving formulas; Hiley formula; innovative; manual method; remote measurement; occupational safety and health; accuracy; reliability; efficiency

Introduction

According to the Code of Practice for Foundations published by the Buildings Department (BD) [1] and the Piling Specification of Hong Kong Housing Authority (HKHA), [2] a driven steel H-pile needs to fulfill an approved pile driving formula. Among numerous pile driving formulae available in the literature, [3–5] the Hiley formula is the most commonly used pile driving formula in Hong Kong. This formula requires measurement of pile set(s) and temporary compression of pile ('Cp') and soil ('Cq') for the last 10 blows at the end of pile driving. The required capacity of a pile is considered to be achieved if the measured pile set is not more than the allowable maximum value calculated by the approved driving formula based on the actual pile length and the measured elastic compression of pile and soil (Cp + Cq). Such measurements are conventionally taken by a worker standing next to the pile during driving, which may pose a potential hazard in occupational safety and health, not to mention that the accuracy may be affected by ground vibrations and human limitations. The problems can be solved by remote and automatic measurement, subject to availability of reliable equipment. Besides, final set graphs currently prepared by the manual method are required to be submitted to the BD for certification of completion. Any alternative method of measurement and hence alternative final set graphs need to be approved by the BD. The following paragraphs present the details and results of a pilot study instituted by HKHA on the use of an innovative remote, automatic measuring device 'Pile Driving Monitor (PDM)' in Kai Tak Site 1B project (KT1B) (Figure 1) that eventually led to BD's approval of the use of the PDM and the acceptance of PDM final set graphs for the project.

Conventional manual method of measurement

Conventionally, a manual final set graph (Figure 2) is drawn by a worker with a pencil in close proximity of the subject pile to trace the pile movement on a piece of paper under a driving hammer (Figure 2(a)). This graph is then interpreted by a member of the site staff (Figure 2(b)) to check whether the pile set, and (Cp + Cq) results obtained for the series of 10 blows satisfy the final set tables derived from the approved driving formula. If not, the pile driving and measuring process must be repeated until the results are satisfactory.

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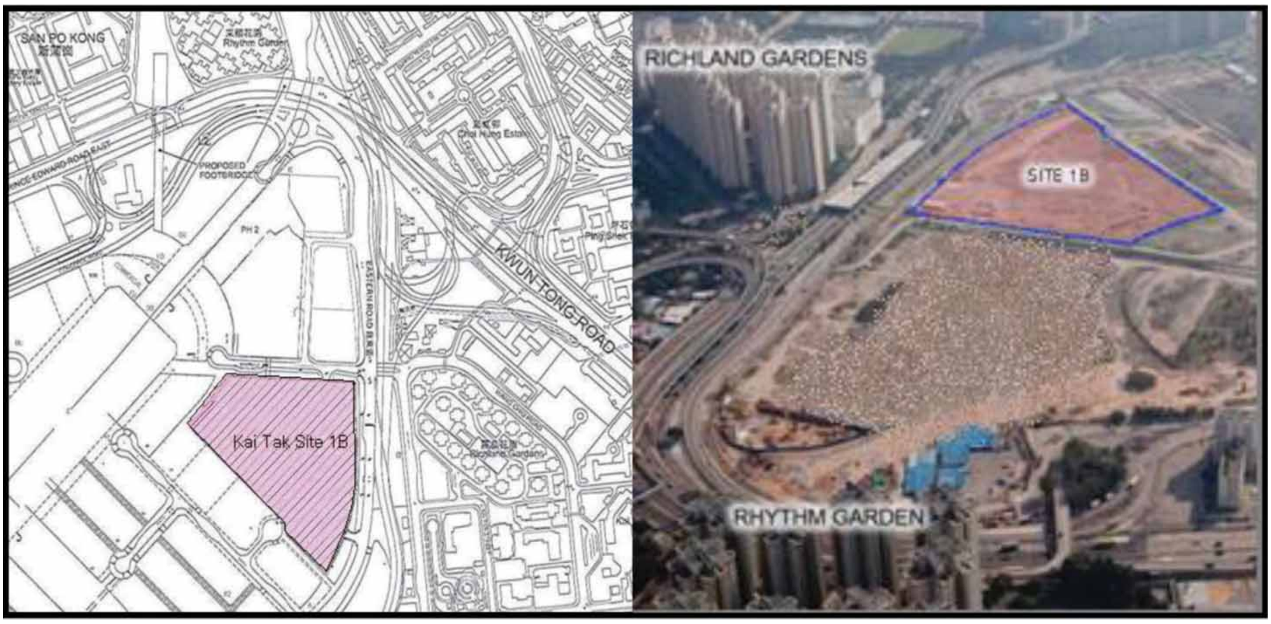

Figure 1. Location plan of Kai Tak Site 1B.

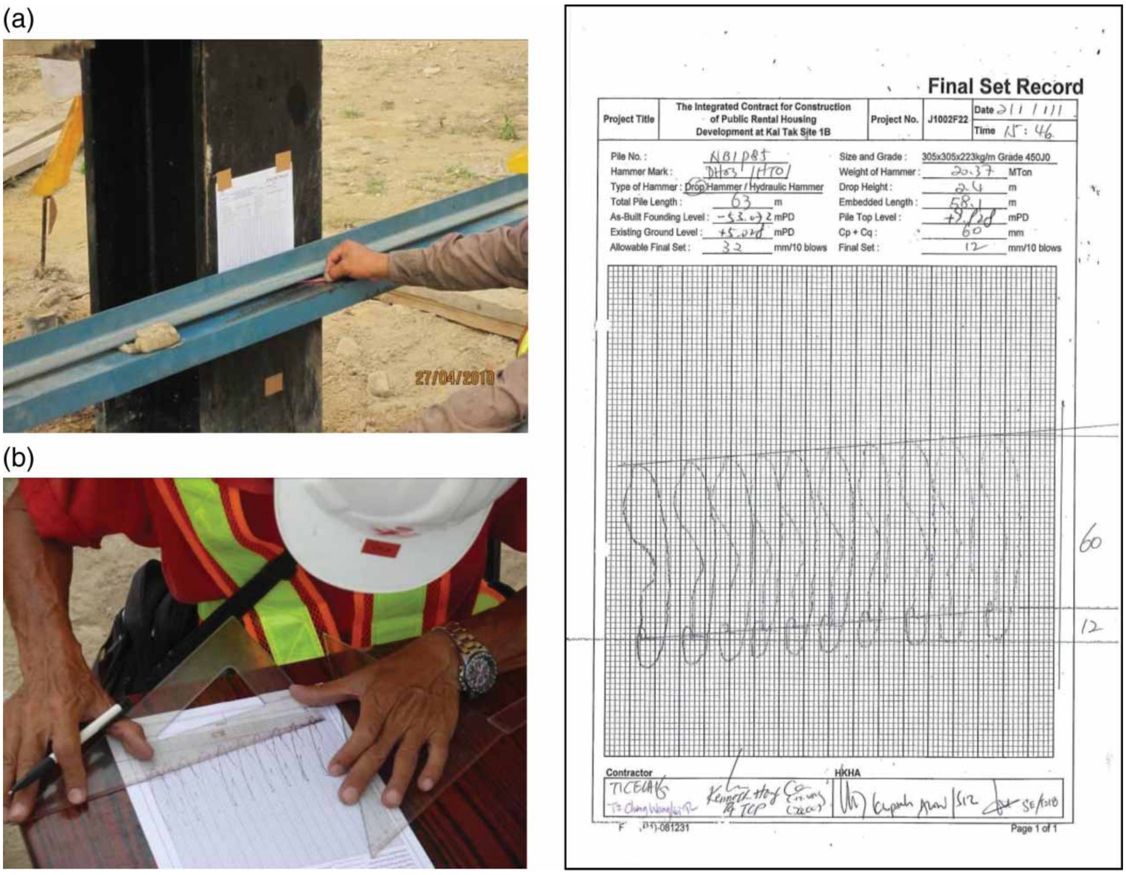

Figure 2. Final set graph by manual method: (a) drawing final set graph by a worker holding a pencil in close proximity to a driven H-pile and (b) interpreting the results.

Innovative PDM for measurement

Introduction of PDM

The PDM is an opto-electronic device, supplied by a Singapore-based company. The PDM is able to remotely, continuously and accurately measure the pile set and (Cp + Cq) of a driven H-pile by a non-contact method (Figure 3(a) and 3(b)). Besides addressing the safety and health concerns of the manual method, the PDM produces an objective final set graph (Figure 3) that does not require result interpretation by a member of the site staff.

General description and specification of PDM

A tablet PC with PDM software installed and USB connection to a PDM device forms the basic mobile computer system to collect measurement data on site. The PDM measurement technology adopts the use of light emitting diode (LED). The LED light is a CLASS 1 LED-DEVICE Classification in IEC 60825-1 Ed.1.2, 2001-08. This LED light transmission is invisible and eye-safe. There are four LED transmitters that transmit a very uniform light field with a dispersion angle of approximately 2.6°, which equates to a 450 mm active zone at a distance of 10 m. A diamond grade reflective strip (Brand '3M' or equivalent) is placed on the pile within the active zone (Figures 3(a) and 4) as a LED light reflector.

During the final set measurement for a series of 10 blows, the receiver continuously scans the active zone for the high intensity reflections from the strip, and detects the location of the strip as an angular measurement. The angular rotation is converted to equivalent linear movement perpendicular to the plane of measurement using the known distance to the target. After completion of the 10 blows, a final position check is made, so that the net movement of the pile, designated as the 'Final Set' for 10 blows is established. The (Cp + Cq) for each blow is the difference between the peak displacement and set. The average (Cp + Cq) is computed in real time as the average of all 10 measured blows.

The PDM measures the reflector position at a peak digitisation rate of 1050 Hz. This is a sufficient rate to measure the transient movements of the pile as a result of the impact, and most importantly, to capture the peak displacement of a pile during an impact event.

The PDM is placed at a sufficient distance from the pile so that all PDM measurements are therefore obtained under effectively 'still' conditions, unaffected by

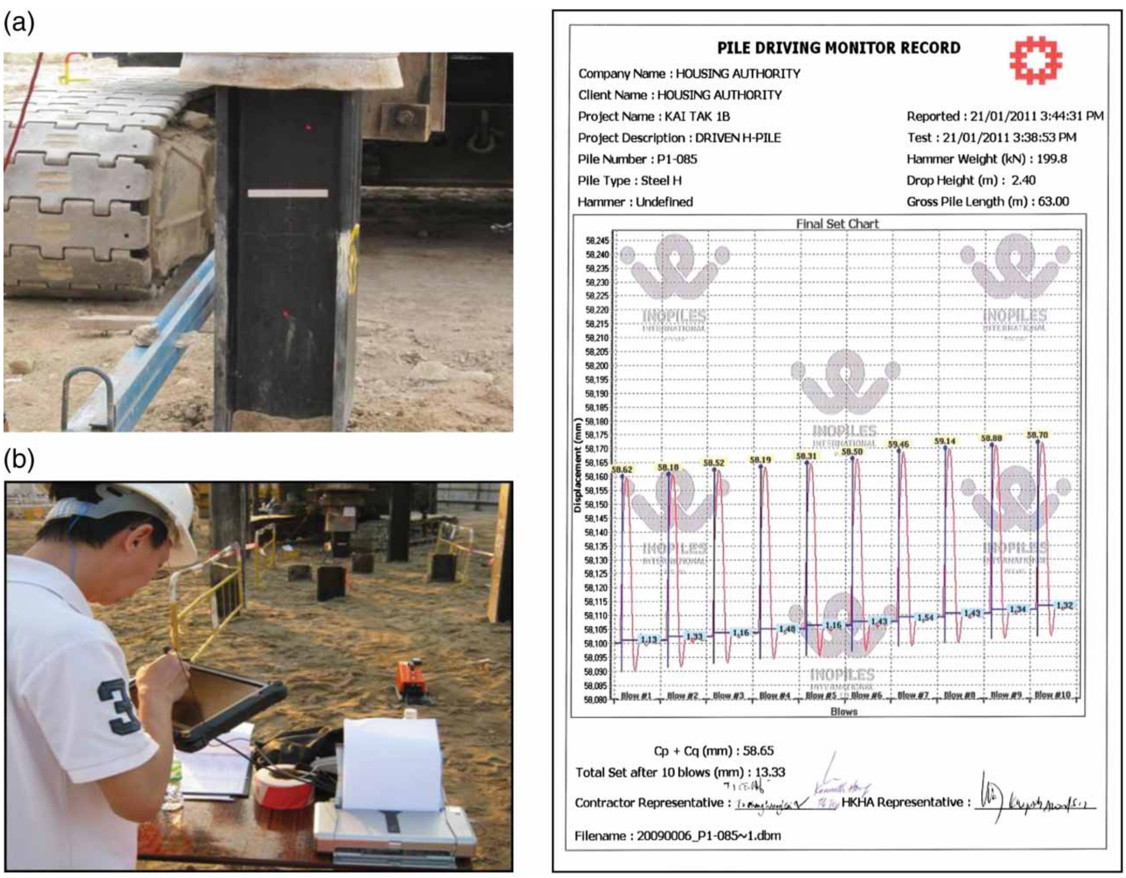

Figure 3. Final set graph by PDM method: (a) diamond grade reflector and (b) tablet PC, printer and PDM.

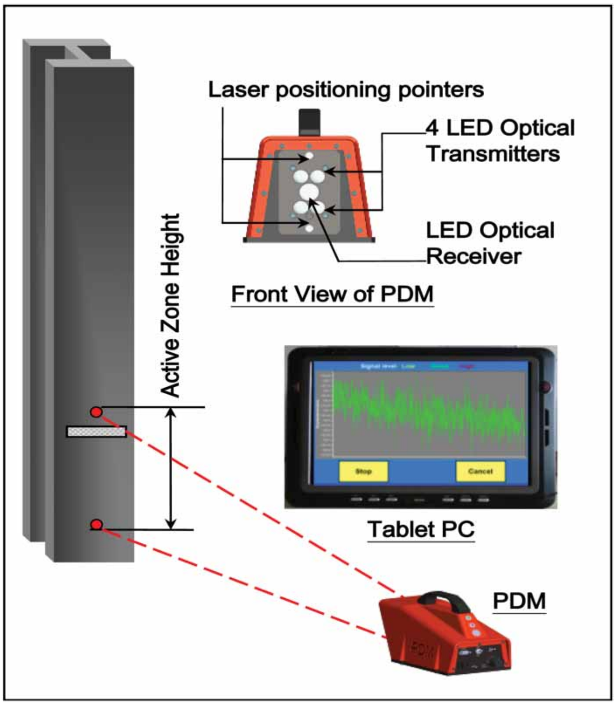

Figure 4. General setup of PDM.

the hammer impact. This is never possible for manual measurement. There are two important reasons for placing the PDM away from the pile:

(i) The energy in surface (Rayleigh) waves radiates in all directions around the pile, and peak vibrations therefore dissipate with distance from the pile. Peak ground vibrations at the PDM placed 10 m from the pile will be significantly less than the peak ground vibrations at the reference beam for manual measurements – possibly 0.5–1.0 m from the pile.
(ii) Massarsch and Fellenius [6] state that the ground wave causing the initial vibrations which radiate around the pile are generated by shearing of the pile shaft through the soil. Therefore, the shear wave velocity determines the duration between impact and vibration effect at any distance from the pile. For the majority of ground conditions relevant to KT1B (sands and clays), the shear wave velocity varies between 50 and 200 m/s. [6] Based on a typical PDM offset distance of between 10 and 15 m, the likely shortest time at which the ground vibration effect first reaches the PDM will be 0.05 s or 50 ms (i.e. 10 m divided by 200 m/s) after impact. Data collected at KT1B show that the peak displacements generally occurred at a time of about 25 ms after impact, much earlier than the arrival time of the ground vibration wave. Hence, the shear wave would not affect the accuracy of the transient pile movement (Cp + Cq) measured by the PDM.

Data security of PDM

The data security is a fundamental consideration in the use of PDM. The following aspects are noteworthy:

(i) The PDM calibration data are contained in an encrypted, non-editable binary file.
(ii) Site measurements are available in real-time, and written to a ‘jpg’ image file. The ‘jpg’ file can be printed out and signed off immediately by all concerned parties, which becomes an immediate, verified record for permanent hardcopy storage. There is no time, and therefore no opportunity for modification of these hardcopy results. In addition, the archived electronic results can be compared against the hardcopy at any time.
(iii) All the raw data for each test, including time series of positions, warnings, tilt, rotation, acceleration are stored in a single encrypted binary file (‘dbm’ file) which can be viewed but not be edited.

Pilot study on PDM

Scope of parallel measurements at Kai Tak Site 1B project

From August to October 2010, the HKHA instituted parallel PDM and manual measurements at the Kai Tak site 1B project (KT1B), where driven H-piles were adopted for 9 domestic blocks with more than 8100 domestic flats. A 20-tonne drop hammer was used for final setting of the driven H-piles. Final set and (Cp + Cq) measurements were taken concurrently by PDM and manual methods for the same pile under the same 10 blows. A total of 120 sets of parallel results were obtained and found in good agreement. The use of the PDM and hence the generated final set graph (Figure 3) for driven H-piles in KT1B was subsequently accepted by the BD in January 2011.

For 41 sets out of the 120 sets of parallel measurements, the PDM measurements were carried out by the Housing Department Material Testing Laboratory in light of their independence from the project. For the other 79 sets, the PDM measurements were carried out by the project team (PT) to increase the sampling size and observe if any significant difference or difficulty arises when measurements were taken by different operators.

Ground conditions of Kai Tak Site 1B

The site was formed by reclamation of fill in 1924 and mainly used for parking aircraft until 1998. The site is underlain by loose to medium dense sand, soft and firm silty clay and alluvium and completely decomposed granite. The groundwater table was about 3 m below ground. The soil layer at the ground surface for placing PDM was dry dense sand. The likely maximum shear wave velocity for this soil type is 200 m/s as suggested by Massarsch and Fellenius [6].

Parallel measurements – spread of final set and pile length

The 120 sets of parallel measurements were carried out over the entire site covering a wide range of final sets and pile lengths as illustrated by Figures 5 and 6.

Comparison of parallel results

Estimated absolute differences between the PDM and the manual method for the final set (Cp + Cq) and final set + (Cp + Cq) are given in Table 1, which are marginal.

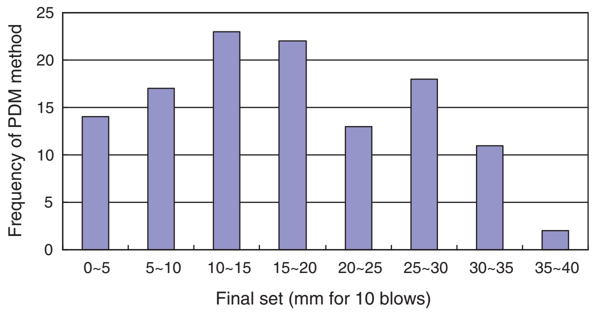

Figure 5. Distribution of final set (mm for 10 blows).

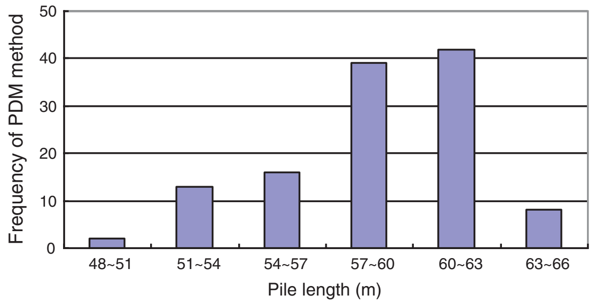

Figure 6. Distribution of pile length (m).

The final set and Cp + Cq measurements obtained by PDM and manual methods are plotted against each other in Figure 7, where the final sets range from 0–40 mm with many less than 10 mm, while the Cp + Cq values range from 48–67 mm.

Sensitivity analysis to Hiley formula

One of the most popular pile driving formulae is the one first published over a hundred years ago in the journal *Engineering News*. [7] In the early 1920s, Hiley had developed the driving formula based on Newton's laws of momentum. [8,9] By treating the hammer and the pile as rigid bodies upon impact, the Hiley formula for the efficiency of hammer blow [10] is as follows:

$$R = \frac{E_h((W + Pe^2)/(W + P))WH}{s + (1/2)(C_c + C_p + C_q)},$$

where E_h is the efficiency of drop; e is the coefficient of restitution of the hammer cushion; R is the driving resistance; W is the weight of the ram; H is the drop height; P is the weight of pile and helmet; s is the set per blow (or final set/10); C_c is the temporary compression of hammer cushion and $C_p + C_q$ are the temporary compression of pile and soil.

As shown in the above Hiley Formula, R is inversely proportional to set + 1/2(Cp + Cq + Cc). Therefore, capacity estimation errors will be proportional to the relative error in this quantity. The ratio of the averages and standard deviations for all 120 PDM and manual method measurements for (Cp + Cq), set, set + Cp + Cq and set + 1/2 × (Cp + Cq + Cc) are given in Table 2. For all four parameters, the computed averages are very close to unity, differing by a narrow margin from +0.1% to −0.7% only. The standard deviations are generally very small except that for the 'set'. This is because the 'set' figures are generally of smaller values (Figure 7) as compared with the other three parameters, resulting in higher percentage variations.

A statistical plot of the ratios of set + 1/2(Cp + Cq + Cc) between PDM and manual methods is shown in

Table 1. Absolute differences between measurements by manual and PDM method (with 95% confidence).

	For PDM measurements taken by	
Parameters differences between manual and PDM method	HDMTL	PT
(i) Est. |difference in final set|	<2.18 mm	<2.18 mm
(ii) Est. |difference in (Cp + Cq)|	<1.68 mm	<2.13 mm
(iii) Est. |difference in final set + (Cp + Cq)|	<2.62 mm	<2.79 mm

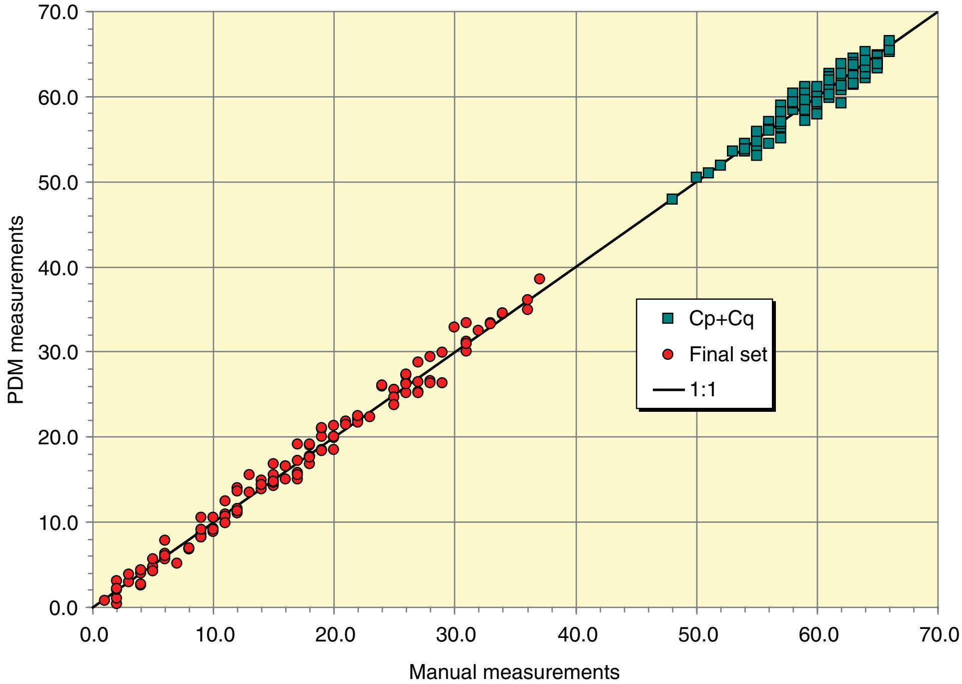

Figure 7. Scatter graph of Cp + Cq and final set for PDM versus manual measurement.

Table 2. Ratio of PDM/manual results.

Parameter	Average	Std. deviation
(i) Cp + Cq	1.001	0.017
(ii) Set	0.993	0.138
(iii) Set + Cp + Cq	1.001	0.018
(iv) Set + 1/2 × (Cp + Cq + Cc)	1.001	0.015

Figure 8, of which their differences are shown to be very small, ranging from −4% to +4%. As noted before, this derived quantity is relevant because it is inversely related to the capacity estimation. The graph indicates that 101 of the 120 capacity estimates were within 2%, and all estimates were within 4% which is in itself small in geotechnical engineering terms.

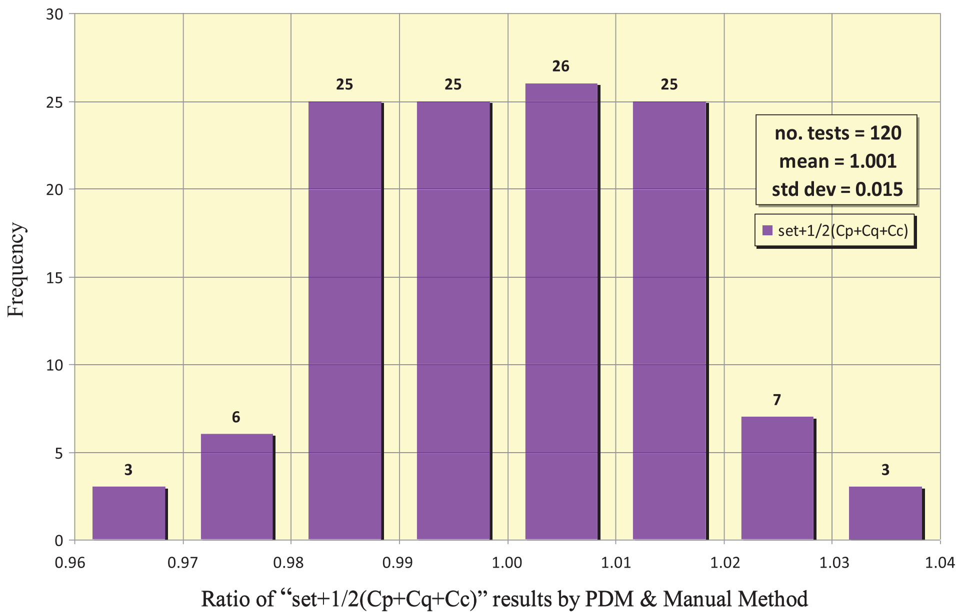

Figure 8. Comparison in set + 1/2(Cp + Cq + Cc).

Findings and discussion

The PDM results compare well with results using conventional manual method. It is considered that the marginal differences are likely due to in large part to errors in the manual method, rather than the PDM. Besides, the comparison study demonstrates well the following advantages of the PDM in respect of occupational safety and health, accuracy, reliability and efficiency:

Manual method	PDM method
(i) Safety and health	
• with a potential hazard of falling objects and high level of construction noise (accepted to date only because of no credible alternative)	• with significant improvements (PDM device 5 m+ away from a pile and hammer)
(ii) Accuracy	
• accuracy at best 1 mm (min. width of pencil tip which will not be broken during measurement)	• accuracy better than 0.2 mm (sub-millimetre level)
(iii) Reliability	
• relying on a stable reference beam	• remote measurement (5 m+ away) without the need of a stable reference beam
– high vibrations from hammer impact can cause settlement of the reference beam which may or may not be evident	– measurement unaffected by vibrations from hammer impact
• some subjectivity in the graphical interpretation of the set and average temporary compression for 10 blows	• objective measurement of set and temporary compression for each blow, not affected by manipulation or subjective assessment
(iv) Efficiency	
• physical problems with execution (e.g. due to notable movement of reference beam, breaking of pencil, poor quality of graph drawn etc.) result in the need for repeat measurements	• less disturbance and uncertainty, reduce the need to repeat measurements in order to optimise percussive piling hours under restriction of noise permit

Conclusions

From the parallel measurements at KT1B, it can be concluded that:

(a) the final set and temporary compression measurements by the PDM compare well with those obtained by the conventional manual method;
(b) The PDM achieved a breakthrough improvement in occupational safety and health and demonstrated advantages of accuracy, reliability and efficiency for the pile set measuring work; and
(c) PDM has a good potential to replace or supplement conventional manual method in future projects of driven piles, noting that the use of PDM and the generated final set graph in Kai Tak Site 1B have already been approved by the BD on a project basis. (http://www.bd.gov.hk/english/inform/BC/SEC11-01HD.pdf)

Notes on contributors

Ir C.H. John Pak joined the Housing Department, HKSAR Government immediately after graduating from the University of Ottawa in 1979, and became a Chartered Engineer in 1983. Ir Pak is serving as a Chief Structural Engineer leading the structural vetting team for exercising third-party regulatory and structural control over Housing Authority's buildings. Ir Pak developed the quality control regime for production of precast structural elements in the mainland, and has involved in various building projects including the application of a significant number of volumetric precast constructions in buildings to enhance quality and sustainability. His main interests include materials recycling and reuse in building construction, innovations in site safety and schematic E-transfer of structural submission.

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Ir W.M. Hammus Chui graduated from the Hong Kong Baptist College and Asian Institute of Technology in 1985 and 1988, respectively, and became a Chartered Engineer in 1991. Ir Chui joined the Housing Department, HKSAR Government as a Structural Engineer in 1994. Ir Chui has been involving in many different public housing development projects with challenging foundation works and innovations implemented with a view to enhancing quality and sustainability of the works. Now as a Senior Structural Engineer, Ir Chui is leading a team of professionals, technical and site staff to carry out the design and contract management for public housing development. His main interests include innovations in piling and building design, construction and testing technology.

Ir F.H. Romeo Yiu graduated from the Hong Kong University of Science and Technology in 1998 and became a Chartered Engineer in 2007. Before serving as a Structural Engineer in the Housing Department, HKSAR Government, he has been engaged in design and administration of numerous piling projects in public and private sectors. Ir Yiu is currently responsible for the design and construction of various types of residential blocks and auxiliary structures. His main interests include waste reform for application in construction, reuse of foundation, innovations in pile foundation design, construction and related testing technology.

Dr J.P. Seidel obtained his BEng degree with first class honours and PhD degree from Monash University in Melbourne. He is currently the Chairman and Technical Director of both Foundation Specialists Group and Inopiles Pte. Ltd., and the Associate of Civil Engineering Department, the Monash University. His experience over 30 years has been in consulting, construction, government, research and academia. He lectured extensively in the area of foundation engineering practice, and has written in excess of 80 technical papers on his areas of research and practice. He developed the PDM as a method to bring enhanced quality assurance and safety to the foundation industry.

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