

## **Pore pressure response during high frequency sonic drilling and SPT sampling in liquefiable sand**

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### **ABSTRACT**

The potential for systematic variations in SPT N –values between mud rotary and sonic drilling methods has been the focus of a pilot investigation at a site that exhibited extensive liquefaction during the 22 February 2011 M 6.3 Christchurch Earthquake. In an attempt to quantify the impact of drilling methods on N-values, 2 pairs of closely-spaced sonic and mud rotary boreholes were advanced in deposits of predominantly silty sand and sand silt with SPT tests at 1.5 m intervals. Pore pressure transducers (PPTs) were employed at depths ranging from 4.6 to 17.5 m to monitor the effects of soil disturbance imparted by the sonic drilling procedure. The excess pore pressure response provides an indirect correlation to the level of soil disturbance due to drilling and sampling. The PPT data demonstrated clear trends during the sonic drilling process. Key preliminary findings indicate that: 1) transient pore pressures are relatively small as close as 300 mm from the sonic casing ( $r_u < 0.15$ ); 2) excess pore pressures generated during advance of the casing are largely dissipated by the time of the SPT test; and, 3) changes in pore pressure during normal, non-vibratory and common aspects of the drilling process can be as large as that due to the core barrel advance with vibration.

The direct comparison of the N-values demonstrates weak trends in the ratio  $N_{rotary}/N_{sonic}$ ; however, the close proximity of the boreholes to each other may have affected the N values. Additionally, much of this difference is considered to be within the range of variability of SPT data in uniform soil deposits and no systematic trend is evident on the basis of the small database obtained in this first phase of the investigation. Additional SPT data from similar investigations are being collected in order to develop a statistically significant basis for comparison.

## **1 INTRODUCTION**

### **1.1 Background**

The empirical methods routinely used in practice for assessing liquefaction resistance using N-values (Idriss and Boulanger, 2008; Youd, et al, 2001) are largely based on SPT data obtained in boreholes advanced using “non-vibratory” drilling methods (e.g., mud rotary, solid stem auger). While each drilling method imparts a level of soil disturbance the predominance of SPT data from “non-vibratory” methods used in the development of the liquefaction triggering procedures suggests that similar methods are preferable when evaluating liquefaction susceptibility of sandy soils. In fact, current “best practice” requires that SPT be performed in accordance with ASTM D 6066, which does not allow “vibratory” methods.

The prevalence of shallow gravel layers throughout the Christchurch region often precludes the use of CPT testing and drilling is required for many projects to obtain soil samples and

Standard Penetration Test blow counts (SPT N-values), and to reach the target investigation depth. Rotary wash drilling with tri-cone bits or HQ-double tube core barrels have often been utilised, however, in the aftermath of the 22 February 2011 Christchurch earthquake, there was recognition by some in the drilling industry that there would be a large demand for the ability to rapidly drill through the gravelly soils, obtain SPT blow counts and collect continuous core. The methodology identified as most suitable for this task was high frequency vertical vibratory (“sonic”) technology. For the purposes of this paper, high frequency sonic drilling is defined as drilling with a vertical vibratory frequency of between 120 and 150 Hz.

Due to its vibratory nature, questions were inevitably raised about sonic drilling as it pertains to liquefaction assessment. Often raised questions include:

- Does the methodology result in soil disturbance that is substantially greater than that imparted by common rotary methods?
- If so, what is the potential influence on SPT N-values; i.e., N values artificially high in loose sand, and artificially low in medium dense to dense sand?

It is the authors’ experience that these questions have also been raised in the geotechnical engineering community along the West Coast of the U.S. and Canada where liquefaction assessment is often a primary investigation objective.

## 1.2 Purpose / goals of investigation

The purpose of this investigation was to evaluate the possible degree of soil disturbance during high frequency sonic drilling and provide a preliminary assessment of potential influence of high frequency sonic drilling on SPT N-values. The primary goals of the investigation were to:

- measure excess pore pressure generated during sonic advancement;
- assess residual excess pore pressures at the time of the SPT test; and
- compare N-values from adjacent boreholes advanced by mud rotary and sonic methods.

## 1.3 Methodology

The characteristics identified as most important for a suitable investigation site included:

- a soil profile consisting primarily of sandy soils extending to a depth of roughly 20 m, the range of depth over which the simplified liquefaction procedures are applicable – with no gravel to influence SPT N-values;
- a range of densities from loose to dense; and
- the site was known to have sustained liquefaction-induced damage during the 2010-2011 Canterbury earthquake sequence.

Two locations at the site were selected for drilling and instrumentation. In an attempt to quantify the possible impact of the sonic method on N-values with direct comparison of N-values from closely-spaced sonic and mud rotary boreholes, SPT data were obtained from two sets of 3 boreholes (2 mud rotary / 1 sonic) at each site. The use of 2 mud rotary holes allowed installation of two PPTs at different depths. The site was well characterized with 6 CPT soundings during a previous investigation, and the sandy deposits found to be suitably uniform laterally allowing for a direct comparison of N-values obtained by closely spaced boreholes. The soil deposits were predominantly silty sands and sandy silts with N-values from mud rotary borings generally ranging from 8 to 30 blows/30cm.

At each location, a CPT was first performed and target depths for installation of 2 PPTs identified as discussed in Section 3. Following each CPT, 2 rotary wash boreholes were drilled to just below the target PPT depth using a 75mm-dia tri-cone bit (deflected discharge) and 105mm-dia casing system. SPT samples were obtained at 1.5m intervals, and a standpipe

piezometer was installed in each borehole and then the PPT. To maintain hole stability and reduce the potential for plugging of the piezometer screen, polymer drilling fluid was utilised. The bottom of the borehole was sounded immediately prior to performing the SPT and no heave was recorded in any of the holes.

The final stage of the investigation consisted of drilling a single sonic borehole (105mm-dia core barrel, 133mm-dia casing), performing SPT at the same depth interval as the adjacent mud rotary hole, and monitoring the pore pressures throughout the entire drilling process as described below. The 3 boreholes were laid out in a triangular pattern as illustrated in Figure 1. All rotary and sonic drilling was performed with a Mobile 1000 drill rig equipped with a SonicSampDrill Rotosonic 0-150 Hz drill head and automatic SPT hammer (Figure 2).

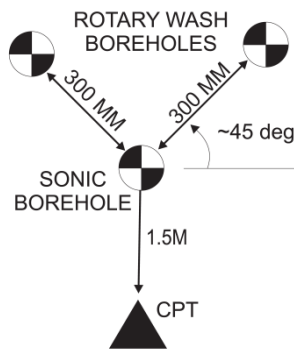


Figure 1: Layout of boreholes and CPT at each site



Figure 2: SonicSamp roto sonic drill head

The primary steps during sonic drilling were as follows: 1) the core barrel is advanced 1.5m using sonic vibration – no water is circulating through the system; 2) the sonic head is disconnected from the rod holding the barrel and connected to the outer casing; 3) the casing is advanced to just above the depth of the barrel tip using sonic vibration – water is circulating through the annulus between the core barrel and the casing to remove cuttings; 4) the core barrel is retrieved and a SPT is performed; 5) the process is repeated. Figure 3 presents a graphical illustration of the drilling sequence.

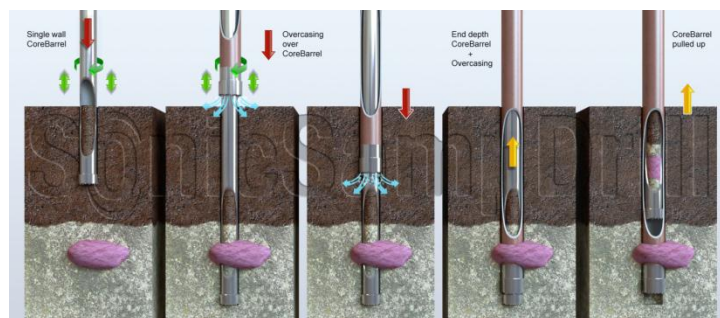


Figure 3: Sonic drilling sequence (courtesy of SonicSampDrill)

During rotary wash drilling, the sonic vibration was simply turned off. The use of the same drill rig and SPT hammer for all boreholes insured equivalent hammer energy for all SPT tests. All SPT testing was performed in general accordance the ASTM International test standard ASTM D 6066 (2011). The SPT samples were logged in accordance with the Unified Soil

Classification System, and particle size distribution or fines content tests were performed on select samples.

## **2 SITE DESCRIPTION**

### **2.1 Location and earthquake damage**

The site was located in the suburb of Bromley in eastern Christchurch; approximately 3km from the Pacific coastline and about 100m from a series of large water treatment ponds that feed into an estuary. An approximately 2m deep drainage channel ran along the southern site boundary. The site was essentially flat, and located in a light industrial use area.

At the time of the 22 February 2011 Christchurch earthquake, the site contained several structures including a large concrete tilt panel warehouse with slab-on-ground floor and a timber-frame office building with a suspended concrete floor. These structures reportedly sustained major liquefaction-induced damage including differential settlements in the order of +100mm and racking and partial collapse due to lateral spreading of the site towards the drainage channel (identified by others as having a total of displacement in the order of 200 to 400mm).

### **2.2 Subsurface conditions**

The site is mapped as being underlain by sand, silt and peat of drained lagoons and estuaries (Brown & Weeber, 1992). A previous post-earthquake geotechnical investigation by others consisting of 7 CPT soundings indicated that the site soil profile generally consisted of about 1.5m of soft clayey silt overlying interbedded layers of poorly graded sand and silty sand with occasional layers of low plasticity to non-plastic silt and sandy silt. The density of the soils was noted to generally increase with increasing depth. The data from the CPTs and boreholes completed for this SPT study generally confirmed the results of the previous investigation. The results of the CPT, and the mud rotary SPT N-values are summarised in Figures 4 and 5.

The depth to groundwater was measured between approximately 1.5 and 1.6m. Based on the available data, it was concluded that the soil conditions were relatively uniform across the location of each group of 3 boreholes and CPT.

## **3 INSTRUMENTATION AND MONITORING PROGRAMME**

### **3.1 Instrumentation**

As previously described, a standpipe piezometer and PPT were installed in each rotary wash borehole adjacent to the sonic hole. Each piezometer had a 300mm long screened interval located with its centre point at the target PPT depth (ranging from 4.6 to 17.5m – refer to Figures 4 and 5). To facilitate accurate installation of the piezometers and minimise borehole disturbance, prefabricated screen sections complete with filter sand pack and bentonite seals were utilised (Figure 6). The piezometer pipe had an inside diameter of 25mm and the sand pack was approximately 30mm thick around the pipe and wrapped in filter fabric. The top and bottom bentonite seals were 1.25m long and 75mm in diameter. The use of these prefabricated units allowed the screen interval to be set in about 10 mins with accuracy in the order of +/- 25mm. After setting the piezometer and allowing several minutes for the bentonite seals to expand, the annulus above the screened interval of the piezometer was backfilled with tremmie cement grout. The grout was placed through the drill casing as it was withdrawn to minimise the potential for relaxation of the wall of the borehole. After allowing the piezometers to set for 48 hours, they were thoroughly flushed and conditioned by low pressure pumping of clean water through them for several minutes.

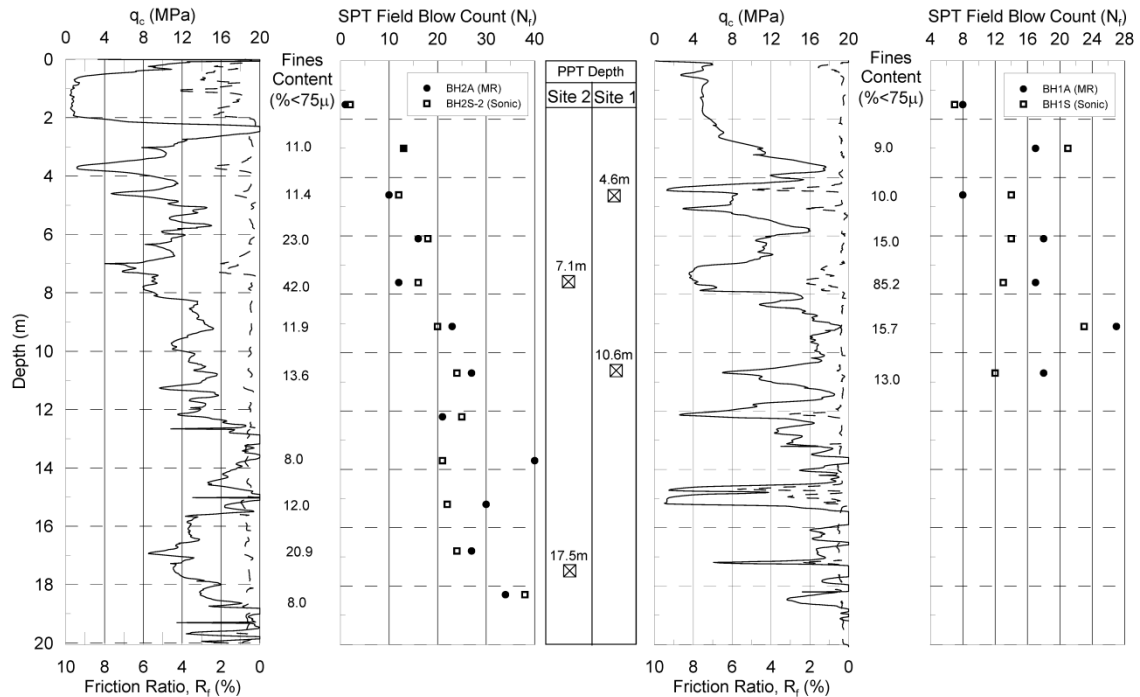
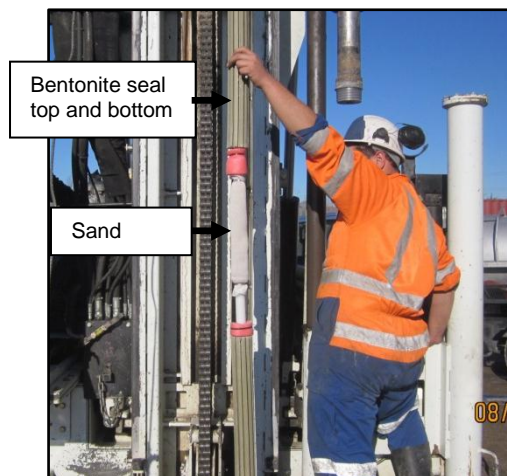


Figure 4: Site 2 CPT and SPT data

Figure 5: Site 1 CPT and SPT data

To monitor the pore pressure changes within the soil during drilling, the water level in each piezometer was continuously monitored using a *Levellogger Edge* “water level data logger” manufactured by Solinst Canada Ltd. The units utilise piezoresistive silicon with a Hastelloy sensor and are temperature compensated. They have a maximum sampling rate of 480 Hz and measure absolute pressure with an accuracy of +/- 0.05 to 0.10 kPa (for the model nos M10 and M20 used). After flushing the piezometers, the PPTs were suspended at the target depth. A fifth PPT was suspended near the top of one of the piezometers, above the high water level, to record barometric pressure at 10 minute intervals for barometric compensation of the measured water pressures.



3.2 Monitoring Figure 6: Prefabricated piezometer screen

Transient, excess pore pressures were monitored within 300 mm of each sonic borehole to measure: 1) the change in pore pressure from hydrostatic conditions as the sonic casing approached the elevation of the PPTs; 2) the extent of the zone of elevated pore pressure from the sonic casing; and, 3) the rate of dissipation of excess pore pressure that occurred prior to performing the SPT. The PPTs provided clear trends in the pore pressure during advance of the

core barrel and overcasing, removal/replacement of drill stem for SPT tests, and changes in circulation of drilling fluid.

Prior to the beginning of sonic drilling, the PPTs were set to read at 10 minute intervals and allowed to run for 48 hours to confirm that they were responding correctly. This static water level data was downloaded and compared to the water levels checked manually with an electronic “dipper.”

Prior to the beginning of sonic drilling, the PPTs were set to begin logging simultaneously at a frequency of 480 Hz. The real time data collection was periodically monitored during drilling to confirm that the loggers were working properly. The drilling crew was instructed to drill and sample as they would during a normal job with engineer / geologist site supervision. No unusual conditions or operational issues were encountered during drilling, and both boreholes were completed normally. The bottom of the borehole was sounded immediately prior to each SPT and no significant (i.e., > 30mm) heave was encountered with the exception of a small amount of heave (~200mm) in borehole BH-1S at the SPT sample depth of 10.6m. The depth was rechecked after 5 minutes and found to be stable. The driller cleaned the hole by slowly raising the outside drill casing 200mm and using low pump pressure to “wash” the casing back down to the SPT depth.

#### 4 GENERAL OBSERVATIONS

The primary objectives during this first phase of the pilot project were the assessment of soil disturbance during drilling as inferred from pore pressure response, and quantification of excess pore pressure in the soil at the time of SPT testing following sonic advance. For this reason the sonic boreholes were closely spaced to the rotary wash boreholes containing the PPTs. The sonic holes were drilled after the mud rotary holes, and given their very close proximity disturbance of the soil at the sonic locations from the rotary holes and piezometer installation cannot be precluded. While an attempt was made to demonstrate relative trends in N-values assuming borehole disturbance would be minimal, it became clear during the field work that this would be difficult. The values of  $N_{\text{rotary}}$  and  $N_{\text{sonic}}$  from the adjacent test holes are shown in Figures 4 and 5. No systematic bias in the N values provided by the two methods is evident; however, the proximity of the boreholes and small data set preclude generalization regarding the influence of the drilling methods on the N-values.

The full time histories for the deepest PPTs at each sonic location are shown in Figures 7 and 8, along with enlargements of the pore pressure response at the depth of each PPT. The maximum rise in pore pressure measured by the 4 PPTs was 11.1 kPa and the maximum computed pore pressure ratio,  $r_u$ , was 0.13. Table 1 presents a summary of the main data at each PPT location. It is notable that a pore pressure response for both the sonic vibration and SPT blow counts was clearly measured. As would be expected, the pore pressure response is greatest when the drill bit / SPT is closest to the PPT. The peak pore pressures due to the sonic vibration can be seen to rapidly dissipate over a period of approximately 2 minutes; dropping to or very close to hydrostatic by the time the SPT is performed. The distinctive double peak in pore pressures during advance of the sonic drill is a result of the drilling method, i.e., the core barrel is advanced with vibratory drilling, the vibration is turned off to connect the casing and then turned back on to advance the casing.

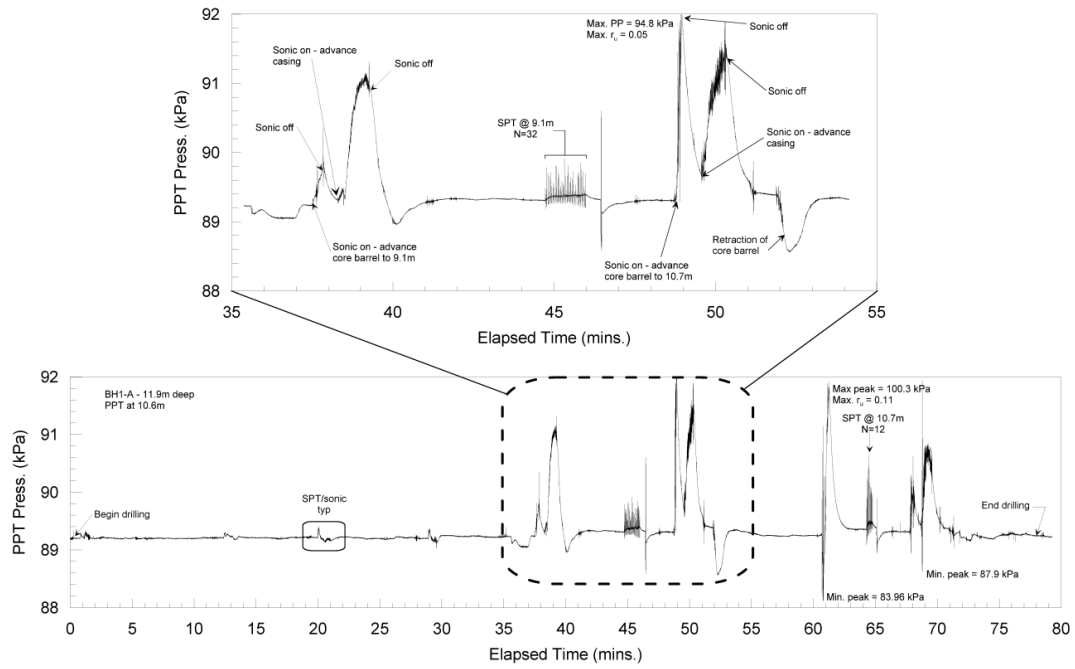


Figure 7: Pore pressure vs time – BH1-A at 10.6m

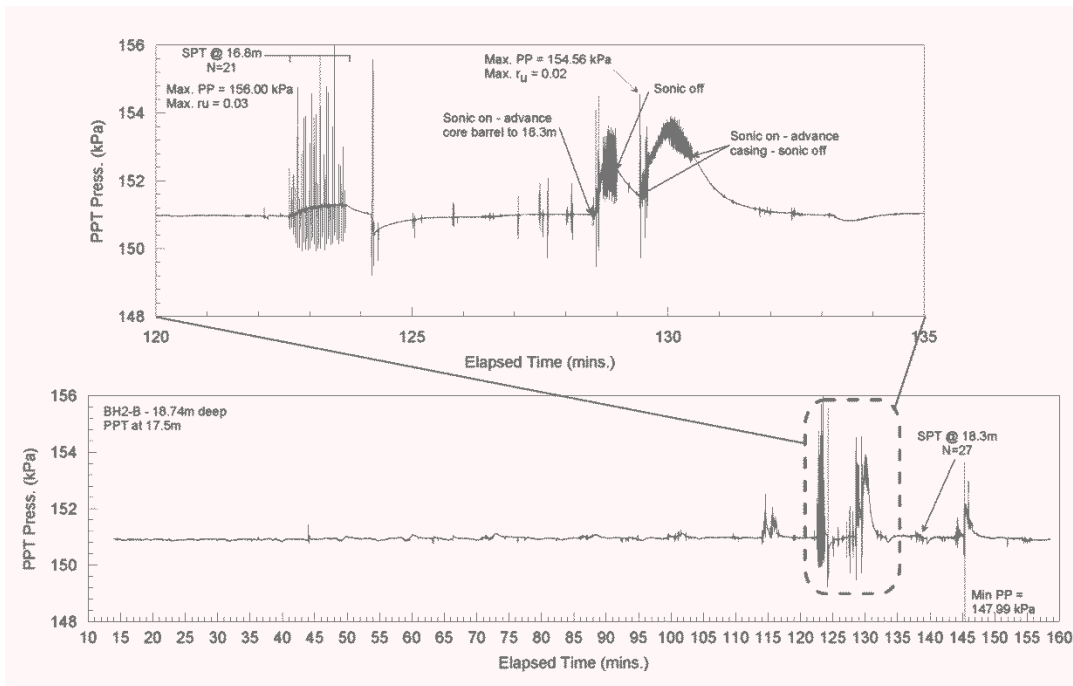


Figure 8: Pore pressure vs time – BH2-B at 17.5m

Table 1: Data summary at each PPT location

PPT	Depth (m)	Eff. vert. stress (kPa)	Hydrostatic PP (kPa)	Max. measured pore press (kPa)	Pore press. ratio
1A	10.6	104.7	89.2	100.3	0.11
1B	4.6	57.1	26.7	28.3	0.0001
2A	7.1	80.2	49.8	60.3	0.13
2B	17.5	164.6	150.9	156.00	0.03



## 5 FINDINGS AND CONCLUSIONS

The primary findings and conclusions that in the authors' opinion can be made from this initial investigation are as follows:

- Pore pressure measurements taken at a horizontal distance of 300mm of the sonic drill bit gave estimated  $r_u$  values prior to SPT testing ranging from 0.0001 to 0.13. The  $r_u$  values are likely much greater at the tip of the sonic casing however the gradient of pore pressure between the casing and the PPT was not modelled in the investigation.
- Excess pore pressures due to SPT sampling and flushing of the borehole can approach those due to sonic drilling. The simplified SPT-based empirical methods for assessing liquefaction potential implicitly incorporate the effects of these “non-vibratory disturbances” (i.e., SPT sampling and flushing of the borehole) if one accepts the premise that they are generally performed in the same manner irrespective of the drilling method used.
- Soil disturbance and significant excess pore pressure generation (defined as  $r_u \geq 0.8$ ) is presumed to occur immediately adjacent to the sonic drill bit. However, on the basis of the PPT data obtained in this study, this effect is demonstrated to be minor ( $r_u \geq 0.15$ ) at a distance of 300 mm from the tip of the sonic core barrel across a range of fines contents. This zone of influence is likely a function of soil type, density, and confining stress, and is the focus of additional investigation.
- In relatively clean sands, the excess pore pressures due to the sonic vibrations are shown to essentially dissipate to hydrostatic in approximately 1 to 2 minutes – less time than typically elapses between cessation of sonic drilling and performing the SPT.
- If it can be assumed that the pore pressure generation and dissipation is equal in both the horizontal and vertical directions, the influence of excess pore pressure on SPT N-value can be considered to be negligible over the distance which the N-value is measured (i.e. between 150mm and 450mm in advance of the sonic casing).
- The comparison of SPT N-values obtained during high frequency sonic drilling and rotary wash drilling at this site are considered equivocal as discussed in Section 4. This is attributed to the close proximity of the boreholes and possible ground disturbance during rotary drilling, and to the small data set. Additional SPT data from more widely spaced boreholes in laterally uniform sand deposits are being collected to expand the database in support of correlations that may be more statistically significant.

## 6 ACKNOWLEDGEMENTS

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