Macro Standard Penetration Test measurements Examined with a micro scale PDM device

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ABSTRACT

The Standard Penetration Test (SPT) requires 3 data points - the seating drive and 2 test drives each to 150mm penetration. The combined number of blows to penetrate 300mm for the test drive is the N–value. The SPT is far from "standard" as the name implies and despite following the procedures to a given testing code. Energy and other corrections are required to effectively use the SPT N – value in design. The Pile Driving Monitoring (PDM) is based on LED opto-electronic technology and measures pile set and temporary compression by non-contact measurement from a safe distance. The peak pile velocity can also be calculated. This technology has been applied to SPT measurements in a similar way to observe the set and energy. The 3 data points for the N- value are measured as 30,000 data points with the PDM. Additionally the velocity, and hence energy is able to be obtained. With 10,000 times the usual data for each SPT, insights are revealed on errors that are occurring in this simple and ubiquitous test. The "standard" seating drive as 150mm, while appropriate before the electronic age, is now shown to be a significant and routine variable in the digital age. Correlations with N - values in the literature are for a specific energy efficiency. Assuming rather than measuring the energy efficiency of the hammer used is the common practice in Australia. Measuring and accounting for this Energy correction allows greater confidence and economies in design to occur.

Keywords: Standard Penetration Test, Pile Driving Monitor, Energy ratio

1 INTRODUCTION

The Standard Penetration Test (SPT) is a widely used field test. The SPT hammer (63.5kg) falling 760mm is used to drive a 51mm outside diameter (35mm inner diameter) split barrel sampler to obtain disturbed soil samples. This was its original intent. Additional data was obtained from counting the number of blows to obtain the samples. The test was then standardised as the penetration of the last 300mm with 150mm as a seating drive prior to measuring the test drive. A history of the development of the test and its limitations is provided in Davidson et al. (1999).

The SPT has been correlated to soil strength, modulus, settlement, and even used to asses pile capacity (Clayton, 1995; Burland et al., 1977; Meyerhof, 1976). However, Skempton (1986) recommends various correction factors be applied to account for variable hole length and diameter, drill rig and energy loss. Seed et al. (1985) also examined correction factors as critical in liquefaction assessment.

The Pile Driving Monitoring (PDM) was developed by Dr. Julian Seidel to accurately measure pile set and temporary compression by non-contact measurement from a safe distance. The peak pile velocity can also be calculated. It is based on LED opto-electronic technology and uses a continuous laser scan approach. While the equipment was intended for the piling industry, the principle of accurately measuring the set and velocity for an element driven into the ground was extended to the SPT, which is a split spoon sampler driven 450mm into the ground.

The 150mm increments used to assess the number of blows has an accuracy typically of -10mm to +15mm for most cases, but can be larger. This is due to 3 reasons

- the 5mm to 10mm chalk mark, which is thick enough for the supervisor to observe from a safe distance;
- the supervisor being at least 3 metres away from the test due to safety requirements;

- If the number of blows exceed 150mm, then that blow is “transferred” by reducing the number of blows in the next 150mm. Conversely, the SPT blows may actually be at 145mm (say), but if the next blow is significantly above the 150mm mark (at say 165mm), then 145mm is used as that test increment, which increases the next increment to be above the 150mm. The supervisor has a few seconds or less with automatic trip hammers to make this assessment.

Thus, the number of blows is the supervisor’s best estimate as it approaches the 150mm mark. The blows do not stop exactly at the 150mm mark, but could be several millimetres on either side of that mark, and this occurrence is not explicitly stated within the Standard procedures.

In contrast, the PDM approach measures, the actual set / penetration to 0.1mm accuracy for each SPT blow count. The penetration is summed to arrive at the actual number of blows. The accuracy is then ± 0.1mm from the instrument. However due to background “noise” such as vibration of the operating drilling rig itself, this accuracy is more likely to be ± 1mm. There is a slight hammer rotation (and hence reflector reference) in this rig used in the study which may also affect the reading, although this occurred mainly on the hammer lift where no reading is being taken (Figure 1).

2 ENERGY TRANSFER

There are many corrections factors to be applied to convert the in-situ N–value to a useful design value. Energy is widely considered the key correction factor. Energy transfer is affected by the type of drill rigs, hammers used, operator skills as well as the ground conditions. Some of the variables that may affect the energy transfer are (Davidson et al., 1999):-

- An inclination of the drill string up to 3 degrees did not influence the velocity at impact
- Energy transfer is reduced for lengths less than 15m.

Australia predominantly uses trip hammers. Correction factors need to be applied based on the energy ratios (Table 1) with no corresponding documentation for Australia. Robertson and Wride (1997) suggest a correction of 0.8 to 1.5 for automatic hammers.

Table 1: Correction factors based on Energy ratios for trip or automatic hammers

Energy Ratio	Reference
55% to 62% due to heavy anvil **60% to 83% depends on anvil weight**	Skempton (1986)
76 to 90%	Seed et al. (1985)
60 to 73%.	Clayton (1990)
80% to 100% - North America **60% United Kingdom**	Bowles (1996) but uses E_{70}

ASTM D1586-08 recommends normalizing results from any SPT test using energy measurements, and is mandatory when carrying out liquefaction assessments (ASTM D6066-96-2004). Australian Standards do not currently specify such requirements and energy is not commonly measured. Thus any correction if applied is based on the international literature.

Different types of hammers used influence the N-value, with different 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}):-

$$N_{60}\,E_{60} = N_{SPT}\,E_{SPT}$$

N_{60} is the estimated N-value for the old safety hammer (cathead and rope). An automatic trip hammer is estimated to be about 80% efficient which is 30% more than a safety hammer. The N-value therefore requires a correction to equate the values from the different hammers. Skempton (1986) suggests the weight of the anvil also affects the energy transfer. N_{60} is the currently accepted standard and many correlations are based on converting the field SPT value to that energy value. This Energy correction allows greater design confidence and economies in design to occur.

The equation shows that the more efficient hammers require a higher energy correction factor e.g. a 150% correction for a 90% energy ratio. Thus if an in-situ SPT N - value of 8 (say) is used directly without an energy correction, then this would be incorrectly interpreted as a loose material for a granular soil, while the energy correction would result in a medium dense soil strength classification. Similarly, a clay strength classification would change from firm to stiff.

3 TEST SITE AND PDM SET UP

The test site was at The University of Queensland, Pinjarra Hills agricultural research area. This site is used as a field training for final year students in the Mining and Geotechnical Engineering degree course. Students in groups of 10 or less with 4 groups per day are rotated on various activities and the SPT/ sampling drill rig activity was 1 of 4 activities. An Edson 3.5 t rig was used. This drill rig is typically limited to 10 metres maximum depth with no rock coring facility. Shallow boreholes were drilled with 1 SPT per group. However all boreholes were within 5 metres of each other.

The one CPT result at this location showed a stiff to very stiff clay in the top 0.75 metre and increasing to hard at termination depth. The uncorrected SPT N- value varied from 12 to 21 (median N = 15) to the 2.5 metres maximum depth for 4 test boreholes. The tactile classification would be a very stiff clay.

The PDM research had to be carried out as a background only, with the key activity being the training of students for standard site investigation procedures. THE PDM measurement involves placing a reflector as a reference point for the PDM device (Figure 1). Measurements were taken as the SPT was carried out in the usual way.

Figure 1. PDM obtaining data with reflectors on SPT hammer

4 PDM TEST DATA

4.1 Penetration Values for Seating and Test Drive

A typical result is shown in Figure 2. This shows the original reference position at 0.3mm at t=32 seconds, followed by the hammer drop where the hammer goes out of the line of sight of the PDM, hence the negative values as it is lifted. The -423.5mm and -423mm lines (prior to the first SPT blow) shown in Figure 2, if extrapolated would intersect at 760mm, i.e. the hammer drop.

In this result, the hammer then falls to a vertical position of 53.3mm at t=36.5 seconds after falling in 0.2 seconds. At t=38.9 seconds, the vertical position is 48.0mm. In some cases, there is a rebound while in other blows, there is nominal settlement. This can also be due to the natural vibration of the drilling rig, and needs to be investigated further. As the hammer is at a standstill, then the barrel rotation is not considered a cause. The average of these 2 positional values is used in Figure 3. Only the first 5 SPT blows are shown in Figure 2.

The PDM measurements occurred at 240 Hz, i.e. 240 readings per second. There is 0.2 seconds for the hammer fall and 5 seconds between blows. In contrast to using this PDM approach, the drilling supervisor must “eyeball” the blow being in or outside of the fixed 150mm increment i.e. it is a judgement on whether the below just before or just after is closer to the 150mm chalk mark. Yet this is meant to be a factual value. Using the typical SPT procedure and measuring the number of blows per 150 mm increment then the BH 2 (2.0m) result is:-

- 4 / 5 / 9 for each 150mm increment. Thus N = 14 as measured by the drilling supervisor by eye and the reference chalk marks
- The PDM vertical set measurement show those 3 readings were actually at increments of 191mm / 123mm / 154 mm

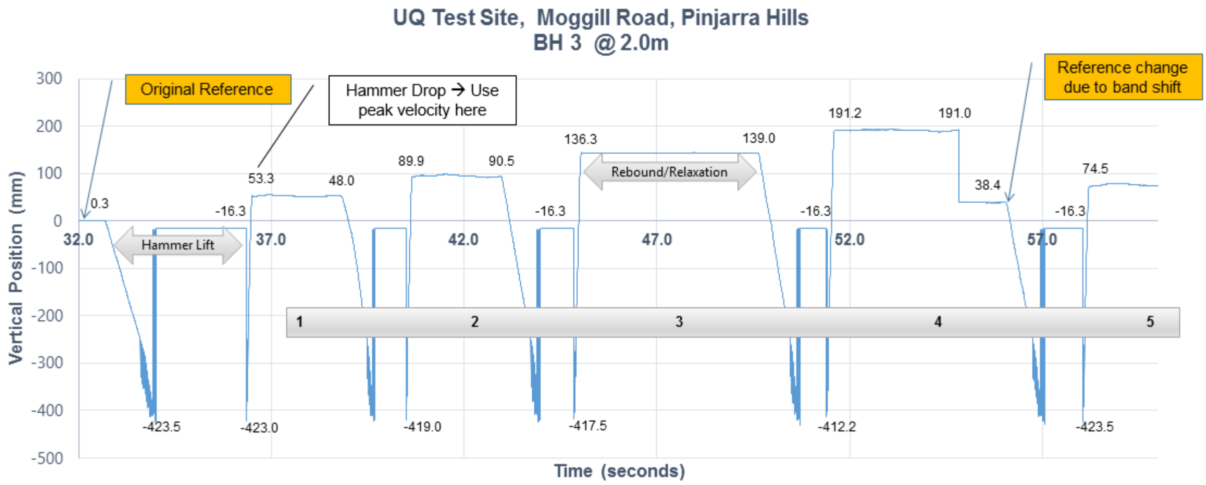

Figure 2. Vertical position as measured

The supervisor made the decision (in those few seconds) not to use the 3 blow counts as the seating drive, as 137.8mm was below the 150mm. That extra blow meant the seating blow was now actually 191.3mm – even further away from the 150mm standard, and a “factual” record of 4 blows for the seating drive is now used. These decisions are typically made every day in the field, and represent the errors in using chalk mark technology as the current state of practice. The supervisor could not know that the penetration would increase for the next blow. The transfer of seating penetration of 41mm (191mm – 150mm) to the test drive is a significant error of 27% in that increment (ratio of 41 mm /150mm)

While the various standards suggests 150mm of seating drive, the results show the blows for the seating drive are similar in the range of 50.7mm to 39.6 mm / blow (Refer Figure 3) i.e. beyond the 150mm “standard”. Thus, by definition blow No. 5 is captured in the test drive, despite its obvious association to the set range and not the test drive set /per blow. The test drive varies from 13.6mm to 26.5 mm set.

The result by this digital approach would then be:-

- 5, 7, 10 for N = 17 for penetration of 228mm / 150mm / 150mm.
- While the supervisor recorded 4, 5, 9 for N = 14

Given the current technology to measure accurately, the question for industry is should we be accepting this “error” in measurement? The 150mm made practical sense prior to the digital age, but now seems out of step with the twenty first century with our ability to now measure accurately.

While this adjusted PDM measured N - value for this depth was 21% above the "by eye" value, overall the difference with the other values varied from 13% less to 21% more, with a median of 8% higher for the PDM result.

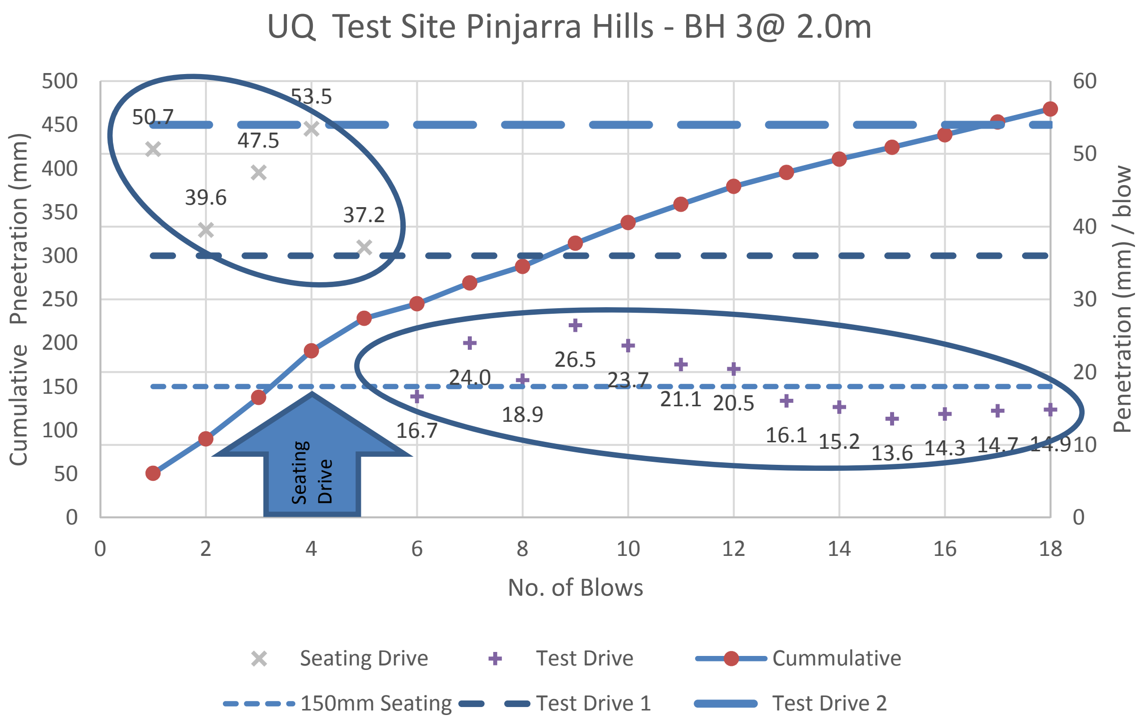

Figure 3. Blow counts compared with penetration per blow at BH 3

Figure 4 shows the SPT results for BH4 at 1.5m. In that borehole the 150mm seating drive was actually 156mm. However that last blow count of 24.5mm seems to be more closely associated with a test drive reading rather than the higher seating blow sets.

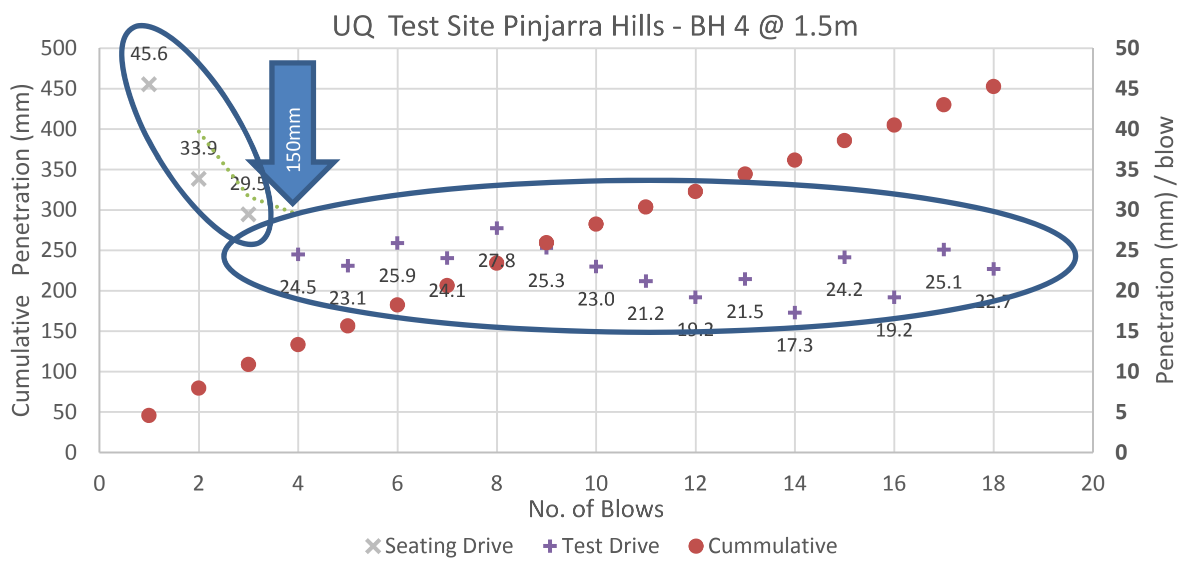

Figure 4. Blow counts compared with penetration per blow at BH 4

4.2 Velocity Values and Energy Correction

As the vertical position and time is known, then the velocity can also be calculated.

Figure 4 shows the hammer drop reached a peak velocity of 3.42 m/s. This is initially near zero velocity (shown as -.01m/s) before falling, but that plateau is actually outside of the PDM laser. The negative and spiked results occurs as the falling hammer first enters into the PDM range, with negative values and initial distortions (which are disregarded), before stabilising with the peak velocity just before impact and decelerates to zero velocity. The velocity does vary with each blow count, with the energy ratio calculated from these measured velocities for the 18 blow counts for this SPT, varying from 79% to 83% for this drilling rig.

Thus an energy correction factor of 1.3 (80%/60%) would apply to this SPT measurement.

Considering the energy correction and the imprecision of the "eyeball" approach, the SPT N - value for BH3 (2.0m) would now be 24 as compared to N =14 as the in situ value and as measured in the traditional manner. Note that due to the short rods used Skempton (1986) would recommend a further 0.75 reduction, and an anvil correction may also affect that value.

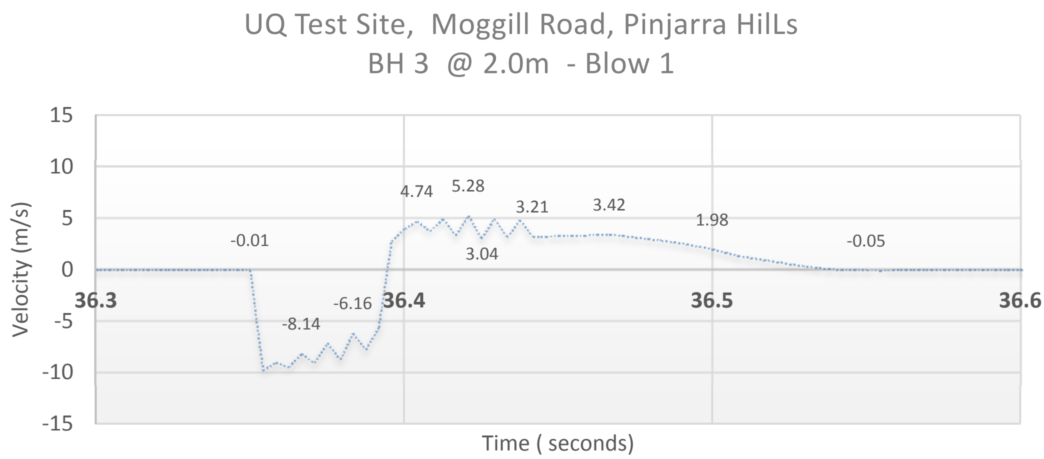

Figure 4. Hammer drop peak velocity

4.3 Summary of Results

Table 2 provides a summary of results with a comparison of the actual penetration used for the SPT value and with a "corrected" value allowing for a seating "error" as evident from the PDM measurement. The variation in energy ratios is also shown.

Table 2: Summary of SPT values examined with PDM measurements

Borehole / Depth	SPT N-value using supervisor's records	Penetration measured with PDM and with a "corrected" seating	Energy Ratio
2 (2.0m)	3,5,7: N = 12 152/148/168mm= 469mm	152 / 150 /150mm 3, 5, 6 : N = 11	81%
3 (2.0m)	4,5,9: N = 14 191/123/154mm= 468mm	213 /150 / 150mm 7,8,10: N= 18	81%
3 (2.5m)	5,7,8: N = 15 164/141/146mm= 451mm	213 /150 / 150mm 7,8,10: N= 18	85%
4 (1.0m)	6,6,9: N = 15 153/156/146mm= 455mm	42 / 150 / 150mm 1,6,7: N= 13	81%

4 (1.5m)	5,7,7: N = 14 157/166/153mm= 476mm	109 /150 / 150mm 2,6,7: N= 13	80%

These results show:-

- The seating drive is not 150mm and the test drive is not 300mm
- The energy ratio is approximately 80% to 85% for this drill rig
- When the more accurate penetration values are accounted for, the true N- value is ± 20%

5 OTHER SITE DATA

The data discussion was for one site only. Figure 5 shows for another site, where the seating drive shows 3 blows for the 150mm increment, yet clearly the 4th blow, while within the 300mm for the N-value test drive according to the standard approach is more associated with the seating rather that the test drive.

These results consistently suggest, that the time has come to re-consider the intent of the 150mm seating drive rather than use the 150mm as a constant according to the Standards in use. The seating drive intent was to dis-associate the initial blows with the test drive to account for material fall in to the base of the hole, or the disturbance of the hole-base material from drilling. The 150mm in common use is a good first approximation, but as this digitally derived data has shown, this inherent "assumption" of 150mm as a constant can affect the N- value from the test drive.

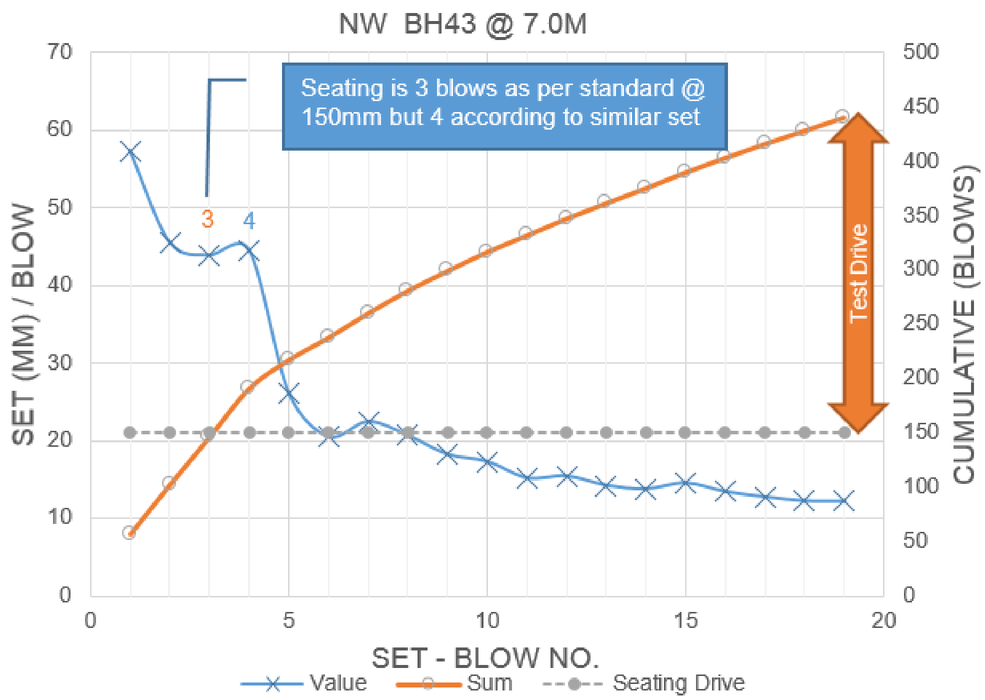

Figure 5. Seating Drive and test drive measurements

6 CONCLUSION

Despite the many Standards associated with the Standard Penetration Test and even the name of the test the measured value is far from "Standard". The PDM measures to 0.1mm accuracy, and shows the imprecise measurements in this standard approach even for 3 X 150mm penetration.

With 10,000 times the usual data for each SPT, insights are revealed on inaccuracies in this simple and ubiquitous test. In carrying out the SPT, we have 0.2 seconds for the hammer falling and less than 0.05 second it takes to come to a standstill, and a further 5 seconds before the next below is delivered. The accuracy of the drilling supervisor's assessment in that time frame is examined. With some automatic hammers the time can be less than 1 second between blows.

The PDM shows the SPT "factual" blow count has an inaccuracy of up to 21% for the main test site discussed. This is due to the seating drive variable, and the interpretative transfer of blow counts between the 150mm increments that occurs with every SPT in the field i.e. the blows can be above or below the 150mm increments. While that approach was practical 50 years ago, the ability of instruments in the digital age for more accurate measurements, raises the question on whether we should update this "standard" test. The seating drive is a constant value of 150mm according to the test procedure, yet seating has been shown to vary about that value.

In some cases movement continues downwards, after blow termination by several millimetres. In other cases, there can be a rebound or relaxation following the SPT blow. The relevance of these considerations are discussed to expose the high degree of inaccuracy in this 150mm measurement test procedure.

The energy measured (which is not typically carried out for Australian Projects) shows a 1.4 correction is required for this drill rig. Without regular calibrations of the drilling rigs by this or other energy methods, a significant error may occur in applying the SPT N value directly as most correlations in the literature are based on the N_{60} value.

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