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Effects of Percussion Drilling and Non-Standard Testing Equipment on Penetration Resistance and Liquefaction Assessment in Gravelly Soils

K.A. Hartel[1], M.J. Burrows[2], T.J. Colgan[3]

ABSTRACT

The Christchurch Southern Motorway Stage 2 project is a 13 km-long motorway extension which includes construction of eight new bridges. Alignment is underlain by predominantly gravelly soils of variable relative density, interbedded with discontinuous, often loose sand lenses. Three series of subsurface investigations were advanced across the alignment at various project design phases. Because the gravelly soils precluded use of cone penetration testing, each phase of explorations consisted of drilling boreholes and measuring penetration resistance with a split spoon sampler. Preliminary design phase boreholes were advanced using various percussion drilling techniques, while the final design phase program utilized mud rotary and rotary core (non-percussion) drilling equipment. Each investigation phase included boreholes across the entire alignment, typically to a depth of 20 m. Penetration resistance was measured in all boreholes by advancing a split spoon sampler using standard weight hammer and drop. A solid cone tip was employed in preliminary phase investigations, while the standard split spoon sample shoe was used during the final design phase program. Measured penetration resistance was normalized with respect to overburden pressure, hammer energy ratio, and borehole diameter, allowing the resulting normalized penetration resistance to be compared across each of the drilling methods. Observed trends in the effect of drilling method on measured penetration resistance are presented in this paper, and the effect of these trends on subsequent liquefaction assessment is also discussed.

Introduction

The Christchurch Southern Motorway (CSM) has been identified as a key strategic link within the Canterbury region, and when completed, will provide a through traffic route between Christchurch City Centre and the town of Rolleston to the southwest. Stage 2 of the motorway (CSM2) comprises the western extension of the CSM, involving a combination of new motorway and widening of existing roadway over a 13.5 km, generally linear alignment. The CSM2 project includes design and construction of seven bridge overpass structures and one highway underpass as required for motorway access and transportation across the motorway. The CSM2 alignment is situated on former alluvial flood plains, with topography sloping gradually down from west to east. The general slope is punctuated with minor variations in elevation associated with former river channels. Overall, the area is considered to be relatively flat.

Published geological mapping (Brown and Weeber 1992) indicates that the alignment is underlain by river alluvium of the Yaldhurst and Halkett Members of the Springston Formation. River alluvium of the Yaldhurst Member consists dominantly of alluvial sand and silt overbank deposits, while the underlying Halkett Member consists of older, coarser alluvial gravel, sand, and silt.

The interbedded gravel, sand, and silt of the Springston formation extend to depths in excess of 25 m

[1]Technical Director-Geotechnical, WorleyParsons, Burnaby, Canada, karen.hartel@worleyparsons.com
[2]Geotechnical Engineer, AECOM, Christchurch, New Zealand, marcus.burrows@aecom.com
[3]Geotechnical Engineer, AECOM, Christchurch, New Zealand, tiarnan.colgan@aecom.com

across the alignment. A characteristic of these materials is a high degree of variability in plan and with depth with respect to stratigraphy and relative density. While gravelly material (loose to very dense) predominates over the upper 25 m, discontinuous lenses of sand (often loose and of variable thickness) occur throughout.

The site seismic hazard is defined by proximity to the Alpine Fault, approximately 120 km southeast of the alignment, as well as a number of active faults within 50 km of the alignment. Seismic design criteria for design of highway infrastructure including bridge foundations and embankments are provided in the New Zealand Transport Agency's Bridge Manual 2013, which provides design and performance criteria for the Serviceability Limit State (SLS), Ultimate Limit State (ULS), and Maximum Considered Event (MCE). Geological conditions anticipated at the site combined with a relatively shallow depth to groundwater across the proposed alignment create potential for liquefaction and associated settlement due to earthquake shaking. Therefore, the primary objective of the subsurface exploration program required for detailed design of the proposed infrastructure under seismic loading was to adequately delineate zones of potentially liquefiable material.

Exploration Programs

Drilling Method

Subsurface investigation programs were conducted in stages in conjunction with Investigation and Reporting (I&R) and Design and Project Documentation (D&PD) phases of the project. Predominance of gravelly soils precluded the use of cone penetrometer testing (CPT), making machine borehole drilling the favored option with respect to characterization of subsurface stratigraphy and determination of in situ relative density of the encountered. I&R investigations utilized rotary air flush and cable tool drilling (both percussive techniques), while D&PD investigations utilized mud rotary wash and rotary core drilling methodologies, as follows:

- Air-flush rotary percussion: 125 mm or 150 mm dia. solid face drill bits with tungsten "buttons" advanced by pneumatic pressure supplied by a compressor. Cuttings are returned to the surface through air circulation.
- Cable tool: percussion drilling performed with 100 mm or 150 mm dia. heavy carbide drill bits chiseling through subsurface material. Cuttings are retrieved by use of a bailer.
- Mud rotary wash: 92 mm tungsten tri-cone drill bit advanced by hydraulic push and rotation. Cuttings are returned by circulation of bentonite drilling mud through the hole.
- Rotary core: 100 mm diamond tip coring bit advanced by hydraulic push and rotation. Bentonite or polymer drilling fluid is supplied to the bottom discharge core bit to cool and lubricate the drill string as it is advanced. Cuttings are returned via a core barrel extracted from inside the drill string using a wireline and overshot.

Standard Penetration Testing (SPT)

Standard penetration testing (SPT) performed to New Zealand Standard 4402.6.5.1:1998 was conducted in all boreholes. The standard procedure specifies use of a 63.5 kg weight falling 760 mm to advance the drive shoe into the test material. Seating blows are recorded over the initial 150 mm of penetration. The penetration resistance (N-value) is then defined as the number of blows to drive the sampler an additional 300 mm of penetration, with blows per 75 mm typically recorded on the borehole logs.

In practice, refusal criteria vary, but typically, the test will be terminated at 50 blows with the corresponding penetration noted. The test is also considered to reach refusal when there has been no successive advance of the sampler after 10 blows. In gravelly soils, the New Zealand Standard allows replacement of the standard hollow drive shoe with a solid cone, without differentiation in terms of definition of N-value. A solid cone was utilized with the rotary air flush and cable tool systems during the I&R phase, while the D&PD investigations used the standard drive shoe, allowing sample recovery at each test interval. SPT were performed in average vertical increments of 2.5 m in rotary air flush boreholes, 1.5 m in cable tool boreholes, and 1.0 m in rotary wash and rotary core boreholes. All SPT equipment was calibrated prior to use, with hammer energy ratios measured, which along with corrections for borehole diameter, overburden pressure, rod length and the use of sample liners allows the correlation of measured N-value to normalized $(N_1)_{60}$ values.

Soil Characteristics - Particle Size Distribution

The soil profile across the alignment consists generally of a surface layer of topsoil underlain by interbedded gravel, sand, and silt of the Springston formation, which extends to the depth explored, typically 20 m to 25 m. Specifically, these materials consist of the following:

- Gravels (GW, GP, GM): loose to very dense fine to coarse sandy gravel to gravel with varying quantities of sand, silt, and cobbles.
- Sands (SW, SP, SM): loose to dense fine to coarse gravelly sand to sand with varying quantities of gravel and silt.
- Silt (ML): occasional lenses of loose to medium dense, non-plastic to low plasticity silt, containing varying quantities of sand.

Particle size distribution (PSD) testing performed on the Springston materials during the D&PD phase investigation is presented on Figure 1. Samples were selected for testing to provide the range of PSD across the alignment within the gravels, sands, and silts; testing included samples recovered from the split spoons and bulk samples recovered from test pits.

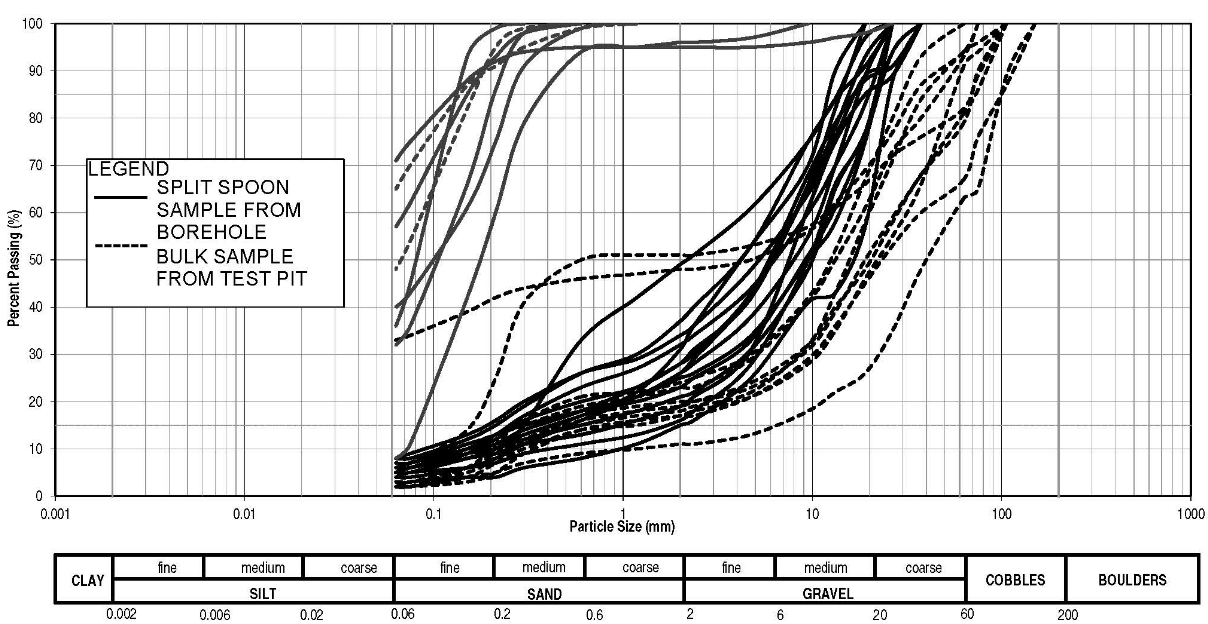

Figure 1: Particle Size Distribution

Comparison of N-values

Interpretation- Effects of Large Particles

Interpretation and comparison of N-values in gravelly soils is complicated by the presence of large particles (coarse gravels and cobbles) which can account for misleadingly high penetration resistance. Large particles can block the drive shoe and either prevent the sampler from advancing (refusal) or be driven down with the sampler, potentially increasing the penetration resistance. In order to compare penetration resistance in the gravelly soils across the alignment where many of the tests terminated at refusal (i.e. 50 or 60 blows for < 300mm penetration, depending on refusal criteria considered), the measured penetration resistance was extrapolated to an “equivalent” value that would be anticipated for the full penetration. For I&R investigations, this assessment involved consideration of the incremental penetration resistance recorded on the borehole logs (in 75 mm increments), as well as notations indicating depth of refusal or number of blows with no advancement of the sampler. In many D&PD investigations, the penetration resistance was recorded in 25 mm increments over the test interval, which made it possible to distinguish between relatively uniform penetration resistance, considered representative of the soil matrix, and sharp increase in penetration resistance, considered attributable to presence of a large particle blocking sampler advance. Consideration of the incremental penetration resistance in conjunction with per cent sample recovery and visual observation of the sample material facilitated extrapolation of N-values. Extrapolated N-values were not used for engineering calculations; however, these values were useful in terms of comparison between the various drilling and sampling methods.

Comparison of Results

In order to assess potential trends in N-value considering drilling method, the extrapolated normalized $(N_1)_{60}$ values across both investigation phases were compared. A total of 750 SPTs were performed in the Springston formation soils; 401 tests were performed in boreholes advanced using rotary drilling, with the remaining 449 tests performed in percussion based boreholes, split between 148 tests in cable tool boreholes and 301 in air flush boreholes.

Extrapolated $(N_1)_{60}$ values are plotted vs depth on Figure 2. The plot indicates the large degree of scatter in results; however, trends between drilling methods can be observed by considering superimposed trend lines, which represent average $(N_1)_{60}$ over discrete depth intervals (2.5 m) for each drilling method.

These trend lines indicate that over all depth increments, despite the scatter in the data, the penetration resistance measured in the percussion-based boreholes is lower than that measured in the non-percussion based boreholes. This trend was found to be relatively constant across the entire 13 km site, suggesting that the trend is not related to local variability in subsurface conditions. Data were also evaluated in terms of differences between individual drill crews or drill rigs, with no discernable pattern observed. Similarly, there were no unique trends evident when penetration resistance in gravels and sands were considered separately.

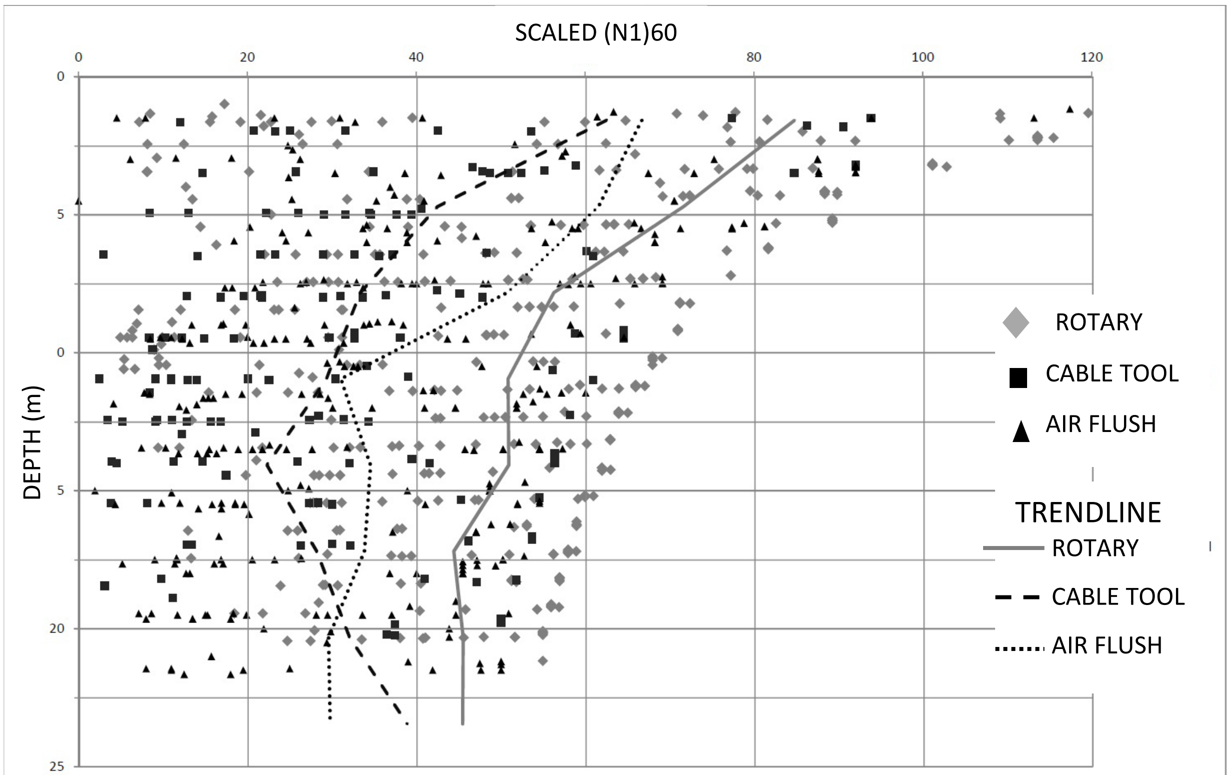

Figure 2: (N1)60 vs Depth for All Tests

Discussion

Effect of Percussion Drilling

Percussion techniques rely on repeated impact to advance the drill bit. In gravelly soils, this results in fracturing or crushing of clasts, and significant disturbance of soil around and ahead of the drill bit, which can account for reduced penetration resistance. Literature suggests that the depth of soil affected can be on the order of three times the borehole diameter, and Connor (1980) and Mallard (1983) data suggest that N may be reduced to one-fifth of an "undisturbed" value as a result of percussive techniques in sands and gravels. Given the air flush and cable tool borehole diameters ranging from 100 mm to 150 mm, the associated zone of disturbance could be anticipated to encompass much of the SPT interval.

Other drilling procedures can lead to disturbance over the test interval in granular soils, including piping or suction, which can occur when removing the drill stem at the test interval within the saturated zone, without adequate compensation of effective confining pressure by maintaining a head of water or drilling fluid in the borehole. This was addressed in the rotary drilling through use of bentonite drilling fluid, but may have contributed to disturbance over the test interval in the air flush method, which is dry, or cable tool drilling, depending on specific procedures. Caving can occur in granular soils when borehole sides are unsupported by casing, or where there is inadequate confining pressure supplied by head of water or drilling fluid in the borehole. Caving can be identified when inserting the sampler, by confirmation that the sampler depth is consistent with the drilled depth of the test interval. Where caving has occurred and is not identified, the penetration resistance would be representative (in part) of the collapsed, loosened soils rather than the in-situ soils. Information presented on the percussion based borehole logs was insufficient to assess the potential occurrence of piping or caving.

Effect of Solid Cone

Literature is inconclusive with respect to possible effect of solid cone on penetration resistance in gravelly soils. Shahien & Farouk (2013) present suggested correlations between standard penetration resistance, N SPT, and penetration resistance measured using the solid cone, N SPT(C), for a variety of soil types. The correlations associated with coarse soils and gravels are presented on Figure 3.

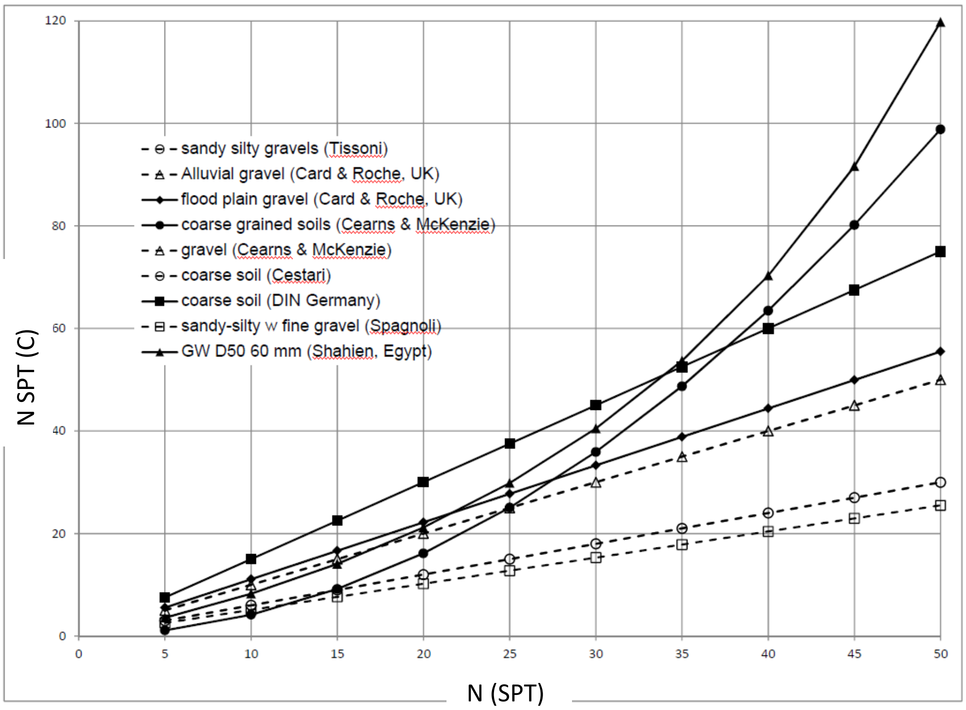

Figure 3: Correlations between SPT N and SPT N(C)

As indicated on Figure 3, correlations for coarse soils and gravels presented by Shahien & Farouk suggest that N SPT(C) could range from approximately 50% to 200% of the N SPT value. The solid cone was only utilized for testing within the percussion-based boreholes at the project; testing within mud rotary drilled boreholes involved the standard shoe exclusively. Therefore, there are insufficient data to assess the possible effect of the solid cone tip on penetration resistance for the project soils.

Liquefaction Assessment for Bridge Foundation and Embankment Design

Liquefaction triggering within saturated soil deposits was assessed with respect to Idriss and Boulanger (2008) methodology using SPT data. Raw N values at each borehole were normalized with respect to overburden pressure and hammer energy ratio, and further corrected for fines content to derive equivalent $(N_1)_{60\text{-}cs}$ at each test interval. Liquefaction induced settlement over saturated depth was then calculated for sands and gravels using Ishihara and Yoshimine (1992) and Bin et al. (2008) methodologies, respectively, which relate maximum shear strain during cyclic loading to volumetric strain. Settlement due to seismic densification of unsaturated soils was also assessed at each borehole location using Tokimatsu and Seed (1987) methodology. These assessments resulted in calculations of free field settlement under design seismic loading at each individual borehole. At each structure location, these estimates were considered relative to deflection criteria for design of bridge foundations and approach embankments. Because each phase of investigations included boreholes concentrated at structure locations, it was possible to compare free field settlement at each structure calculated based on data from percussion-based drilling with that calculated from non-percussion-based data.

Eight bridge structures were considered during I&R and D&PD programs, Table 1 indicates the average calculated settlement at each structure for both percussive and non-percussive drilling methodologies during the ULS seismic event. The number of boreholes at each structure is indicated on Table 1, as is the range of settlement calculated at the individual borehole locations.

Table 1: Calculated MCE Settlement per Bridge Structure (mm)

Bridge Structure	Calculated Settlement (mm)					
	Percussion			Non-Percussion		
	Average	Range	# BH	Average	Range	#BH
Weedons Road	125	11 – 330	3	6	1 – 12	3
Robinsons Road	10	0 – 31	3	1	0 – 2	4
SH1 Overpass	14	4 – 31	3	6	1 – 11	3
Waterholes Road	52	5 – 161	4	1	1 – 2	2
Trents Road	39	6 – 67	8	5	4 – 6	2
Shands Road	160	51 – 327	9	6	2 – 13	3
Springs Road	325	245 – 424	5	75	46 – 101	3
Halswell Junction Road	310	237 – 393	3	105	49 – 187	3

Comparison of percussion-based and non-percussion-based average settlements by bridge location demonstrates a consistent trend of higher settlement calculated using percussion-based data. This trend is evident across the entire alignment including locations where calculated settlement from either data set is relatively nominal. This is reflective of the consistently lower penetration resistance measured in percussion-based boreholes, and is further indication that the observed trend is not exclusively attributable to local variability in soil characteristics. Bridge structures in Table 1 are listed from west to east across the alignment, and calculated settlements generally increase from west to east. This is partially attributed to the groundwater conditions across the alignment, as depth to groundwater decreases from east to west, and shallower groundwater translates to greater thickness of potentially liquefiable soils in the upper portion of the profile for structures at the east end of the alignment.

Conclusions

The large scale of the investigation programs implemented for the CSM2 project provide a statistically relevant data set to allow comparison between penetration resistance measured in percussion-based and non-percussion-based explorations in gravelly soils. Project data indicate that the combination of percussion-based drilling and solid cone sampler tip result in lower average penetration resistance as compared to rotary based drilling and standard SPT shoe. Although this data support trends reported in the literature with respect to effects of percussion drilling on penetration resistance, the data set was insufficient to evaluate the site-specific effect of the solid cone on measured penetration resistance. Regardless of potential effect of solid cone, use of the standard shoe offers significant advantage of sample recovery, which greatly aids interpretation of penetration resistance in soils containing large particles where refusal is relatively common. Sample recovery is also essential for definition of the stratigraphic profile, particularly where thin discrete layers of loose material are anticipated. Analyses of liquefaction triggering and free field seismically induced settlement are highly sensitive to $(N_1)_{60}$ as demonstrated in the free field settlements calculated at the eight bridge structures across the project alignment, considering percussion and non-percussion data separately. When these data sets were considered independently, penetration resistance data collected in percussion boreholes lead to a less economical foundation design at select structure locations where pile foundations were considered to mitigate excessive settlement.

Percussion-based drilling is often implemented in New Zealand where gravelly deposits are anticipated, due to the infeasibility of CPT, and efficiency of these methods as compared to rotary drilling. At sites underlain by gravelly soils where geotechnical design includes liquefaction assessment, an alternative investigation approach which includes mud rotary drilling, SPT and split spoon sample recovery at 1 m intervals, and recording penetration resistance in 25 mm increments, has been demonstrated to be effective with respect to soil characterization and development of engineering parameters required for infrastructure design.

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