Use of the dynamic cone penetrometer to assess the liquefaction susceptibility of Christchurch alluvial soils

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ABSTRACT

Thorough geotechnical investigation and in-situ testing of alluvial soils is often fraught with difficulties. Unfavourable and/or dramatic changes in material characteristics in locations where inter-bedded layers of alluvial gravel, sand, silt and/or organic materials are present, often means that a combination of Cone Penetrometer Tests (CPTs) with “pre-drilling” and rotary mud and/or sonic drilling needs to be undertaken so that adequate minimum investigation data and depth is achieved.

In Christchurch alluvial soils, sample disturbance, artesian ground water pressures, and/or base heave, often result in incomplete data and some doubt as to the reliability of the investigation results. Two configurations of the dynamic probe (DP) have been identified by the authors as a reliable and cost-effective method to obtain geotechnical data for liquefaction hazard assessment purposes: dynamic probe heavy (DPH) and super heavy (DPSH-B). Collectively DPH and DPSH-B are referred to as DP.

This paper describes the logistical, technical and financial advantages of using the above dynamic probe tests and presents comparisons between test results obtained at numerous control locations using DPH/DPSH-B, and CPT and Standard Penetration Test (SPT) apparatus. Recommendations for normalising factors to correct DPH/DPSH-B test results and calculate an equivalent SPT N_{60} value are discussed, and comparisons between the results of liquefaction hazard assessment based on DP to SPT and CPT data is also presented.

1 BACKGROUND

Dynamic probing (DP) is a geotechnical investigation tool that provides continuous equivalent SPT-N data for depths of up to 20m and is referenced in the British and German Standards for Soils Testing and ISO 22476-2. It is used in many countries as indicated in the literature, including, MacRobert et al (2011) and Gadeikis et al (2010). The DP test equipment is compact and mobile, and able to be utilised when access constraints prevent the use of conventional larger track or truck mounted machine borehole drilling rigs. The blow counts obtained from the test are most commonly converted and presented as equivalent SPT N blowouts. Presentation of this data is typically as a continuous soil strength profile, unlike conventional SPTs which are typically undertaken from the borehole base at 1m to 1.5m depth intervals.

2 GEOLOGY AND GEOTECHNICAL MODEL

Christchurch city geology is broadly described as predominantly alluvial channel and overbank deposits comprising interbedded silts, sands, and gravels, with lenses of organic silts and clays (Brown & Weeber, 1992). Groundwater is typically encountered between 1 and 3m below ground level although this can vary depending on local geomorphology and in response to seasonal rainfall and evapotranspiration rates. The site investigation information now available on the Canterbury Geotechnical Database reinforces that that substantial variability in the soil conditions, both laterally and with depth, can be expected.

3 EQUIPMENT DETAILS

In the above standard specifications several different combinations of hammer weights, drop heights, and cone diameters are available for different anticipated ranges of soil strengths; (Dynamic Probe - Light, Medium, Heavy, and Super Heavy). Details for the DPH and DPSH-B are specified in the above listed standards.

The DPH rig is mounted on a two wheel adjustable chassis, with an attached or separate petrol power pack, and can be manoeuvred onto a site by one person. With a width of 790mm and a net weight of 110kg (plus hammer weights, rods and jack) the rig is very portable. The DPSH-B rig used for this study is mounted on a self-propelled terra rig (approximately1.2m wide and 3m long).

The test procedures used follow the ISO 22476-2:2005 (E) standard. Hammer blows are undertaken at a rate of 15 to 30 blows per minute and counted for each 100 mm penetration, which is then recorded as DPN_{100}. At each addition of a 1m driving rod the full rod string is rotated using a torque wrench. The measured torque is used to estimate the skin friction on the drive rods and used to correct the recorded blow count for rod skin friction effects. At the conclusion of testing the rods are withdrawn by a mechanical or hydraulic jack leaving the sacrificial cone behind.

4 CHRISTCHURCH APPLICABILITY

Within New Zealand, the DPH and DPSH-B have been utilised by a number of geotechnical consultants for more than 20 years, and has been used in geotechnical investigations throughout New Zealand in a variety of ground conditions ranging from residual soils to alluvial and colluvial soils. The earthquake events in Christchurch since 4 September 2010 have highlighted the high liquefaction potential of significant parts of Christchurch and the importance of undertaking appropriate investigations to assess liquefaction hazards. The assessment of liquefaction hazard is typically based on an analysis of either CPT data or SPT ‘N’ data. This data is respectively typically derived from track or truck mounted CPT and machine borehole rigs.

Gravel lenses/layers within the alluvial soils can present a significant limitation to CPT testing, and where the layers are shallow can result in shallow refusal on gravels overlying liquefiable soils. We have observed many cases where this has occurred in investigations we have undertaken and have also noted that this is a feature evident in CPTs for the area wide investigations undertaken by EQC.

The DP is capable of penetrating the shallow gravel layers on many sites in Christchurch where CPT equipment has refused and DP testing has revealed low strength and potentially liquefiable soils below. DP testing is considered to have a significant advantage over the CPT on the basis that the DP can penetrate gravel layers and provide a strength profile on these layers.

5 DP TO BOREHOLE SPT CORRELATION PROGRAMME

For this study a series of test locations were selected on 23 different sites in Christchurch where data was available from SPTs collected using high quality rotary mud machine boreholes, DP tests, and in some places CPTs, all obtained from relatively coincident test locations. At 19 locations a separation of about 5m was used between machine boreholes and DP tests. This was reduced to a separation of 1m to 2m at four of the locations, in the Halswell area of Christchurch, improving the correlation of the DP results with the adjacent borehole SPTs.

6 CORRECTION FACTORS TO ENABLE COMPARISON OF BOREHOLE SPT AND DP DERIVED SPT

A moving average of three DPN_{100} increments is calculated to compare borehole SPT N-values, which are obtained over a 300mm test increment. A number of correction factors are then used to standardise both the borehole SPT and DP data. Corrections applied to the DP data include:

a) Hammer Efficiency

The efficiency of the energy transfer from the falling weights to the DP driving rods is periodically calibrated (e.g. annually) using PDA high strain dynamic testing. This used SPT analyser equipment, manufactured by Pile Dynamics USA in general accordance with the recommendations of ASTM D4633-10 (Standard Test Method for Energy Measurement for Dynamic Penetrometers). The hammer energy ratio (ER, measured in percent) is the ratio of the measured energy transferred into the rods to the theoretical energy. Adopted energy ratios for the DPH and DPSH-B rigs used and reported in this paper are 92.7% and 75.95%, respectively and result in energy correction factors (C_E) of 1.545, and 1.266 respectively.

b) DP Solid Cone to SPT Split Spoon Factor

The solid cone tip used in the DP test displaces the soil rather than cutting a sample from it as with the tubular SPT split spoon. Gawad (1976) undertook research comparing the resistance of a number of different diameter solid cones with a standard ASTM SPT split spoon sampler in medium to coarse sand. This indicated that when standardising from a 51mm diameter solid cone driven by continuous penetration in an uncased situation (as with a DP) to the 51mm diameter split spoon sampler at the base of a cased borehole, a multiplying factor of 0.56 should be applied to the apparent N-value. Regression analysis from the Halswell area database (35 data points) with the DPH indicates a factor of 0.56 provides reasonably good correlation in sand and sandy gravel but appears to be slightly low for clean gravel, (overall R^2 = 0.84). Regression analysis for a much larger data set (nearly 200 data points) from 20 DPH locations confirmed a factor of 0.56 (Figure 5) which has been applied in this study for all DPH analysis. Similar regression analysis from the 10 sites providing DPSH-B data indicated an overall factor of 0.65 was more appropriate for data obtained from that rig with a larger diameter cone.

c) Dynamic Probe Area Ratio

The energy applied to the cone area over each 100mm penetration increment is normalised to account for the difference in cone areas between the DPH and the DPSH-B tests. Corrections have been applied to the borehole SPT values, after Clayton (1995), to account for rod length, borehole diameter, and hammer energy efficiency (the SPT data used in this study was obtained from hammers recently calibrated for energy efficiency) to calculate an SPT N_{60} value.

Additionally, corrections were made for the SPT Split spoon liner. The standard ASTM SPT split spoon sampler has a 51mm outside diameter (OD) and a 35mm inside diameter (ID) with an 8mm wall thickness. Many Christchurch drilling companies use the standard 51mm

OD/35mm ID cutting shoe at the base connected to a split spoon, which allows a removable liner with a 3mm wall thickness to be installed inside. This sampler has an ID of 41mm without the liner. The liner is normally intended for environmental sampling to prevent contamination. When the sampler is used without the liner the frictional resistance to driving is reduced, giving a lower apparent SPT N-value. Clayton includes the results of research into the effects of omitting the split spoon liner. This data indicates that from tests in the same materials and similar depths, consistently greater N-values would have been achieved with a constant 35mm ID split spoon compared to the larger 41mm ID sampler without the liner. Our analysis of the graphical data indicates that a mean multiplying factor of 1.2 should be applied to N-values obtained from the 41mm ID sampler (without liner) to give the equivalent standardised N-values for the 35mm ID sampler.

7 RESULTS AND DISCUSSION

7.1 Comparison of DPH N60 and Borehole SPT N60

A comparison was made between the corrected DPH records and the adjacent machine borehole SPT records for four Halswell sites. This is shown on Figure 1 plotting the N_{60} variation with depth. The soils in the upper 7.5m to 9m of the area comprise interbedded silts and sands. The graphs on Figure 1 (Sites 1 to 4) comparing the derived DPH N_{60} (continuous lines) values with SPT N_{60} (point locations) indicate a reasonably good correlation within these near-surface materials.

Below approximately 9m the Halswell site is underlain by sandy gravel alluvium. The plots indicate DPH N_{60} values varying between about 20 and 80 (continuous lines) below 9m. At Site 2, at 8.9m depth, the borehole SPT N_{60} = 62 whereas the DPH derived N_{60} = 49. This degree of variation could quite easily be due to the presence of cobbles within the gravels giving a localised apparent strength increase.

7.2 Comparison of Tip Resistance Between CPT and DPH Derived Data

A comparison was also made between the corrected DPH blow counts converted to equivalent CPT tip resistance (DPH q_c) and the adjacent CPT sounding. The only correction factor applied to derive equivalent tip resistance from DPH data is an allowance for inertia (e.g. no correction for solid cone, and 100% hammer energy efficiency assumed). This comparison, developed for five locations from the Halswell site, is shown on Figure 2. It should be noted that all five CPT tests terminated at the first layer where the soil strength exceeded SPT N_{60} = 35, the practical limit of the CPT machine. At Sites 4 and 4A, the two CPT tests straddle a single DPH test location indicating the variation between two CPTs 7m apart.

7.3 Particle Size Effects

The effects of particle size on the relationship between DPH N_{60} and SPT N_{60} data have been evaluated for four test sites in Figure 3, using 35 data points. The pairs of tests (BH and DPH) were located 1m to 2m apart. Regression analysis confirmed Gawad's factor of 0.56 for converting DP solid cone to SPT split spoon using all materials – silt, sand and gravel, with a coefficient of determination of R^2=0.84. The silt and sand data plotted just below the linear regression line and the gravel data plotted around to above the line. The linear regression line plotted just above the ideal 1:1 line (dashed).

The Gawad (1976) correction factor converting solid cone to split spoon was developed from research using medium to coarse sand. When testing gravel the cone tip geometry may require a different conversion factor compared to sands. When a split spoon is driven it is essentially advancing a ring at the tip that is more likely to intercept, and be affected by, coarse gravel sized particles, than the point of a cone that can more easily push them to the side.

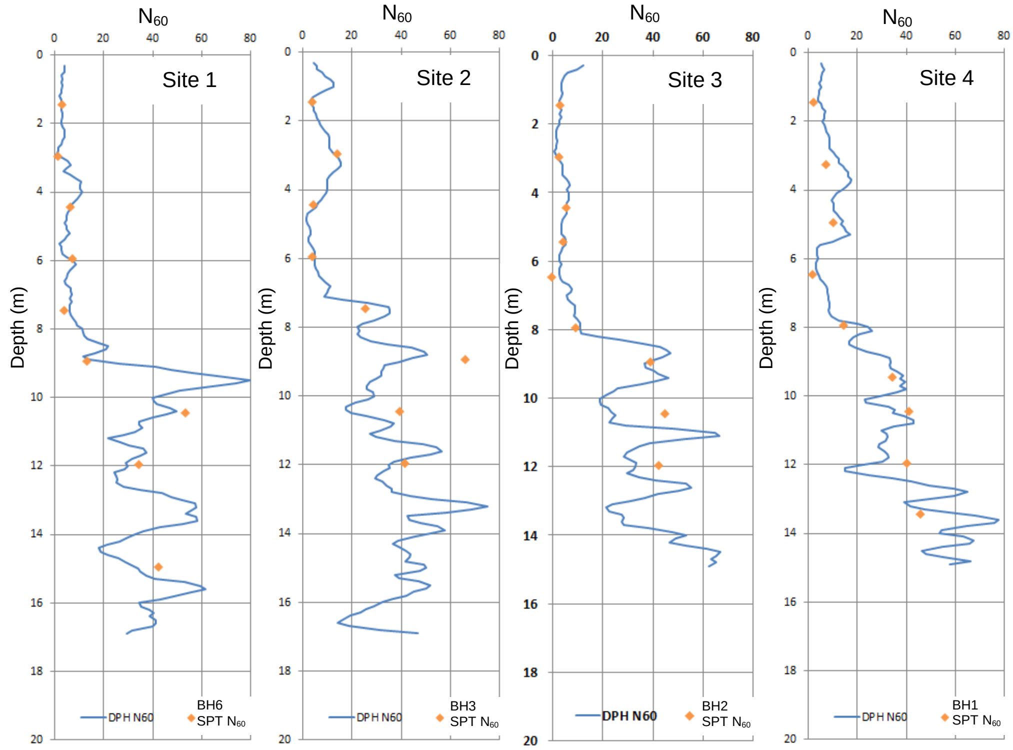

Figure 1: Halswell Sites 1 to 4 (DPH N_{60} and SPT N_{60} vs Depth).

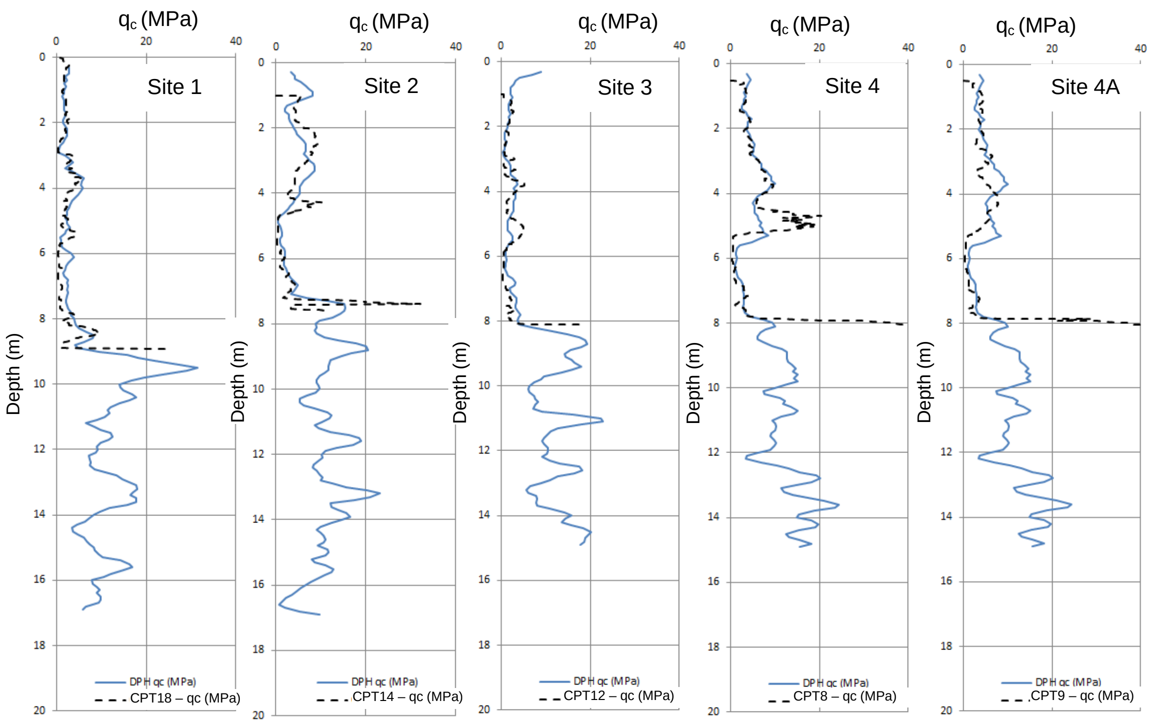

Figure 2: Halswell Sites 1 to 4 and 4A – comparison of CPT tip resistance and equivalent tip resistance derived from DPH data

Figure 4 shows data from 10 sites using a DPSH-B test rig. Figure 5 shows nearly 200 DPH N_{60} data points, from 20 sites in Christchurch, including the Halswell data from Figure 3. The sites for the DPSH-B and DPH data shown in these figures are different. While the separation between machine boreholes and DPs in Figure 3 was 1m to 2m, the additional sites in Figures 4 and 5 had a separation of up to 5m. Key points from the comparison include:

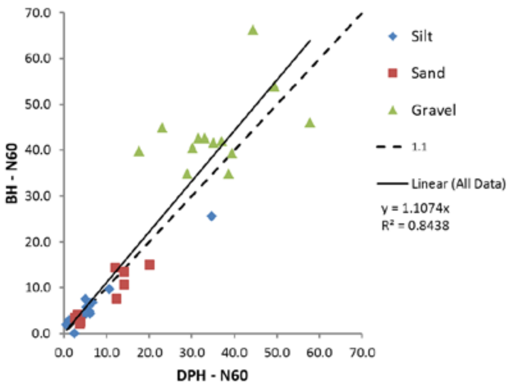

Figure 3: Comparison of BH N_{60} – DPH N_{60} results for Sites 1 to 4

- In Figure 4, showing the DPSH-B data, the linear regression line through the origin is very close to the ideal 1:1 line (dashed) but the large spread of the point cloud gives a low coefficient of determination of R^2=0.245. Much of the gravel data plots above the line, and much of the silt below it. This test rig may be more sensitive to changes in grain size of the material being tested and further comparisons will be undertaken.
- In Figure 5 showing the DPH data, the linear regression line through the origin given a coefficient of determination of R^2=0.527. The point cloud for the DPH data is located close to the ideal 1:1 line (dashed) but as with the DPSH-B much of the gravel data plots above the line and much of the silt below it.
- Variability in the soil composition/strength/stratigraphy (even over a short distance of 5m) could explain the much greater variation in the silt and gravel data in Figures 4 and 5 compared to Figure 3, where the separation between machine boreholes and DP probes was only 1m to 2m.
- Substantial horizontal and vertical changes in the geological stratigraphy and strength profile, over short distances, have been highlighted by the post-earthquake geotechnical investigations in Christchurch. In spite of this geological variability we consider that a satisfactory relationship, centred on the ideal 1:1 line (dashed), is evident in the presented DP N_{60} and SPT N_{60} comparisons of Figures 4 and 5. We recognise that there are anomalies in the data, as in most geotechnical empirical data correlations, but conclude that the technique is useful for Christchurch conditions.

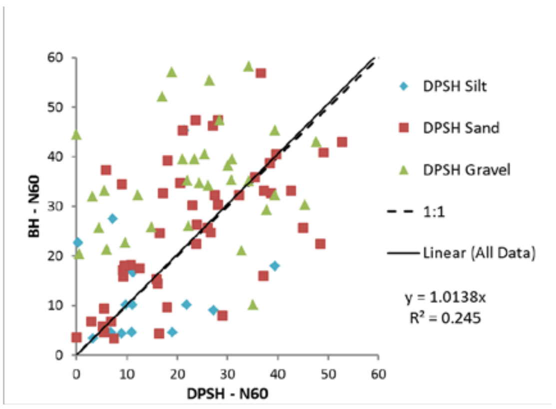

Figure 4: Comparison of BH N_{60} – DPSH-B N_{60} results for Sites 5 to 11 + 21 to 23

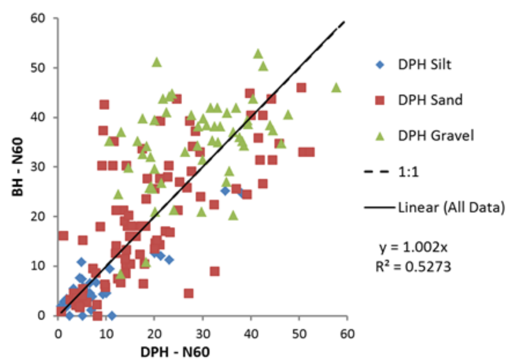

Figure 5: Comparison of BH N_{60} – DPH N_{60} results for Sites 1 to 20

8 ANALYSIS OF LIQUEFACTION SUSCEPTIBILITY

Methods for correcting DP data to derive equivalent SPT N_{60} values have been outlined above. We have found that the derived DP N_{60} values can be used for the analysis of liquefaction susceptibility for Christchurch sites. Key points related to this include:

- The DP data has the advantage of being an equivalent ‘continuous’ strength profile (i.e. data points at 300mm centres).
- The DP profiles are a “blind tool” and require borehole samples from nearby to confirm the deep ground profile. An estimation of fines content must be made from another data source in order to assess liquefaction-induced volumetric strain in a DP strength profile. This can be either in the form of a fines assessment from a nearby CPT data, or from machine borehole samples.

An analysis of liquefaction susceptibility has been undertaken at four Halswell sites where machine boreholes were located within 1m to 2m of DPH tests. A total of seven CPT tests were also undertaken on these sites. The liquefaction assessment has been completed in line with the MBIE guidelines for liquefaction assessment using the methods of Idriss & Boulanger (2008), with the water table set at 1m depth and a magnitude Mw 7.5 earthquake. Both the geotechnical ultimate limit state and serviceability limit state levels of seismic shaking were considered i.e. 0.35g and 0.13g, respectively. Liquefaction induced settlement estimates were undertaken using the method of Zhang et al. (2002).

Figure 6 shows a comparison between BH SPT and DPH N_{60} data with CPT predicted liquefaction settlements. Fines content in the N_{60} analyses were estimated from the borehole soil descriptions. Our analysis of this small data set indicates the greatest variation from the 1:1 line occurs where the continuous DPH profile shows a substantial change in strength between the discrete SPT test locations (i.e. 1.5m centres), refer to the illustration of DP profiles vs SPT in Figure 1.

The magnitude of the settlements derived from any liquefaction analysis is highly dependent on the level at which liquefaction is triggered within sub-layers. A few percentage points difference in the strength of a layer can cause a 30% to 50% difference in the total settlement at a particular location.

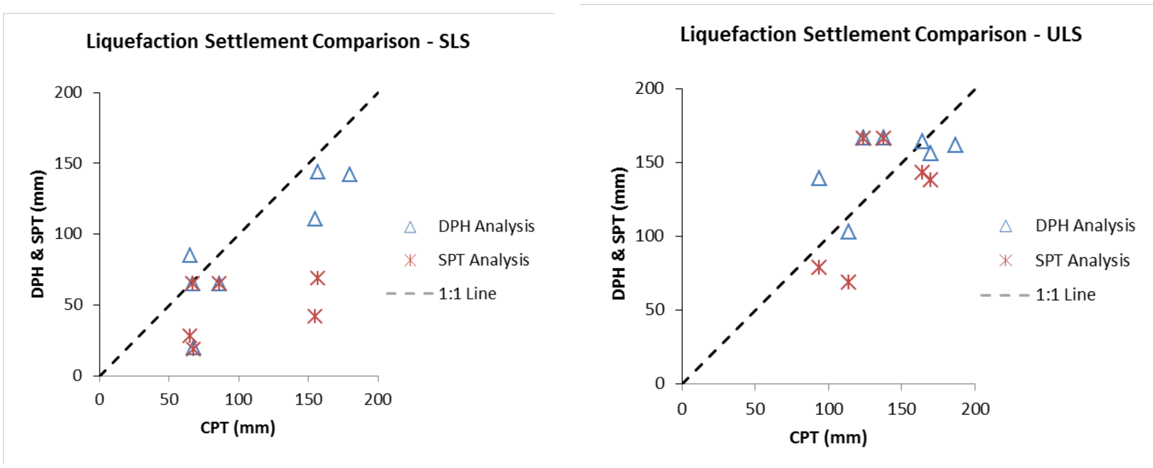

Figure 6: Settlement comparison (Test locations 1m to 2m apart)

9 CONCLUSIONS

From this study the following key conclusions are made:

- DP tests have been used to provide a continuous strength profile, of alluvial soils in Christchurch; a major advantage compared with discrete SPT data.
- The DP test can penetrate stronger near-surface gravel deposits, which can prematurely refuse CPT soundings. The DP test rigs are relatively small compared to other deep ground profiling investigation rigs and are more accessible to confined sites.
- When conversion factors are applied to the DP data, the derived DP N_{60} values correlate reasonably well to the borehole SPT N_{60} values: the correlation being close to the ideal 1:1 line. The solid cone to split spoon factor varies with DP solid cone diameter and material grain size. Average correction factors have been presented in this paper.
- The DP test is 'blind' and should be used to support primary liquefaction analysis techniques using data from other deep ground investigation methods e.g. high quality CPT and SPT data from rotary mud boreholes.
- Further refinement of the DP correction factors and N_{60} correlations is ongoing.

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