Real Time Monitoring of SPT Using a PDM Device – The Failings of Our Standard Test Revealed

B. G. Look and J. P. Seidel
Foundation Specialists Group, Australia

S. T. Sivakumar and D. L. C. Welikala
Queensland Department of Transport and Main Roads, Australia

ABSTRACT: The Standard Penetration test (SPT) is one of the common in situ tests used in geotechnical engineering. Three 3 data points are required - the seating drive and 2 test drives to 150mm penetration each. The 150mm is not an exact value and 25% variation was found when measured by various experienced supervisors and measured digitally. Seating blows are then transferred from the seating drive to the test drive or vice versa. This counting variation is even more pronounced in residual soils at the soil-rock interface, for high N-values or where SPT to refusal is often carried out with automatic trip hammers. Additionally, energy and other corrections are required to effectively use the SPT N – value in design. Thus SPT measurement is far from "standard" as the name implies and despite following the procedures to a given testing code. This paper shows the differences between visual counting and digital measurements.

1 INTRODUCTION

1.1 *Standard Penetration Test*

The Standard Penetration test (SPT) is one of the common in situ tests used in geotechnical engineering to determine properties of subsurface soils. The SPT requires 3 data points - the seating drive and 2 test drives to 150mm penetration each. The N-value is used to estimate the approximate shear strength properties of the soils (Clayton, 1995). Various corrections should then be made to the in- situ value to allow for type of hammer, energy corrections, etc. (Skempton, 1986).

Different types of hammers influence the N-value, with varying energy efficiencies. The measured N-value is standardized by using the measured energy to the theoretical potential energy (Energy ratio E_{SPT}) to convert to the 60% Energy (E_{60}):-

$$N_{60}\,E_{60} = N_{SPT}\,E_{SPT} \qquad (1)$$

N_{60} is the estimated N-value for the old safety hammer (cathead and rope). A trip hammer is estimated to be about 85% efficient – a 1.4 correction if used in design. The N-value therefore requires a correction to equate the values from the different hammers. Seidel (2014) describes this energy transfer mechanism from hammer to the split spoon sampler and shows while standards are based on measuring the energy entering the SPT rods, energy losses occur due elastic compression of the rods, and stress-wave reflections from the resistance of the sampler. Seidel (2014) evaluates these losses by Wave Equation Analysis.

The SPT therefore requires an accurate count of the SPT Blows (N - Values), and an energy conversion to be appropriately applied to design. Measuring the energy efficiency of the hammer used is not common practice in many countries, including Australia. And while visual counting blows may seem simple enough using chalk marks, Look and Seidel (2015) show the inaccuracy of this visual counting when measured digitally using a Pile Driving monitor (PDM) equipment.

1.2 *Pile Driving Monitor*

Dynamic analysis of pile capacity is carried out accurately using wave analysis or by approximate methods such as a pile driving formulae. These formulae (the oldest is the Engineering News Record (ENR), Gates, Janbu, Hiley, modified Hiley/ Gates, etc.) are based on the transfer of the kinetic energy from a falling pile hammer to the pile and soil. There is a loss of energy due to temporary compression and mechanical friction losses. The major differences between formulae is the way in which energy losses and the mechanical efficiency of the process is applied to the formula.

The Hiley pile driving formula is commonly used and described as the most elegant, but Fragaszy et. al. (1988) found the Gates pile driving formula was the best predictor, Hiley was reasonable and ENR was the worst predictor of the formulae compared. Hiley applies an efficiency factor which varies with the type of hammer as shown in Table 1a (Fleming et al., 2009 and QTMR, 2011) and Table 1b (Tomlinson and Woodward, 2008).

Table 1a. Typical output Efficiency (k) of hammers

Hamer Type	Power Efficiency k	
	(Fleming et al. 2009)	QTMR (2011)
Steam or compressed air	0.9	0.95
Drop (triggered fall)	1.0	1.0
Drop (winch – operated)	0.8	0.8
Diesel	0.6 – 0.8	0.9

Table 1b. Typical Efficiency (η) of pile driving hammers

Hamer Type	Efficiency of Hammer / cushioning system (%)
Hydraulic	65 – 90
Drop (winch – operated)	40 – 55
Diesel	20 – 80

Table 1a equates to Table 1b when the effect of cushion, pile and hammer weight are included. This shows the range of factors applied for a given hammer and for just one of the many pile driving formulae. Yet there is no fixed value as efficiency varies between projects and pile driving rigs. The "best guess" efficiency when dynamic formulae is applied is the state of practice which leaves a pile resistance estimate varying by over 40%.

When dynamic analysis using wave equations, CAPWAP analysis or various pile testing is used as the basis for design, these methods provide added confidence as a construction control. Piling codes then allow increased reduction factors (or reduced factors of safety) to be applied.

The Pile Driving Monitor (PDM) uses LED to track the movement of a reflector attached to the moving object, safely placed about 10-15m from the pile and accurate to better than 0.1mm at 10m range. There are no connections required. Thus the device is first and foremost a safety device to avoid operators measuring with a ruler below a pile driving hammer with falling parts, broken cushions or spalling concrete above.

The device is also a quality measuring device. The PDM device measures pile set (safely) and energy directly. The variable and assumed energy values of Table 1 is now a measured value with increased confidence of energy input into the Hiley formula. This approach of set and energy measured digitally is widely used in Hong Kong and Queensland piling projects.

1.3 *Pile Driving Monitor used with the SPT*

Pile driving is similar to the SPT, when a hammer is used to drive an object into the ground. The PDM measures set and temporary compression and the peak velocity (energy) can also be determined.

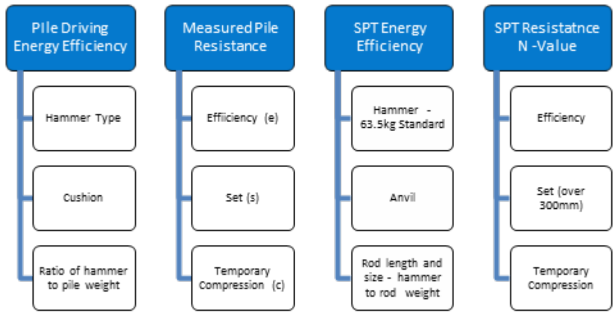

Fig. 1 Comparing pile driving Resistance with Split Spoon Resistance – SPT N value

The SPT hammer weight (W) and drop height (h) is standard at 63.5kg and 760mm respectively. The set (s) is "fixed" at 300mm, but the rebound (c) is unknown. The capacity is measured in terms of the number of blows. When the old and new technology are combined, the 3 data points for the N-value are now measured as a few thousand data points for a 200 Hz PDM device (a 2000 Hz device is currently also available).

Look and Seidel (2015) show the "recorded" penetration is for 150mm, but the human eye cannot measure the 5mm of hammer sinking in soft soils or in seating blows or rebound in hard soils and weak rock, as well as temporary rod compression. The seating drive is also seldom a "standard" integer value of 150mm. That data shows the N - value is ±25% in the supervisor's "factual" logs, when this digital data is compared to the drilling supervisor's interpretation of the "factual" N – value.

The SPT relies on the supervisor's assessment in less than 1 second for the hammer to come to a standstill from a free fall, and even less time for automatic trip hammers.

The hammer efficiency and temporary compression can be measured with the PDM. Additional data is used to further assess the "standard" measurement errors with the current SPT procedure.

2 TEST SITE AND DATA COLECTION

2.1 *Test Site and Research Testing*

This data was collected at an upgrade of the Bruce Highway, Queensland, Australia. The drilling program involved SPTs to refusal, followed by rock coring. In a parallel with this geotechnical activity, the PDM research was carried out on the SPTs.

Fig. 2 PDM monitoring of SPT

In some cases monitoring of the hammer occurred in a parallel with monitoring of the rod below the anvil. By using 2 PDM devices, the energy transfer difference from the hammer to the rods could be determined. The PDM measurement involves placing a reflector as a reference point for the PDM device (Fig. 2). Measurements were taken as the SPT was carried out in the usual way.

An SPT analyzer (by Pile Dynamics) was used to instrument the rods in a few cases. This measures the energy transferred by the hammer by attaching a sub assembly with accelerometers. Strain gages and accelerometers obtain the force and velocity signals which are converted to energy transfer.

The PDM measures the hammer energy (by velocity), the moment before it hits the anvil while the analyzer measures the energy transferred (by force) from below the anvil. This PDA energy ratio (ER) measurement was found to range from 57% to 80% (median 69%), while the hammer energy was 88% (median).

2.2 *SPT N-Values*

Borehole C85 was at the top of extremely weathered (XW) meta-siltstone. Borehole C139 profile was a silty clay alluvium over a sandy clay residual soil at 4 metres depth. Table 1 summarizes the N-values measured in the conventional manner. A drilling rig with an automatic trip hammer (ATP) was used for C85, while the other test results were obtained with a free fall trip hammer.

Table 2. SPT N - values

Ref. /Depth/Mat'l	SPT Readings	N- Value
C85 /6.0m/XW	30 blows /40mm	N* = 225
C139 /1.5m/Alluv.	4/ 8/13	21
C139 /2.5m/Alluv.	8/21/22	43
C139 /4.0m/Resid.	6/11/20	31
C139 /5.5m/Resid.	6/14/23	37

Seidel (2014) showed by WEAP analysis that energy loss increases with N-value. In XW rock where the N-value increases to an extrapolated value (N*), then the requirement for the energy correction becomes more critical. Hence residual and XW results are discussed in this paper with alluvial SPTs and ERs in a subsequent paper.

2.3 *PDM Results*

For C85 in XW rock the supervisor logged 30 blows for 40mm (N* = 225). The PDM recorded 13,593 readings in the 45 seconds of the test, with results summarized in Fig. 3. This quantum of data allows temporary compression of rods, rebound and seating to be recorded digitally which is not discernible by eye.

At 30 blows, 47.8mm penetration had occurred (N* = 188) – not 40mm as visually recorded. The first 4 blows had a set of 20.3mm, indicates a seating drive is occurring. This results in "corrected" values of N* = 284.

In this case the difference does not seem consequential. It serves mainly to illustrate the error that occurs by measured N values by eye and with a 10mm chalk mark "error drift" and is within accuracy expectations within a 45 second time frame. However this is not always the case. No elastic compression occurred for the first 2 seating blows. But from the 3rd blow a typical temporary compression (c) occurs with each blow – 5.5mm shown in Fig. 3. This was previously unaccounted for due to technology limitations. The background equipment vibration "noise" is also evident.

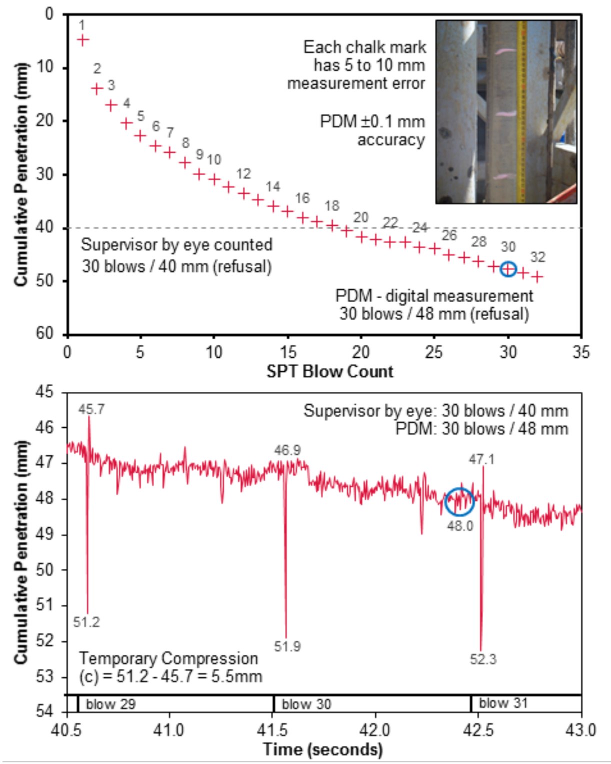

Fig. 3 Variation of blow count at C85

This seating measurement error is evident in all SPTs measured digitally. Fig. 4 shows the position of each blow for test C139. The seating drive was "measured" at 6 blows –but the PDM shows a penetration of 140mm had occurred and not 150mm as required by the test. The SPT standard requiring an integer value which in practice is a value close to 150mm for a "measurement." In this measurement, an additional 10mm transfers into the seating drive blow count.

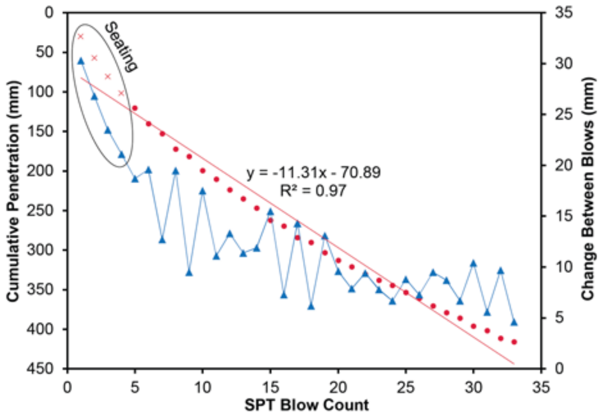

Fig. 4 Variation of each blow count at C39 @ 4.0m

Additionally, the seating has stopped at 4 blows (101.7mm), yet the standard requires 150mm. Look and Seidel (2015) has shown the seating may be also larger than 150mm. Thus seating is not a constant – but a reasonable approximation for the technology of 50 years ago.

This seating correction results in an N-value of 40. Energy corrections are then required for N_{60}. For the same drilling rig in alluvium a correction of 1.08 applied as the ER was measured as 65%, but 1.17 correction (ER = 70%) in the residual soils for the same hammer and drill rig.

3 CONCLUSIONS

At the time of SPT standardization, using chalk marks for measurements was appropriate, but these digital readings show the inaccuracy in such measurement of blow counts, which may affect designs based on N - values. If the SPT is used only as an index of a relative change, then the procedures applied herein would not apply.

The PDM device has been successfully used for pile driving for several years but is here used with the SPT to measure blow counts in terms of set and temporary compression, similar to pile driving. At the same time energy ratio is also measured. ER is not a constant even for a given rig and depends on the stiffness of the soil being measured and rod length. This ER correction needs to be applied for the N-value to be used as a design parameter.

Current SPT design relies on accuracy of measurements, based on visual observation, and not digital recording shown herein. Perhaps it is time for the ubiquitous SPT to enter the digital age, as visually counting values in 150mm increments is shown to vary and is an "interpretative" number.

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