Standard Penetration Test Measurement Variations Exposed Using a Digital PDM Device

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ABSTRACT: The failings of the Standard Penetration test (SPT) was revealed in a companion paper. These include 1) counting of integer values over 150mm increment is inexact 2) a seating drive which is not a constant 3) Energy transfer which (even for given drill rig) depends on the soil type the test is being carried out in and the variability in energy transfer from the hammer to the anvil to the rod. Thus the SPT is far from "standard" as the name implies. Energy and other corrections are required to effectively use the SPT value in design. The analogy with pile driving is shown, with energy transfer between SPT blows, depending on drill string location, rod length and material stiffness. Digital measurements provide improved accuracy which the current measurements observed using chalk marks cannot provide.

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. Key aspects are discussed in Clayton (1995). A companion paper (Look et al. 2015) provided an overview of the similarity with pile driving and measurements using the SPT hammer.

The SPT requires an accurate count of the SPT Blows (N-values), and an energy conversion to be appropriately applied to design. At the time of SPT standardization before the digital age, measurements using chalk marks was appropriate, but parallel digital readings show that counting of blows between increments consistently has an error. These include:-

1) The seating drive is "fixed" at 150mm yet when the measurement set is examined, this seating can vary from less than 50mm to 200mm when similarities between sets are compared
2) The test drive is based on 150mm increments. In practice, the drilling supervisor uses the blow count with the closest estimate to the 150mm mark and applies that integer value. For example, they may use the blows at (say) 140mm as close, which automatically transfers a 10mm error to the next 150mm increment. But vice versa if that number of blows at 140mm is not used, the value used may be at 175mm (say). Thus the 150mm blow count is not an exact value.
3) Energy is transferred from the hammer to the anvil, and to the drilling rods which then drives the split spoon sampler into the soil. This value is not constant and depends on the length or rod and the soil hardness (Seidel, 2014). The most significant factor affecting the measured N Value is the amount of energy delivered to the drill rods (Sherif and Radding, 2001).
4) Additional to the above temporary compression and rebound is occurring which is dependent on the anvil, rod length and soil hardness. None of these is observed visually, but affects the measurements.

The Pile Driving Monitoring (PDM) device can be used with the SPT to digitally measure blow counts in terms of set and temporary compression, similar to pile driving. At the same time energy ratio is also measured. This has been applied for buildings, road and marine infrastructure projects. It is also required for piling projects in Queensland and Hong Kong.

1.2 *Pile Driving Monitor used with the SPT*

The 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 above. The device is also a quality measuring device to measure pile set and energy.

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.

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 parallel with this geotechnical activity, the PDM research was carried out on the SPTs. Look et al. (2015) discussed initial results in a companion paper. Further data at this site is discussed in this paper (Table 1).

At Borehole C106, monitoring of the hammer occurred in parallel with monitoring of the rod below the anvil. By using 2 PDM devices, the displacement and 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. The PDM sampled at 240Hz i.e. 240 readings per second, while the SPT was in progress in the usual way.

At borehole C139, a PDM was used to monitor the hammer and an SPT analyzer was used to instrument the rods below the anvil. This measures the energy transferred by the hammer by attaching a sub assembly with strain gages and accelerometers to obtain the force and velocity signals, which are converted to energy transfer. This measures energy on the top of the rods. GRLWEAP analysis suggests that a 10% energy loss may occur between the bottom and top of the rods, but only top of rods was able to be measured in this research.

The PDM measures the energy (by velocity) the moment before the hammer hits the anvil while the analyzer measures the energy transferred (by force) from below the anvil. These energy ratio (ER) measurements are discussed herein.

2.2 *SPT N- Values*

Table 1 summarizes the N-values measured. 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 1. SPT N-values

Ref. /Depth/Mat'l	SPT Readings	N- Value
C85 /6.0m/XW	30 blows /40mm	N* = 225
C106 /1.0m/CL	6/ 7/10	17
C106 /1.5m/CL	6/ 8/10	18
C106 /2.0m/CL	6/ 5/8	13
C106 /2.5m/CL	4/ 6/11	17
C106 /3.5m/CL	5/ 8/12	20
C106 /4.5m/CL	5/ 9/13	22
C106 /5.5m/CL	7/ 9/15	24
C139 /0.5m/CI	4/ 6/ 9	15
C139 /1.5m/CI	4/ 8/13	21
C139 /2.5m/CI	8/21/22	43
C139 /4.0m/CI	6/11/20	31
C139 /5.5m/CI	6/14/23	37

2.3 *Counting Accuracy*

The digitally measured increments (should be 150mm if accurate) was combined with additional data from Look and Seidel (2015) in Fig. 1. This shows there is a 20% chance the value measured is greater than 167mm or less than 129mm which is no small error in a 150mm "standard". The lowest and highest values recorded was 109mm and 191mm, respectively.

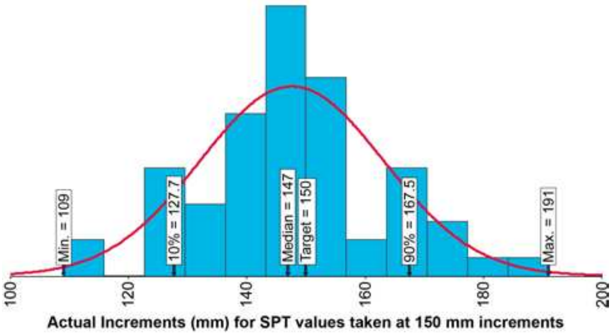

Fig. 1 Digital measurements of 150mm increments

Because two 150mm increments are used for the N-value, compensating errors occur. Fig. 2 compares the chalk mark measurements with the PDM digital measurements for the SPT N-value for the test drive (150mm to 450mm increment). Above an N-value of 20, a 20% error was measured. This data shows counting blows is not a "standard" value as implied by the test.

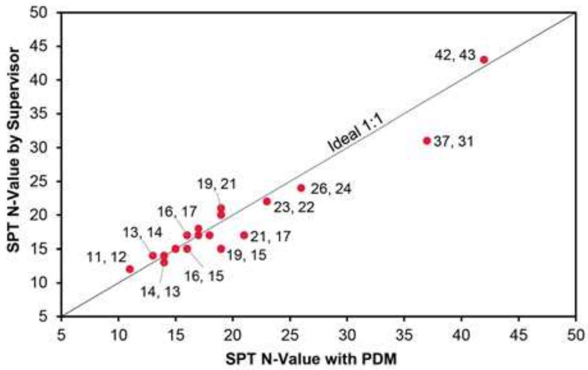

Fig. 2 Measurements by eye and digitally compared

2.4 *Seating Drive*

The PDM measured set for each blow is compared with the measurements by eye. Fig. 3a shows the supervisor measured the seating drive at 158mm, and test drives at 296 and 442mm which is reasonably close to 300mm and 450mm, respectively. However clearly the seating drive stopped at the 3rd blow which is at 131mm. This is also evident in Fig. 3b for the energy ratio with each set for each blow shown. This shows a steady increase in hammer energy ratio for sets greater than 35mm.

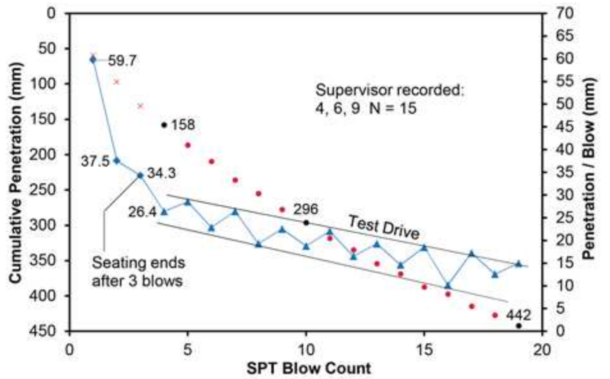

Fig. 3a Variation of each blow count at C139 @ 0.5m

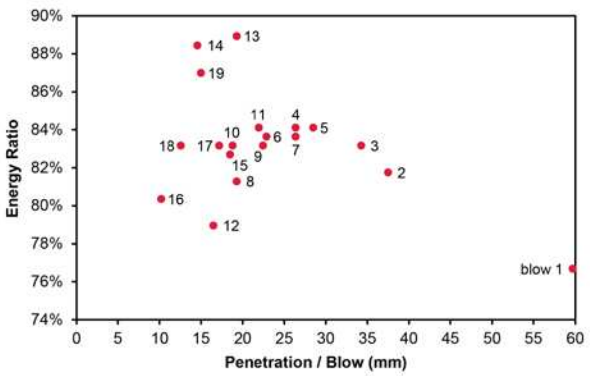

Fig. 3b Variation of energy ratio at C139 @ 0.5m

The "true" seating is also evident in all measurements examined digitally. Fig. 4 is another example for the same borehole at 2.5m depth, where a higher N-value was recorded. The seating drive recorded by the supervisor was 8, yet the seating is complete after blow No.1, with all others clustered. While 150mm is a "standard" seating drive in the test, the digitally measured seating is shown to be significantly different from that fixed increment.

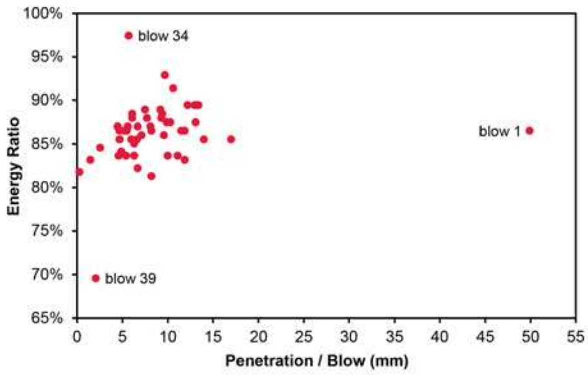

Fig. 4 Hammer energy ratio at C139 @ 2.5m

2.5 *Energy Ratio*

Table 3 compares the energy measured with PDM (at hammer) and the SPT analyzer (below anvil). This shows the energy varies for each blow, with a decrease in energy loss as the ground stiffens.

Fig. 5 plots the analyzer results at the rod compared with the PDM measurements on the hammer with the seating / test drive / depth labelled. As the blow count increases, there is a change in the energy ratio. During the seating drive (with its lower blow count), the hammer efficiency drops.

Table 3. Energy summary measurements @ C139

Depth and 150mm increment	Analyzer Efficiency @ Rod	PDM Efficiency @ Hammer	No of blows / 150mm
0.5m			
Seating	64.7%	86.9%	4
Test Drive 1	66.1%	86.6%	6
Test Drive 2	72.9%	86.9%	9
1.5m			
Seating	63.4%	86.5%	4
Test Drive 1	67.6%	86.1%	8
Test Drive 2	69.7%	87.1%	13
2.5m			
Seating	70.8%	89.0%	8
Test Drive 1	69.7%	86.6%	21
Test Drive 2	69.7%	88.2%	22
4.0m			
Seating	67.6%	88.1%	6
Test Drive 1	67.6%	88.3%	11
Test Drive 2	69.7%	89.5%	20

For all values measured the median energy was 87% at the hammer, but 69% just below the anvil.

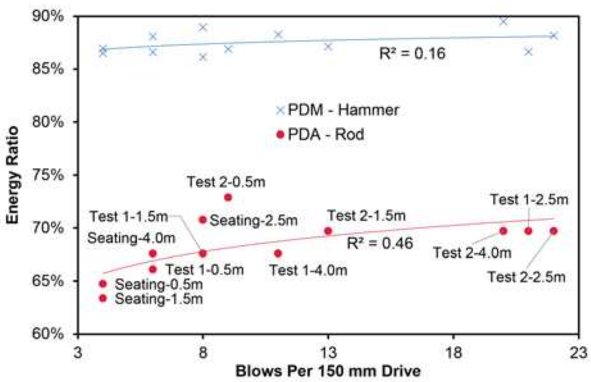

Fig. 5 Comparing measurements with Analyzer & PDM

The PDM energy was less dependent on the blow count values, while the analyzer energy varied from 70% for N-values above 13 and reducing with lower N- values to about 65%. This results in an energy correction of 1.08 to 1.17, respectively, if the PDA analyzer energy ratio is used.

The energy difference was expected between the kinetic energy of the hammer hitting the anvil and the PDA measured energy below the anvil. The energy loss at the split spoon penetrating the soil is the ideal but is not currently practical to be measured. The energy difference using the PDM on both the hammer and below the anvil was subsequently investigated at another building site.

Fig. 6 shows a high correlation between the analyzer and PDM measured displacements. This decreases to $R^2 = 0.8$ when the set per blow reduces to 10mm or less at other locations. The PDM placed below the anvil also measured comparable displacements with the PDM displacement at the hammer, but the velocities were distinctly different. This is due to the weight change (hammer + anvil + rod) and the energy losses. This energy transfer between the hammer and rod is currently being investigated.

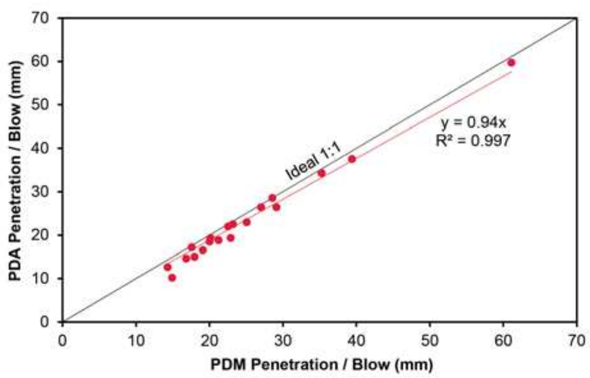

Fig. 6 Comparison of PDA and PDM displacements

3 CONCLUSIONS

Integer values are measured for each 150mm increment in the SPT. PDM measurements show

- The seating drive 150mm is not a constant as assumed in the test.
- Integer values means that blow counts are taken as close as possible to 150mm which may be more or less based on the supervisor's judgement. The "standard" 150mm increments varied from 109mm to 191mm.

Overall this results in ± 20% for simply counting blows above 20. Thus an N-value is not a "factual" value, but an interpretive visual number.

Measured energy losses are essential in using the N-value as a design value. Energy ratios were measured with the PDM at different positions and an SPT analyzer. The energy loss changes with both rod length and soil stiffness. In most (but not all) cases the seating has a higher energy loss than the test drive. The position of any device for measuring this energy loss is important as the energy loss from the hammer drop is distinctly different from the energy transfer loss below the anvil.

The PDM has been successfully applied on various marine and building piling projects over the past few years to both improve safety and accuracy. This paper provides the application of the PDM to SPT measurements to also digitally measure energy, set and compression from a road infrastructure site investigation with the enhanced data collection digitally measured exposing the measurement variation for N- values measured visually.

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