Use of drilling rig instrumentation to assess subsurface profile and material characteristics during piling operations

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ABSTRACT

At the site of a major infrastructure project within South East Queensland, a series of bored piles have been recently installed within a residual and extremely weathered, interbedded sedimentary profile. Geotechnical information for the design of the structure was initially gathered by the completion of a series of borehole investigations across the site and pile capacities were subsequently confirmed by continual geotechnical supervision of the pile excavations during construction. Supplementary geotechnical information was recorded by the instrumented rotary piling rig mobilised for the installation of all piles completed at this site, and this paper presents a retrospective comparison between this recorded data and the other geotechnical information received during the various stages of site investigation work. The general characteristics of the recorded drilling parameters are detailed, and the interpretation and correlation of the data with the previously modelled subsurface profiles present at the site is documented. Comparison of the drilling rig data with strata changes, laboratory test results and estimation of material strength has been attempted.

Keywords: Automated investigation monitoring, weathered sedimentary profile, pile supervision

1 INTRODUCTION

The confirmation of the logged or modelled subsurface profiles and interpreted material parameters at any site is imperative to ensure the adequacy of the proposed design. Subsurface profiles and geotechnical models of a site, as defined from initial geotechnical investigations, are generally utilised for design inputs and are thus required to be confirmed during the construction phase of a project.

Verification of assumed material properties are essential for piling operations in order to confirm that the design pile capacity is achieved. However, as the excavated material is commonly highly disturbed during displacement, the estimation (and thus design confirmation) of the strength of the material that comprises the subsurface profile is often difficult to achieve by a quantifiable approach. This paper details a procedure whereby data collected from an instrumented piling rig has been filtered, analysed and compared to other sources of geotechnical data, and subsequently used to estimate the strength of weathered and weak materials.

2 SITE DESCRIPTION

Piling operations were completed on a site located on the Gold Coast, Queensland, Australia. The piling was undertaken for the Gold Coast University Hospital (GCUH) Station Shell which formed part of an early works package of the Gold Coast Rapid Transit (GCRT) project. A series of cast-in-place pile walls were designed to provide predominantly lateral support for the station area and tunnel approaches in order to allow excavation of the site. A total of over 500 piles were installed between August 2010 and February 2011, with pile diameters ranging from 750mm to 1500mm.

The station site was located at a localised topographic high, with the approach tunnels penetrating the slopes of the ridge. The vertical differential across the site was approximately 14m. The subsurface profile of the site comprised residual soils (silt and clay mixtures) overlying meta-sedimentary rock material belonging to the Neranleigh-Fernvale beds geological formation. Limited quantities of uncontrolled fill and alluvial clays were also encountered at the surface in isolated areas of the site.

The rock profile encountered generally replicated the site topography, and the thickness of residual soil increased from the crest of the hill in both directions. The meta-sedimentary bedrock which was intersected across the site possessed a deep weathering profile and was consistently described as extremely to highly weathered and extremely low to low strength. Weathering reversals were commonly observed, with associated rock strength variation. Some preferential weathering of meta-siltstone over meta-sandstone rock material was also evident across this site.

3 AVAILABLE GEOTECHNICAL DATA

Information obtained from three (3) geotechnical investigations was used to complete the design of the pile walls at the GCRT site. These investigations comprised a total of 22 boreholes located across the station site, advanced by use of a rotary drilling rig. From the results of these investigations a geotechnical model for the site was constructed, detailing the subsurface material units and material properties. Piles were designed to penetrate into the extremely weathered (XW) meta-sedimentary material which was consistently encountered from, or very close to, the ground surface and extended beyond the toe level of each pile. Due to the variation of rock type (interbedded meta-sandstone and meta-siltstone) and rock strength (extremely low to low strength) across the length of the piles, a single set of material parameters were defined to characterise an equivalent material unit, “XW Rock.” Material parameters adopted to represent this hybrid unit for design purposes are detailed in Table 1.

Table 1: Characteristic Rock Strength material properties for equivalent “XW Rock” unit

Unit Weight (kN/m^3)	Median $I_{s(50)}$ (MPa)	$I_{s(50)}$ Interquartile Range (MPa)	Design UCS range (MPa)	Geological Strength Index (GSI)
20	0.11	0.08 – 0.15	1.6 – 2.5	25 - 40

As the design of the pile walls resulted in the piles entirely encapsulated within the “XW rock” unit, the piling data analysed within this paper details the pile excavation profiles drilled through a single material unit. This differs from similar drilling record data previously analysed by others (Gao et al, 2008; Gui et al 2002) as there is no significant geological change present within the length of the data.

A 60m section of a 2m high, near-vertical excavation was also geologically mapped to estimate the orientation of the bedding planes present at the site. The orientation of the beds was consistently measured at approximately $60^0/255^0$ (dip / dip direction). Due to the differing orientations of the structure’s pile walls across the site, this bedding orientation was intersected at varying angles (eg perpendicular or parallel to bedding). However, due to the tight nature of the bedding, the stability of excavations was not affected by this structural arrangement, regardless of the bedding / excavation orientation interaction.

In addition to the initial site characterisation and geotechnical design data, a detailed log was produced for each pile excavation which contained descriptions of the rock material and variation of the estimated rock strength along the full pile excavation length. A pile inspection report was also compiled for each of the nine (9) defined pile walls, which summarised the encountered subsurface and rock strength testing completed on irregular lump samples recovered from within excavation spoil (Point Load Index, $I_{s(50)}$ values). Accordingly, as piles were spaced between 1200 to 1800mm (centre to centre), a continuous subsurface profile could be established along the alignment of each pile wall.

The piling rig used for all pile excavations was a Bauer BG28, a rotary drilling rig with an operating weight of 96T. The rig was fitted with an electronic data management system, B-Tronic, which provided recordings of the operating conditions of various drilling rig parameters at 1-second intervals for each pile excavation. The recorded drilling parameters selected for analysis, based on the results of previous work (Gui, 2008; Gao et al, 2008), included torque, drive rotation speed, pump pressures, winch load and inclination of piling rig mast. Detailed descriptions of each of these parameters are included in previous publications that relate to instrumented borehole drilling data (eg Gui et al, 2002).

4 INITIAL DATA FILTERING

Unlike recommendations by Gui and Hamelin (2004), no initial correlation to site-specific conditions was undertaken as the data recovered from the piling rig was not intended to be directly used for confirmation of design parameters. No definition between the recorded parameters and existing geotechnical information was undertaken prior to commencement of piling works, nor was any preference given to keeping any particular aspect of drilling operations at a standardised rate throughout pile installation. Accordingly, data collected at this site should be considered site-specific and individual pile records may not always be directly comparable to each other.

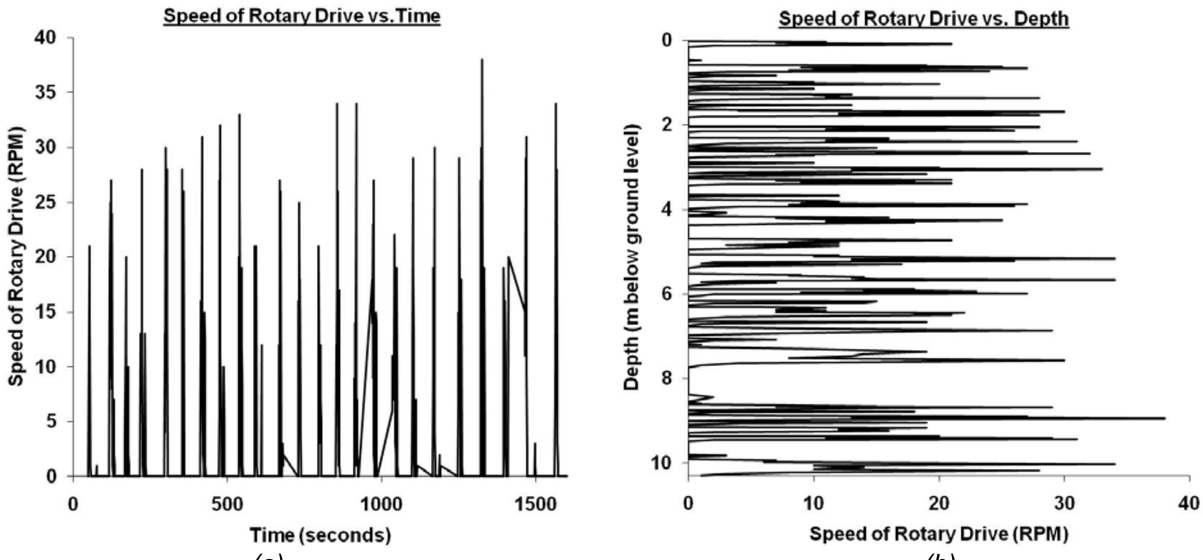
In order to correlate the recorded data with available geotechnical logs, closely offset borehole and pile excavations have been compared. The proximity of each pile record to the nearest borehole was first calculated, and of the approximately 500 piles drilled at the site, 120 piles were located within 10m of the nearest borehole. Twenty-eight piles were located within 5m and just six (6) boreholes were located within 3m of the nearest borehole. For initial data comparison, as presented within this paper, the rig data, pile and borehole logs belonging to these six (6) borehole / pile pairs have been isolated.

No associated depth data was embedded within the drilling rig data, and all recordings were referenced only to the duration from the commencement of excavation. Each drilling record covered the duration of the entire piling operation, and thus included non-relevant data that described activities such as the removal of spoil from the excavation. In order to filter this “non-drilling” time from the dataset and produce a dataset solely comprised of “pure drilling” information, thresholds identifying the periods of time that the auger was productively drilling at base of the excavation between “lifts” to remove spoil were defined. This was generally completed as per the procedure presented by Gao et al (2008), but in this case based on mast inclination, torque and the force applied to the main winch.

The result of this filter was to produce a series of data points which represented each period of time that the auger was physically at the base of the pile excavation (Figure 1a). This data could then be compared to the excavation logs, all of which included notes of the time that certain excavation depths had been achieved. From the timestamp of the filtered data, the piling record was then converted to an approximate depth plot (Figure 1b). Limited linear interpolation was required, as the interval between time/depth information often included numerous “cycles” of auger drilling and excavation clearing.

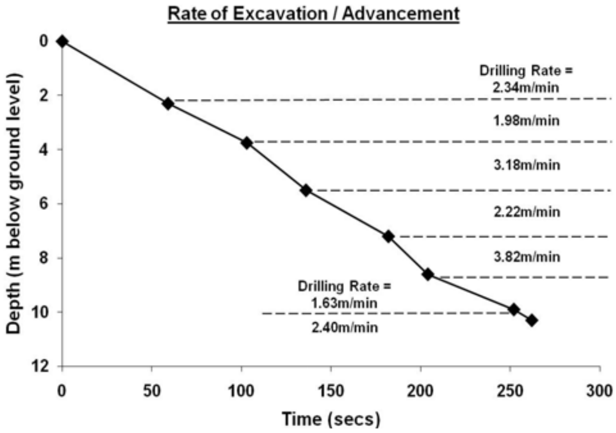
Using the inferred depth and available survey information, the various datasets were assigned a vertical reference and then directly evaluated against the estimated strengths noted on the comparable excavation and borehole logs. Using the depth and time notes included on the excavation logs, the rate of drill advancement was also estimated and attributed to the logged material strength.

As the rate of drilling was expected to be a function of both torque and rotation speed, a normalised parameter that can be used for comparison between pile records, denoted Drilling Effort (DE), has been calculated for each analysed excavation record by dividing the torque (%) with the speed of rotary drive (%). Statistics for the DE parameter, along with all other compiled parameters, have then been calculated for the “pure drilling” component of the data record (refer Figure 2b).

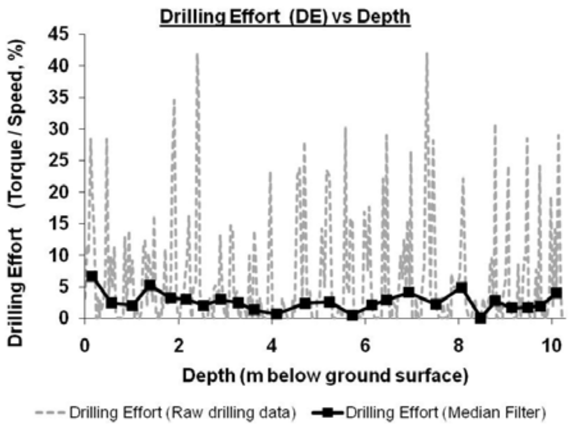


(a) *(b)*

Figure 1: (a) Filtered data showing only time periods of active excavation advancement; and (b) equivalent dataset placed within a vertical excavation log, based on excavation log notes.



(a)



(b)

Figure 2: (a) Calculated penetration rate plotted against depth, based on piling rig data and excavation log notes; and (b) Drilling Effort, raw and filtered with median filter, plotted against depth.

These statistics were then compared with the corresponding borehole and excavation logs to produce a dataset of values applicable to each identified rock type and estimated strength. A median filter, which characterised the median value of each parameter for the “pure drilling” component of each “cycle,” was applied during this comparison. The selection of a median filter is based on the recommendation of Gui (2008), who found such a filter was well suited for drilling parameter data (which inherently contains sharp data spikes due to the cyclical processes involved).

5 RESULTS

Based on the results of the data filtering, a set of characteristic values for all the analysed drilling records have been constructed. The database compiled for each parameter has been sub-classified based on logged material type and estimated strength. Two (2) iterations of this analysis have been completed, based on the material and strength properties either included in (a) the reviewed borehole log; or (b) the pile excavation log. Table 2 presents the calculated statistics applicable to the Drilling Effort (DE) parameter only, and represents a typical table of results constructed for each analysed parameter. The values in this table represent the average value based on the compiled dataset based on each statistic.

Table 3 presents a full set of characteristic drilling rig parameters, based on median filtered values. The selection to use the material / strength data contained in either the borehole or excavation logs as the basis of attributing material types to the drilling parameter records does affect the resultant values, in some cases significantly (eg up to 63% difference between the calculated median DE values). This variation is attributed primarily to the steeply dipping nature of the bedding planes present across the site. Even though the isolated borehole data were all located within 3m of the pile excavation, the

Table 2: Typical values of normalised drilling effort (DE) parameter categorised by logged rock strength class (sourced from pile excavation logs / borehole logs)

Material	Logged Strength	Logged Length	% Rock-mass	Drilling Effort (DE, %)			
				Lower Quartile	Median	Average	Upper Quartile
Sandstone	Extremely Low	11.3 / 14.7	20 / 25	0.8 / 0.8	2.2 / 2.3	8.0 / 6.5	9.8 / 8.8
	Extremely Low / Very Low	8 / NIL	14 / –	0.8 / –	3.1 / –	6.3 / –	8.4 / –
	Very Low	9.1 / 0.9	16 / 1	0.7 / 1.2	2.6 / 3.7	5.9 / 11.8	7.4 / 12.7
	Low	6.6 / 2.8	11 / 5	0.8 / 0.6	2.6 / 1.6	4.8 / 4.9	5.8 / 5.4
Siltstone	Extremely Low	5.8 / 34.8	10 / 59	0.6 / 0.7	1.6 / 2.3	4.1 / 5.5	5.0 / 6.6
	Very Low / Low	3.2 / 3.9	6 / 7	0.5 / 0.6	2.7 / 2.0	7.4 / 6.3	10.1 / 7.6
Interbedded Material	Extremely Low	3.3 / NIL	6 / –	0.9 / –	1.9 / –	5.0 / –	4.8 / –
	Extremely Low / Very Low	8 / NIL	14 / –	0.7 / –	1.7 / –	4.8 / –	5.4 / –
	Very Low / Low	1.7 / 1.7	3 / 3	0.4 / 0.3	1.7 / 2.5	5.4 / 5.4	8.1 / 7.0

Table 3: Site specific drilling rig parameters (from median values) categorised by logged rock strength class (sourced from pile excavation logs / borehole logs)

Material	Logged Strength	Torque (%)	Rotation (RPM)	Pressure (kPa)	Winch Load (T)	Drilling Effort (%)
Sandstone	Extremely Low	6.1 / 6.5	16.7 / 12.5	89.5 / 69.7	11.0 / 11.0	2.2 / 2.3
	Extremely Low / Very Low	4.9 / NIL	20.9 / –	122.7 / –	11.2 / –	3.1 / –
	Very Low	7.9 / 14.0	9.7 / 15.1	64.0 / 45.7	11.0 / 11.0	2.6 / 3.7
	Low	8.1 / 6.7	12.4 / 17.1	89.9 / 92.6	11.2 / 11.4	2.6 / 1.6
Siltstone	Extremely Low	8.0 / 5.4	14.9 / 16.2	107.0 / 104.6	11.1 / 11.2	1.6 / 2.3
	Very Low / Low	10.2 / 8.8	10.2 / 12.0	66.4 / 80.8	11 / 11.1	2.7 / 2.0
Interbedded Material	Extremely Low	3.5 / NIL	15.9 / –	90.4 / –	11.4 / –	1.9 / –
	Extremely Low / Very Low	2.6 / NIL	15.7 / –	110.4 / –	11.4 / –	1.7 / –
	Very Low / Low	4.7 / 6.1	7.1 / 9.4	33.7 / 51.1	11.0 / 11.0	1.7 / 2.5

measured bedding angle (60^0) indicates that for every metre offset between borehole and excavation there is an associated vertical difference of up to 1.7m for corresponding bedding interfaces. Accordingly, the strength estimation data produced from the logging of pile excavations is considered more appropriate for use in comparison with the piling rig records, as this is directly matched data.

Table 2 suggests there appears to be a general increase of effort (DE) required to excavate materials as the material strength increases. However, the same response is not observed when the torque or rotation parameters are analysed individually. From inspection of Table 3, it is noted that no individual parameter appears to exhibit values that directly relate to the logged variation of rock strength. This indicates that combining the parameters responsible for drill penetration, torque and rotation speed, to produce a normalised, dimensionless parameter (similar to the Percussion Index (Pi), as defined by Sugawara et al, 2008) is an effective method of assessing relative material strength, regardless of it not being a intrinsic material property.

Based on pile excavation log strength estimates, a threshold of $DE_{median} \leq 2.2\%$ appears to be a suitable indicator that the drilled material was of extremely low strength. Similarly, a threshold of $DE_{median} \leq 2.0\%$ would indicate that the material was not fully comprised of sandstone (ie siltstone or interbedded siltstone / sandstone). However, from the available data there does not appear to be a simple method to differentiate between the very low strength siltstone and sandstone materials.

The DE parameters also indicate that for equivalent logged strength classes of different materials, the siltstone unit is weaker than both the sandstone and interbedded materials. This is especially pronounced in extremely low strength materials and is consistent with pile excavation logs, in which estimated rock strength of siltstone material was frequently logged as a strength class lower than the surrounding sandstone material (eg extremely low strength siltstone interbedded with very low strength sandstone).

Yue et al (2004) and Gao et al (2008) have both used penetration rate variations to classify material units. The same technique has been applied to the data analysed in this study, as shown in Table 4. There is a general reduction in the median calculated rate of drilling as rock strength increases.

Table 4: Calculated drilling penetration rates, categorised by logged rock strength class

Material	Logged Strength	Range (m/min)	Median (m/min)	Average (m/min)	COV (%)
Sandstone	Extremely Low	1.5 - 4.3	3.3	3.2	30%
	Extremely Low / Very Low	3.1 - 4.7	4.1	4.0	17%
	Very Low	1.6 - 3.9	2.7	2.8	31%
	Low	2.0 - 6.4	2.6	3.8	53%
Siltstone	Extremely Low	1.9 - 3.9	3.5	3.1	34%
	Very Low	2.0 - 4.5	3.3	3.3	56%
Interbedded Material	Extremely Low	4.8 - 5.4	5.1	5.1	8%
	Extremely Low / Very Low	3.2 - 4.9	4.0	4.0	30%
	Very Low / Low	2.4 - 2.7	2.6	2.6	9%

However, the Coefficient of Variation (COV) values are consistently between 30 and 50%, suggesting that there is relatively large variation within the data attached to each individual rock strength category. These observations conform with the results presented by Sugawara et al (2003), who found that rock strength of igneous materials could also be estimated by typical penetration rates, and that significantly larger variation were found within highly and completely weathered rock materials.

6 COMPARISON WITH POINT LOAD INDEX TESTS

A number of Point Load Index (PLI) tests were completed on materials recovered from within the pile excavations isolated for this analysis. These $I_{s(50)}$ values have been compared to the specific portion of piling rig data interpreted to correspond to the depth of the tested sample. Based on regression analysis of the limited dataset available (n = 6), a site-specific empirical linear relationship between the data pairs was noted, as presented in Equation 1. The correlation coefficient, R^2, for this data is 0.72, indicating a strong relationship may exist between the DE parameter and relative rock strength ($I_{s(50)}$).

$I_{s(50)} = 0.12 \times DE - 0.16$ (Equation 1)

Equivalent $I_{s(50)}$ values for each logged rock strength class can thus be calculated using Equation 1 and the DE data presented in Table 2. By weighting each strength class by the percentage of material logged within the analysed pile excavations, a characteristic $I_{s(50)}$ value of 0.12 was calculated for the entire analysed section of the excavated “XW Rock” unit. This compares extremely well with the interpreted median $I_{s(50)}$ value of 0.11 MPa attributed to the “XW Rock” unit for design purposes.

7 CONCLUSIONS

This paper has presented the process of subsurface material assessment based on the filtering and analysis of drilling parameter data recorded against drilling time by an instrumented piling rig. A highly weathered, weak rock unit known to be comprised of interbedded meta-sedimentary materials was initially defined as a single rock unit for design purposes. However, by correlating pile excavation logs with drilling parameter records, a typical drilling rate and a normalised parameter, drilling effort (DE), for each strength class of sandstone, siltstone and interbedded material has been calculated. A site-specific correlation of the normalised DE parameter with PLI test results has also been completed, with the results indicating that, for the limited dataset analysed, the characteristic $I_{s(50)}$ value of the amalgamated rock unit was at least equal in magnitude to that assumed in design.

Although the work presented in this paper is a retrospective data analysis, with initial calibration of drilling parameters with site specific materials the methodology detailed could potentially be used as a QA technique with which to quantifiably compare onsite conditions to those assumed in the design.

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