LOGISTICAL AND TECHNICAL CHALLENGES OF THE GEOTECHNICAL INVESTIGATION FOR THE NEW BRIDGE OVER THE CLARENCE RIVER AT HARWOOD

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ABSTRACT

The new bridge over the Clarence River at Harwood forms an integral part of the Pacific Highway upgrade in northern NSW and is currently under construction by the Acciona-Ferrovial Harwood Joint Venture (AFHJV). The proposed bridge extends 1.5km between abutments, spans the Clarence River with a water span of approx. 560m and is founded on 2m to 2.4m diameter driven hollow steel tubular piles to over 60m depth in some areas.

The underlying geology of the site consists of 30 to 40m of soft estuarine silts, clays and loose to medium dense sands underlain by saturated basal sands, gravel and cobbles up to 25m in thickness. Historical ground investigation information has thus far failed to provide confidence in the characterisation and engineering properties of this basal gravel and cobble layer due to limitations with conventional SPT, CPT and drilling techniques.

A non-conforming ground investigation (GI) scope was proposed to support the bridge detailed design phase undertaken in parallel with the field works. This paper presents a perspective on the challenges of developing a ground model within this complex geological sequence and is was addressed by a diverse, state-of-art GI campaign. It also presents the logistical challenges encountered during the campaign and how alternative approaches such as geophysical methods and sonic drilling can bolster engineering design as well as the efficiency of an investigation program.

1 INTRODUCTION

1.1 PROJECT DESCRIPTION

The new bridge over the Clarence River at Harwood forms an integral part of the Pacific Highway upgrade in northern NSW and is currently under construction by the Acciona-Ferrovial Harwood Joint Venture (AFHJV). The proposed bridge extends 1.5km between abutments, spans the Clarence River with a water span of approx. 560m and is intended to replace the existing lifting deck bridge located 30m upstream of the proposed alignment. The base of the proposed bridge deck is to be positioned at a level coincident with the top of the existing bridge lifting towers, some 30m above mean tidal water level. The bridge deck is supported by 35 piers at 36m to 45m spacing, each founded on two 2.4m dia. (land) or six 2.0m dia. (river) hollow tube steel driven piles. The bridge design evolved in parallel with the ground investigation (GI) which imposed further logistical constraints and prioritisation on the investigation program.

2 SITE GEOLOGY

2.1 GEOLOGICAL SETTING

The project site is located within the Clarence-Moreton Basin, an extensive on-shore Mesozoic sedimentary basin in northeast New South Wales and southeast Queensland. The basin comprises a sequence of fluvial sediments that rest on Palaeozoic basement of the New England Fold Belt. The site is situated within the southern region of the Clarence-Moreton Basin and is underlain by the bedrock of the Bundamba Group.

The portion of the Clarence River at Harwood is influenced by tidal movements and thus the site geology has characteristics of both a meandering river floodplain as well as estuarine environments. A deep paleochannel has been incised into the surface of the bedrock and subsequently in-filled with Pleistocene age fluvial and estuarine sediments. The Pleistocene sediments have been further incised by a paleochannel and in-filled with younger Holocene age sands, silts and clays. The site is thus underlain by a complex sequence of fluvial and estuarine deposits of Holocene to Pleistocene age with soil depths ranging from 30m to over 80m in soil depth.

2.2 HISTORICAL GROUND INFORMATION

Given the long history of the Pacific Highway Upgrade project, ground investigation data at the site is available from historical GIs from 1962 through to 2016. Available data ranged from test pits and conventional boreholes to more advanced ground soundings such as cone penetration tests (CPT) and seismic dilatometers (sDMT).

Of interest for developing a suitable GI scope was the reported constraints regarding the deepest soil layer in the sequence. This material was summarised as medium dense to very dense sandy gravels and cobbles overlying bedrock. This basal sand and gravel layer was encountered in thicknesses from only a few metres at the midspan of the Clarence river to over 25m in thickness at the Northern abutment. It was noted that the depth and nature of the deposit resulted in poor sample recovery and therefore no laboratory test data was available and significant uncertainty remained regarding the mechanical properties of the materials. The material was not encountered south of the Clarence River providing insight into the location and extent of the paleochannel incision and high energy flow environment required to deposit material of this nature.

2.3 SIMILARITIES TO MACLEAY RIVER FLOODPLAIN BRIDGE

Supplementing site specific ground information, Arup drew upon prior experience from the Macleay River floodplain bridge, part of the Kempsey Bypass Project (2011). This experience identified similarities in geological conditions between the two sites where at both locations, a deep gravel and cobble dominant unit was encountered logged as medium dense to very dense. However, key field observations such as drilling resistance and observations of pile driving behaviour at the Macleay River site suggested the material performed as a loose formation under pile driving conditions, providing a contrast of information to that presented on borehole logs.

2.4 SUMMARY OF GROUND CONDITIONS

Ground conditions varied across the site however were generally distinct between the South, North and River crossing locations. Soil depth generally increased towards the north with average soil depths of 32m, 38m and 56m for the South, River and North locations, respectively. The focus of this paper is primarily on the basal sand and gravel units encountered in the River and North portions which largely governed the selection of ground investigation techniques and methodologies.

The underlying geology consists of 30 to 40m of soft estuarine silts and clays and loose to medium dense sands of Holocene to Pleistocene age. This is underlain by a layer of saturated basal sands, gravel and cobbles up to 25m in thickness with gravel grains and cobbles comprised of rounded high strength meta-siltstone.

The final interpreted geological long section is presented in Figure 1 (Arup, 2017) with simplified geological units descriptions listed in Table 1 to provide context for the remainder of this paper.

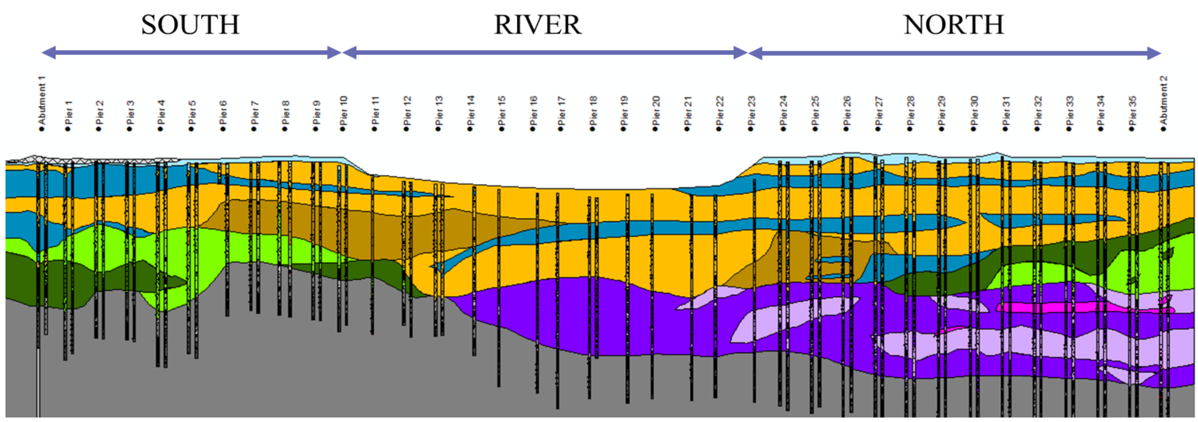

Figure 1: Final interpreted geological long section exaggerated by five times in vertical orientation (Arup, 2017)

Table 1: Summary of geological units at the site in relation to Figure 1 (Arup, 2017)

Geological sequence	Colour	Unit	Material description
Holocene (Clarence River floodplain)		Estuarine Clay	Dark grey silts and clays, very soft to stiff, with shells and minor organics
		Estuarine/Alluvial Sand and Clayey Sand	Grey to dark grey sands and clayey sands, very loose to medium dense, with shells and minor organics
		Estuarine/Alluvial and Clayey Sand	As above – medium dense to dense
Pleistocene (Clarence River floodplain)		Pleistocene Clay	Grey, pale grey and orange/red brown clay (often mottled and fissured), typically stiff to very stiff
		Pleistocene Sand and Clayey Sand	Clean grey, brown and yellow/orange brown sands and dark grey estuarine sands and clayey sands with minor organics, loose to very dense
		Basal Clays	Dark grey and grey-brown clay, trace of gravel, variable consistency from very soft to very stiff
		Basal Sands	Pale grey to dark grey sands, silty sands and gravelly sands, medium dense to dense
		Basal Gravels	Gravels and sandy gravels to cobbles, rounded to sub-rounded, comprised of extremely high strength meta-siltstone grains
Bundamba Group		Rock	Interbedded siltstone and sandstone

2.5 BASAL SAND AND GRAVEL DEPOSITS

The basal sand and gravel deposits comprise interbeds of sandy, rounded coarse gravel to cobbles, saturated medium dense to dense sands and occasional 1m to 2m thick lenses of very soft to very stiff clay. The gravel and cobble layers vary in thickness from only a few metres at the midspan of the Clarence River increasing to over 20m at the northern abutment. The composition of these gravel and cobble materials was later observed to be partially metamorphosed siltstone displaying extremely high strength based on point load testing of some suitably sized cobbles where failure was not achieved. An example sonic core containing basal gravel material is shown in Figure 2.

Figure 2: Example sonic soil core containing gravel and cobble material (left) and recovered cobble stone (right)

3 GROUND INVESTIGATION SCOPE

The critical design uncertainty was the suitability of the basal sand and gravel layer for pile founding capacity and drivability assessments. If sufficient confidence in the engineering properties of this material could be achieved, the savings associated with reducing several metres off each pile length across almost half of the bridge piers could be realised.

3.1 BOREHOLE DRILLING TECHNIQUES

Given the well-known difficulties penetrating gravel and cobble materials via conventional drilling methods, Arup proposed two boreholes each bridge pier (one per pile) consisting of one conventional borehole and one sonic borehole. Sonic drilling allowed for a continuous large diameter soil core to be recovered and sampled which is appropriate for the larger grain sizes of gravel and cobble materials. This method provided an improved resolution of all soil units and in many instances identified lenses and layers which would otherwise be missed by 1.5m interval SPTs.

Wherever possible, conventional boreholes were scheduled in advance of sonic at each pier to limit potential disturbance and impact to SPT testing from the high frequency sonic vibration. The paired conventional boreholes provided SPT information for design engineers estimates of relative density of granular horizons.

3.2 GEOPHYSICAL TESTING

A key limitation of both conventional and sonic drilling methods is the inability to provide reliable information on the density or mechanical properties of gravel and cobble dominant layers. Traditional SPT tests are well known to be unsuitable, CPTs and DMTs are unable to penetrate, and the high frequency vibration of sonic drilling effectively liquefies the soil matrix making meaningful measurements of density impossible.

As such the following series of geophysical test methods were proposed to provide insight into the density, stiffness and spatial characteristics of these materials:

- Cross-hole seismic testing at five selected land-based piers in the North site. PVC casing was installed in paired conventional boreholes (50mm diameter) and sonic boreholes (100mm diameter) to house the seismic geophone receiver and signal source, respectively.
- Natural gamma logging within select boreholes to provide a mapping of relative levels of potassium, thorium and uranium gamma radiation signals. These elements typically occur in higher concentrations within clay soils and conversely in lower concentrations in clean sands. Logging was undertaken through PVC casing for all cross-hole locations and groundwater monitoring wells and prior to pulling steel drilling casing from select over-water boreholes.
- Marine geophysical suite including sub-bottom profiling (SBP), continuous marine seismic refraction (CMSR) and the mapping of riverbed levels using bathymetric survey. This study provided a sub-surface profile by density which was correlated against borehole information and natural gamma logs to support ground model development.

3.3 SUMMARY OF PROPOSED GROUND INVESTIGATION

At the peak of the GI campaign, the following plant, equipment and crew were mobilised on site to complete the scope of works:

- Two conventional borehole rigs and one sonic borehole rig with associated support trucks and crew
- Sealift 1, a non-powered jack-up barge mounting one of the three drill rigs
- One track mounted CPT rig and support vehicle
- Natural gamma logging kit including wireline winch, data logger, signal probe and tripod
- Geophysicist undertaking cross-hole seismic testing or marine geophysical survey from vessel
- Arup field engineers, geologists and site manager

4 LOGISTICAL CHALLENGES

The success of a ground investigation campaign from both a technical and commercial standpoint often hinges on logistical performance and drilling production rates. The following sections discuss some of the logistical challenges encountered on this project which the author hopes may bring value to planning and delivery of future GIs in similar conditions and geological sequences.

4.1 DRILLING PRODUCTION RATES

The rate at which drilling operations progressed on site were tracked and reported daily to provide the project and design team with updates as well as develop a strong baseline for forecasting and sequencing upcoming works. As a valuable by-product of this record keeping, metrics regarding the actual productivity of conventional and sonic drill rigs in each site location may be compared to provide insight on a macro scale. Table 3 presents key productivity metrics including average metres (soil and rock) achieved across the project.

Table 3: Key productivity metrics compared between conventional and sonic drilling methods

	Productivity Metric		**Conventional** (1)	**Sonic**
Project Metrics	Total Boreholes completed (excl. re-drilled locations)		36	28
	Boreholes requiring re-drilling (equipment failure)		3	Nil
	Total Soil Drilled (m)		1743	1444
	Total Rock Core (m)		446	342
	Total Drilled Metres (m)		2289	1786
Meterage	Average Meters drilled per day – Total incl. soil and rock (m)		12.7	18.5
	Record soil depth drilled in single day (m)		37	51
	Average soil depth drilled in single day (m)		12	23
	Minimum soil depth drilled in single day (m)		-10 (2)	1
Time Utilisation	Total Downtime due to Equipment Failure (hr)		81	21
	Lost Time (Equipment Downtime / Operational Time)		4.8%	2.3%
	Average time to complete borehole (days)	South	3.0	2.5
		River	5.0	3.5
		North	8.0	4.5

Notes 1 Metrics are average across all conventional drilling rigs mobilised to site
2 The wooden spoon - on two occasions, sand blowout resulted in overall lost meters for the day

The relative productivity of sonic drilling provides time savings on the order of 30% to 45% compared to conventional methods. The most advantageous production rates were observed in the River and North sites for following reasons:

- Adjustments of sonic vibration frequencies by the driller results in similar drilling difficulty and resistance irrespective of material. It is worth noting that both drilling efficiency and sonic core recovery were markedly and positively influenced by experience of the driller, particularly in deep gravel and cobble horizons.

- Equipment failure in gravel and cobble materials was common for conventional drilling methods. Replacements were often required for casing shoes (approx. every 1-2 boreholes) and tri-cone drill bits as well as the need to abandon and re-drill some borehole locations. The overall lost time and cost of damaged equipment across the campaign was substantial and should be considered for planning GIs in similar materials.

- Sand blowout was common for conventional rigs in deep saturated sand layers when retracting drill rods for SPT, clearing blockages or replacing drill bits or casing shoes. This usually resulted in multiple passes to redrill as the loosening effect within the sand further increased the likelihood of blockages and blowout.

4.2 SONIC CORE SAMPLE MANAGEMENT

A consequence of the large diameter soil core and rapid rate of production of sonic drilling is a substantial volume of soil recovered for each borehole. It was not uncommon for sonic drilling from surface to achieve over 40m of recovered soil depth in a single day. Three metre soil cores of approximately 150mm to 200mm are returned (depending on rod diameter) with time between core runs as little as a few minutes at shallow depths.

Such a significant volume of soil quickly highlighted the need for the following management strategies

- Supervising engineers and geologists require an offsider or assistant (at least for the top 15m) both for manual handling tasks and to ensure technical logging does not suffer from the overwhelming return of core. Further to this, rotation of team members through this role and correct manual handling training is essential to prevent fatigue as part of the health and safety management plan.

- Soil cores were often returned in a saturated state both a result of natural ground water and flushing fluid. During the logging process, the fluid and cuttings must be contained, particularly when onboard the barge or in a sensitive environment. A novel tool of a large diameter PVC pipe cut in half longitudinally was employed to temporarily house soil cores and fluids until logging was completed (Figure 3). Samples may then be easily slid into more permanent storage bags for transport overboard.

- Sampling, storage and disposal arrangements require pre-mobilisation agreement. Figure 3 shows collections of bagged sonic bulk samples with each pile generally representative of a single day's core return.

Figure 3: Photographs of PCV utilised to control soil and fluids whilst overwater (left) and stockpiled sonic core samples with each pile representative of a single day return (right)

4.3 PRIORITISATION OF MARINE OPERATIONS

The 'Sealift 1' jack-up barge mounted either the sonic or conventional rig and was positioned at its closest, 15m downstream of the existing Harwood Bridge (Figure 4). Due to this proximity, the Harbourmaster authority permitted sailing and moves between borehole locations only on slack tide or high to low tidal transition to reduce risk of accidental strike. As 'Sealift 1' is a non-powered vessel, the Yamba Marina based tug-boat 'Francis Freeburn' was essential to all sailing and barge move operations. Drilling positional tolerance was set within 1m of the pile centre which was achievable so long as wind and tide speed permitted safe operations.

The primary portside mooring for 'Sealift 1' was at Yamba Marina which had relatively shallow water depth and caused dragging of the leg spuds at low tide. Marine drilling operations commenced from the North riverbank and progressed southwards where it became clear that spud leg extension would be required to complete mid-span boreholes due to the increasing water depth. The additional weight of the leg extensions required sailing into port only at high tide which added further constraints to the operation.

The critical path of the GI campaign therefore centred around the over-water works and the need for an eventual swap of conventional and sonic drilling rigs on board to complete the borehole pairs. This operation required detailed forward planning and was heavily influence by availability of a mobile crane, availability of 'Francis Freeburn', port space at Yamba Marina and suitable sailing conditions including tide and low wind conditions. To avoid extensive downtime of multiple teams, the rig swap also had to be synchronised with the completion of both the conventional (on board) and sonic boreholes.

Figure 4: Photographs of 'Francis Freeburn' towing 'Sealift 1 out of Yamba Marina (left) and proximity of drilling operations downstream of the existing Harwood Bridge (right)

The execution of this rig swap occurred at a time where the mounted conventional rig had struggled to produce more than a couple of metres progress for several days due to an ever-worsening case of a damaged casing shoe and drill-bit blockages within gravel horizons. Previously drilled boreholes at adjacent piers indicated rock-head was within a few metres however a time deficit was looming to complete both soil and rock drilling as well as the sail to Yamba Marina.

Following negotiation with the design team and consideration of logistical constraints, it was determined that the risk of missing the available window for the planned rig swap could be offset by abandoning the conventional borehole and completing a sonic core at the other pile location of this pier. The loss of resolution was at most two SPT tests in material that was now likely to be greatly disturbed. The SPTs were effectively traded for a complete sonic log (soil and cored rock).

The rig swap was completed with near zero unnecessary downtime of rigs and crew and in a delivery time of around 2.5 days, similar to the time expected to finalise the abandoned conventional borehole.

5 TECHNICAL SUCCESSES

5.1 DRILLING RESISTANCE OF BASAL GRAVELS

Despite the physical difficulties progressing conventional drilling methods in gravel materials, valuable observations could be made and recorded by the supervising engineer and drillers of drilling resistance through various strata. The interbedded nature of the basal deposits and distinctive 'crunch' on first strike of gravel or cobbles, allowed relatively accurate measurements of layer thickness and transitions.

As the drill string was advanced, it was often necessary to pull back and re-drill to prevent locking up of the drill bit between large cobbles. It was often the case that after multiple drill passes, the similarities in resistance of each pass suggested that the gravel and cobble grains were merely being pushed aside and thus the material was sufficiently loose to allow for this movement. These observations were recorded on borehole logs as a valuable piece of information which would be otherwise ignored to the design engineer scanning SPT values of refusal.

Both tri-cone and diamond tipped coring drill-bits were trialled in the basal gravels, each with degrees of success. Whilst tri-cone bits are more suitable for progression and tend to survive longer, soil returned in drilling fluid is generally crushed and provides little information on the true size of the gravel and cobble grains. Diamond tip drill bits on the other hand can core through larger cobbles and pickup gravels providing some indication of size up to the core barrel diameter (PQ in this case), albeit with a shorter lifespan and thus additional cost.

5.2 NATURAL GAMMA LOGGING

One of the more unique techniques employed was natural gamma logging which is more often deployed in the minerals, oil and gas industries. The method relies on the detection of gamma emission spectra of primarily potassium occurring naturally in clay dominant rocks such as siltstones, and shales. Whilst natural gamma logging does not provide distinct 'geological logs', the interbedded nature of the soil sequence at the site coupled with complete sonic soil cores provided a supplementary source of information regarding layer transitions. Seawater was observed to have a relatively insignificant gamma emission signature and thus the depth to mudline could be easily confirmed from gamma traces.

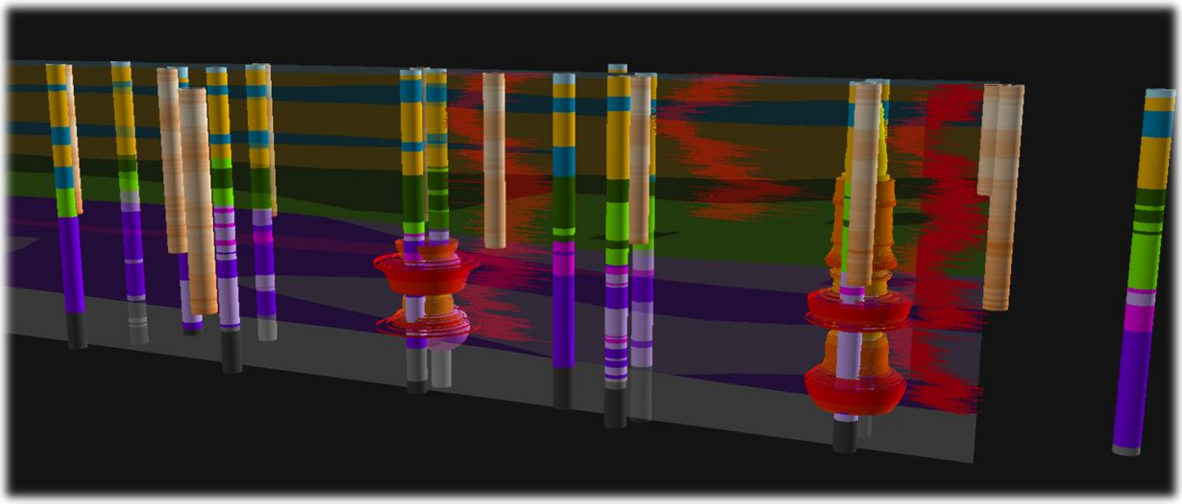

Figure 5: Example of natural gamma traces (red lines) overlayed on a 3D geological model

Natural gamma logging was undertaken within boreholes following installation of PVC for cross-hole geophysics or groundwater monitoring wells as well as prior to pulling up steel casing for overwater boreholes. To test the potential signal attenuation through steel, a comparison was undertaken on a land-based hole through steel casing and then again through PVC with determined a minor attenuation of about 2%.

The equipment was easily operated by an Arup field engineer or geologist following supplier training requiring only operation of a wireline winch and data logger, powered by a 12volt battery or mains supply. For the probe supplied for this project, a winch speed of 3m/min was used, and a trace was obtained on both the up and down legs and undertaken twice at each location. Comparison of the up, down and different passes showed only natural variability with the overall trace shapes largely consistent.

A few useful observations of trends and patterns of natural gamma traces on the project were:

- Generally higher emission signatures at depths coinciding with logged clays and sandy clays and conversely lower signatures in sand dominant materials. Very low relative signatures were recorded for clean sands observed on the South portion of the site.

- A relatively larger range and scatter of emission signatures at depths coinciding with logged gravel and cobble materials. The author suspects that the scatter is a result of the relatively high concentration of clay particules within the meta-siltstone gravel contrasted with void/water space between the grains.

An example of natural gamma logs within the context of a 3D ground model is presented in Figure 5 showing higher relative readings within clay dominant materials (shown in darker colour sets, see Table 1).

The typical time from setup to pack-down for a 65m borehole was typically one hour; a month hire cost of the equipment totalled A$6000 thus making this technique remarkably efficient. This leads the author to conclude that for complex interbedded sequences, the return on investment and value add to geological logs from an accompanying natural gamma log is substantial and hopes to see the technique more widely researched and employed for use in the geotechnical industry.

6 CONCLUSIONS AND RECOMMENDATIONS

A comprehensive and diverse GI campaign was completed for the proposed bridge over the Clarence River at Harwood which included conventional and sonic drilling and geophysical test methods. The scope of works was developed and delivered to manage the technical and physical challenges of obtaining reliable material information of deep gravel deposits. Reflection on these challenges and successes, the author draws the following conclusions and recommendations:

- Substantial value can be added for designers, clients and projects by pursuing non-traditional investigation techniques such as sonic drilling and geophysical surveys. The best outcomes occur where emphasis on a 'right tool for the right job' approach is adopted and by utilising a diverse range of techniques to build sound evidence-based ground models.

- Sonic drilling coupled with cross-hole seismic testing and marine geophysics is a viable strategy for obtaining meaningful engineering properties for gravel and cobble dominant beds where conventional SPTs are unsuitable. Sonic cores provide engineers and geologists with meaningful observation of grain size and characteristics whilst geophysics can provide small strain material behaviour properties and densities.

- Natural gamma logging presents a time and cost-efficient technique for sub-surface profiling and is a valuable supplement to a borehole log, particularly in complex and interbedded sequences.

- Observations of drilling resistance and physical challenges of penetrating gravel and cobble materials should always be recorded on logs as they can provide insight into relative density to contextualise refusing SPTs.

6.1 AREAS FOR FURTHER RESEARCH

- Investigation of the zone of influence of sonic drilling vibration to determine whether results of SPT, CPT or geophysical tests adjacent to a previously drilled sonic borehole are compromised.

- Further research into the application of natural gamma logging and other easily deployed and efficient geophysical test methods to extract additional geological and geotechnical data from drilled boreholes.

- Feasibility of positioning geophone arrays at ground surface to detect SPT blows at depth as a seismic source providing a "reverse down-hole seismic" test during conventional borehole drilling. Such a method could be reasonably and cost efficiently deployed for many ground investigations to capture data on material properties.

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