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Geophysical and Geotechnical Characterisation of the Saltwater Creek Bridge Site, Morten Bay Rail Project, Queensland, Australia

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ABSTRACT: This paper describes how surface geophysical techniques have supplemented intrusive geotechnical methods for the geotechnical investigation and driven pile design for Saltwater Creek Rail Bridge (BR270) and Saltwater Creek Shared Path Bridge (BR1240) on the Moreton Bay Rail Project, north of Brisbane. The geophysical methods included seismic refraction (SR) for imaging subsurface P-wave velocity and multichannel analysis of surface waves (MASW) for imaging subsurface S-wave velocity. The SR method is used to determine the depth of the bedrock and its lateral variation. The MASW method models S-wave velocity which is used to identify the variable strata above the bedrock. Due to inherent limitations of geophysical methods, a strict criteria was followed when interpreting geophysical data. This included site specific correlation to data from geotechnical drilling. Features that were cross checked included changes in depth of stratigraphic layers against corresponding changes in geometry of seismic velocity contours; correlation of P wave and S wave velocity values against material types and properties given in borehole logs; and S wave velocities were used to assess the inferred N-SPT values and subsurface strata. A comprehensive geotechnical model of interpreted ground conditions along the Saltwater Creek Bridge alignment was developed using borehole information and the results of surface geophysical surveys. As-built pile information indicate that the as-built pile toe elevations are reasonably close to design pile toe elevations at each pier location for each bridge.

1 INTRODUCTION

The Moreton Bay Rail Project (MBR) consists of a new rail passenger line due to open in mid to late 2016, which will link Brisbane's main northbound rail line to the suburbs in the Moreton Bay region north of Brisbane. The upgrade involves a 12.6 km heavy gauge dual-track to be built between Petrie and Kippa-Ring and the construction of six new rail stations including an upgrade of the existing Petrie Station. The upgrade will include the construction of 11 rail bridges, 2 shared path bridges and 7 road bridges. Bulk earthworks along the proposed alignment will comprise both cuttings and fill embankments.

This rail link passes over three waterways, including low lying saltmarsh land around Saltwater Creek at Rothwell (Figure 1). The design of the Saltwater Creek Bridge consists of 22 piers, is 325 m long and carries the MBR alignment across Saltwater Creek at Hays Inlet. The rail alignment is constrained by land availability and flood levels in the creek and the bridge configuration is defined by the environmental regulatory requirement to keep embankment construction above Highest Astronomical Tide (HAT) of 1.36 m, with the bridge soffit being above Q1000 and Q2000 flood levels.

This eastern section of the rail alignment through the Saltwater Creek / Hays Inlet area includes soft ground favouring an embankment height that is kept as low as possible to minimise settlement, however with the top of formation above 100 year ARI flood level. This leads to a bridge form with shallow depth and therefore fairly short spans.

The adjacent Saltwater Creek Shared Path Bridge (Figure 1) runs parallel to the rail bridge with approximately 3 m clear separation between the structures and adopts the same span configuration. It has a separate superstructure and foundations however shares the approach embankment and abutment spill-through.

The bridges are formed from standard 15 m Queensland Rail Prestressed Concrete (PSC) slabs with a single span of standard 25 m Queensland Rail PSC girders provided across the low flow channel of Saltwater Creek to minimise disturbance to the creek habitat.

The rail bridge piers are formed from eight 550 mm driven prestressed octagonal piles, arranged in two rows of four in order to resist the braking loads, which extend directly to a 3 m wide reinforced concrete headstock. The abutments are formed from four 550 mm driven prestressed octagonal piles with a reinforced concrete headstock.

The shared path bridge piers and abutments are formed from three 550 mm driven prestressed octagonal piles extending directly to a reinforced concrete headstock.

The design and construct contractors for the MBR was CPB Contractors (formerly Thiess) and Golder Associates (Golder) was the geotechnical designer. Aurecon AECOM Joint Venture (AAJV) was the structural designer.

Figure 1. Saltwater Creek Rail Bridge and Shared Path Bridge - Plan View

2 SITE GEOLOGY

The geology of the bridge site comprised alluvial, estuarine and coastal plain deposits, and residual soils underlain by various rocks of Tertiary, Jurassic, Triassic and Devonian aged formations as indicated in the Geological Map of Brisbane and Caboolture scale 1:100,000 series (Sheet No. 9543, Year 1986, and Sheet No. 9443, Year 1979) published by the Department of Mines.

The available borehole information indicates that the subsurface conditions within the proposed bridge location comprises up to 12.8 m thick of very soft to firm alluvial silty clay and loose to medium dense sands. The alluvial materials overlie stiff to hard residual sandy clay and sandy silt materials derived from the weathering of underlying sedimentary rock. The sedimentary rocks consist of sandstone, claystone, mudstone and interbedded sandstone and mudstone. The rock strength generally increases with depth from distinctly weathered (DW) of extremely low to low strength rock to slightly weathered (SW) of medium to high strength rock.

3 GEOTECHNICAL DESIGN & CHALLENGES

The main geotechnical challenge for the Saltwater Creek Bridges was the environmental constraints for the site investigation to obtain geotechnical data for the pile design. As shown in Figure 1, the Saltwater Creek Bridges were located within a tidal environment within the marine park area; which includes environmentally sensitive marine species such as salt couch across the majority of the site and pockets of mangroves near the lowest lying areas. Within this area, the approval process for environmental permits for the full construction works required about 3 to 4 months. During the detailed design, the available environmental permit only allowed minimum disturbance of the area, i.e. maximum of one metre width disturbance of the marine park vegetation (mainly saltwater couch with some pockets of mangroves) along the proposed bridge alignment.

Based on the Scope of Works and Technical Criteria (SWTC) requirement and AS 5100.3-2004 Bridge design - Foundations and soil supporting structures, the minimum number of boreholes shall be one per pier and abutment for each bridge.

A pre-investigation reconnaissance walkover of the bridge site revealed that drill rig access into the areas of the abutments was going to be difficult for various reasons including environmental constraints i.e. mangroves, marine park habitats, saltwater couch grass and thick vegetation areas which require clearing. To obtain all the permits for the intrusive site investigation activities was going to take months, and was not compliable with the time deadlines for the project.

For this reason a relaxation to the SWTC and AS5100 requirements for a borehole at each pier and abutment location was requested. To satisfy the intent of the clause and in order to progress the design and considering the environmental permit restriction, an innovative site investigation method, i.e. geophysical survey investigations using Seismic Refraction (SR) and Multichannel Analysis of Surface Waves (MASW) methods were adopted. The objective of the MASW survey was to understand the soil consistency for material above rock level (mainly for soft to firm soils), while the objective of the SR survey was to understand the top of rock level. Figure 2 illustrates the geophysical survey undertaken with minimal disturbance to the sensitive marine park environment.

Figure 2. Minimal ground disturbance to marine environment during the geophysical surveys at Saltwater Creek Bridges

4 METHODOLOGY OVERVIEW

In order to assess and to interpret the ground conditions, as well as to develop the geotechnical model along the proposed bridge alignments, the following methodology was adopted during the design process:

- For the DD (detailed design) 15% to 80%, available information from previous investigations, namely two boreholes (BH62 and BH20), six variable dynamic cone penetrometer tests (VDCP02 to VDCP07), and one piezocone penetration test (CPTu08) were used;
- For the DD 85%, four additional Stage 2 investigation boreholes (BH1240-01, BH1240-07, BH1240-13 and BH270-22) and geophysical surveys (i.e. Seismic Refraction (SR) and Multichannel Analysis of Surface Waves (MASW) surveys) were carried out along the BR270/BR1240 alignments. The main objective of the additional geophysical survey is to fill the gaps between the available geotechnical information and also to refine the initial ground model.

The following additional measures were also undertaken as part of risk mitigations:

- End of Drive Pile Driving Analyser (PDA) testing – which involves measuring dynamic response of pile to driving for every hammer blow during installation - was carried out at selected piles to assess pile toe levels, pile capacity, pile driving criteria for adjacent piles (i.e. drop height and final sets) and induced stresses in the piles during the pile driving. End of Drive PDA testing was carried out during pile driving on a minimum of one pile at every third pier of each bridge;
- Restrike PDA testing was carried out on a minimum of 1 pile per pier, for all piers that were not selected for End of Drive testing. Additional Restrike testing was also carried out at pier locations where piles effectively "refused" at shallower depth than predicted;
- Signal matching analyses using the "CAPWAP" program was carried out for each PDA test;
- All the piles were observed by a qualified geotechnical engineer;
- Ultimate bearing capacity of piles were assessed using Hiley pile driving formula which has been calibrated with the Restrike PDA test and CAPWAP analysis to provide a higher degree of QA/QC certainty;
- By referring to AS2159-2009 and using the PDA, a geotechnical reduction factor of 0.76 can be adopted. However for the ultimate bearing capacity analyses, the geotechnical reduction factor was limited to 0.6; and
- Sensitivity analysis for pile design has been undertaken to consider possible variation in the rock surface level from that interpreted from the geophysical survey. A variation in which the rock surface level may vary by 2 m has been considered. (i.e. rock surface being shallower or deeper by 2 m from the current adopted interpretation).

5 SEISMIC REFRACTION SURVEY

The Seismic Refraction (SR) method is the most widely applied geophysical methodology to assist in geotechnical investigations particularly for measuring depth to bedrock and identifying weathered zones. The main objective of the SR method is to measure the P wave velocity (primary wave or compression wave or V_p). The key limitations of the SR method are:

- Unable to detect a weak layer below a stiffer layer;
- Unable to be done over pavement; and
- Affected by external noises such as traffic, rigs, rain, wind, and electrical radiation of high voltage powerlines.

The seismic refraction survey was conducted using a Geometrics Geode, 24 channel engineering seismograph. The following acquisition parameters were used with the seismograph:

- Sampling interval 0.125 ms; and
- Record length: 0.25 to 0.3 s.

In each seismic spread, twenty-four 4.5 Hz geophones, fixed to a "land streamer" Kevlar Band, were positioned at 2 m intervals and connected together via a 24 channel multi-core "take out" cable. All geophones were mounted on a specially designed base plate to best couple the geophones with the ground. Five seismic source positions were used for each 24 channel spread. Seismic energy was provided using a 9 kg sledge hammer striking a square metallic plate at every shot location.

The digitally acquired seismic data was processed using the commercially available SeisImager 2D software package by Geometrics.

6 MASW SURVEY

The MASW method measures variations in surface wave velocity (V_s) with increasing distance and wavelength and can be used to infer the rock/soil types, stratigraphy and soil conditions. The key limitations of the SR method are:

- The 2D sections are developed based on interpolation of 1D data; and
- Reliability of 2D data highly depends on spacing of the 1D profiles.

MASW data was collected using the same equipment as the SR survey (i.e. geophones mounted on a Kevlar Band "land streamer"). Data were collected at 6 m intervals, with the equipment being dragged after each data point location. The following acquisition parameters were used with the seismograph:

- Sampling interval 0.15 ms; and
- Record length: 2 to 4 s.

A 10 m offset was generally found to produce the "cleanest" looking dispersion spectra and was used during the MASW survey. MASW data was analyzed using SeisImager SW software by Geometrics.

7 BENEFITS OF A COMBINED SR/MASW APPROACH

The main advantage to use the two different investigation methods is that each method can constrain the other and each method is specially designed to measure different properties of the subsurface material:

- The SR will give information about the topography of the bedrock as well as provide an indication of the strength of bedrock.
- The MASW will provide information on the condition of the alluvium or any other surficial material overlying the bedrock. Moreover the MASW profile can directly be correlated to the stiffness properties of the subsurface material.
- Additionally, surveying using SR and MASW techniques together can be used to calculate small strain Young's and shear moduli, together with Poisson's ratio. These can be calculated by assumed density values for subsurface materials and using theoretical equations; and correlated with laboratory results from recovered core.
- As the data is captured continuously, a continuous profile of the rock level along the alignment can be produced by both methods. This is a benefit when compared to boreholes, as boreholes alone can often miss undulating rock levels.
- Additionally, to better capture the data along the bridge alignments, we proposed carrying out the geophysics survey prior to the borehole investigation, so that the borehole locations could be targeted based on any critical locations as interpreted from the geophysics results.

8 LIMITATIONS OF GEOPHYSICAL TECHIQUES

The limitations in SR are that the transition/difference between "sandy gravel" and "rock" can be difficult to interpret based on the P waves alone. To mitigate this, the SR readings are interpreted in combination with the field descriptions of the material on borehole logs and the MASW S waves to establish the soil and rock interface.

Both methods of geophysics require spread overlap to capture continuous data, as such at the edge of the investigation (where overlapping data is no longer available); there will be some loss in information. To mitigate this, the geophysics investigations were extended at least 30 m beyond the bridge abutments where accessible to ensure no key information is lost.

9 GEOPHYSICS RESULTS

In general, the quality of the recorded seismic traces was good and allowed picking of first breaks with little ambiguity. The reciprocal times differences, as a result, were generally low. Depth of penetration below ground surface of 15 to 40 m was achieved. Modelled P-wave velocities of subsurface material within this depth ranged from 300 m/s to 4000 m/s.

The measured S-wave velocities range from about 10 to 750 m/s. The S-wave velocity cross section is interpolated from 6 m spaced 1D profiles. Reliable measurements of S-wave velocity were obtained to a depth ranging from 15 to 25 m below ground level. The shaded area at the bottom of the cross section limits the effective depth of penetration of the MASW data.

Understanding of the site geology, correlations with borehole data, and past experience on relationship between P-wave velocity and proprieties rock have been used to best infer what the seismic P-wave velocities may represent in terms of rock properties along the survey line. The inferred rock level is plotted on the sections in Figure 3.

Rock level is defined as distinctly to slightly weathered, low to medium strength mudstone, sandstone and interbedded mudstone and sandstone. The top of this layer coincides approximately with the 2100 to 2300 m/s P wave velocity contour. The SR results indicated that the top of rock level undulates across the length of the site. On the southern side of the main creek channel, the rock level drops gradually from about RL -10 m at the southwest end to about RL -20 m towards the northeast. North of the main creek channel, the rock level is much lower and is inferred to be at about RL -20 m. As also illustrated in Figure 3, the SR results can provide a better accuracy of the inferred top of rock.

The MASW data is most effective at characterising the nature of the soils. Understanding of the site geology, correlations with borehole data, and past experience on the relationship between S-wave velocity and proprieties soils have been used to best infer what the seismic S-wave velocities may represent in terms of soil properties along the survey line. Inferred subsurface layers and their approximate positions are plotted on the section in Figure 4.

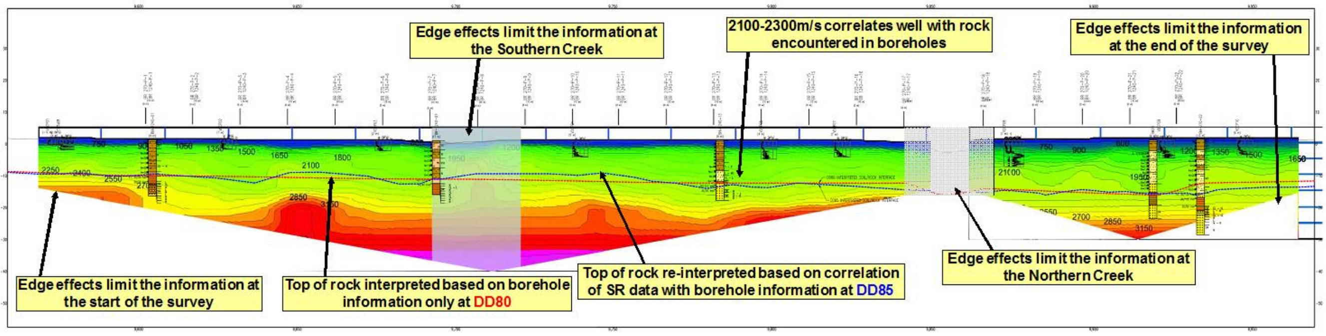

Figure 3. Saltwater Creek Rail Bridge - Top of rock interpreted based on borehole information only (DD 80) and re-interpreted based on correlation of SR results with borehole information (DD85)

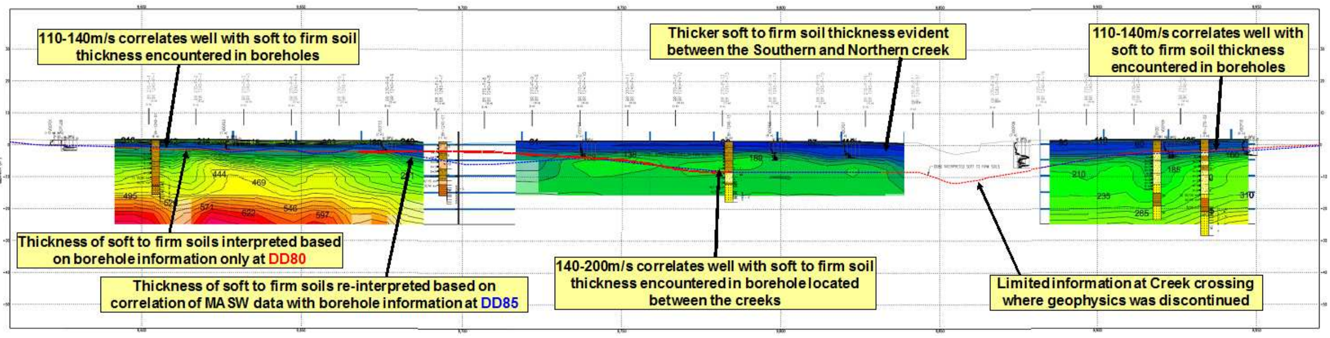

Figure 4. Saltwater Creek Rail Bridge - Inferred subsurface layers based on borehole information only (DD80) and re-interpreted based on correlation of MASW results with borehole information (DD85)

10 CORRELATIONS BETWEEN V_S AND N-SPT VALUES

Correlations between V_s and N-SPT values have been developed for the last half of century. Most of the researchers including Anbazhagan et al. (2012) utilised uncorrected N-SPT values in developing the correlation while Sitharam and Anbazhagan (2008) developed using corrected N-SPT values and obtained great correlation pattern. However, Uma Maheswari et al. (2010) reported that V_s predicted the corrected and uncorrected N-SPT values with comparable accuracy.

This paper evaluates the uncorrected N-SPT values obtained from available site investigations within the proximity of the MASW lines. The hypothesised empirical relationship used is a power-law relationship between the uncorrected N-SPT values and V_s as:

$$NSPT = (V_s/Y)^X \qquad (1)$$

where NSPT = inferred N-SPT values; V_s = measured S wave velocity; and X and Y = site specific parameters.

As described in Equation 1, X and Y are site specific parameters which can be assessed from a regression analysis. The regression analysis and the inferred N-SPT value results are illustrated in Figure 5 and 6 respectively.

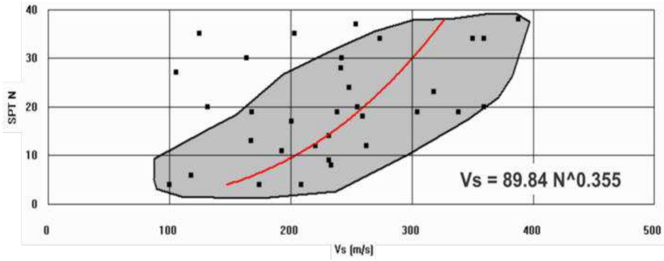

Figure 5. Regression Analysis

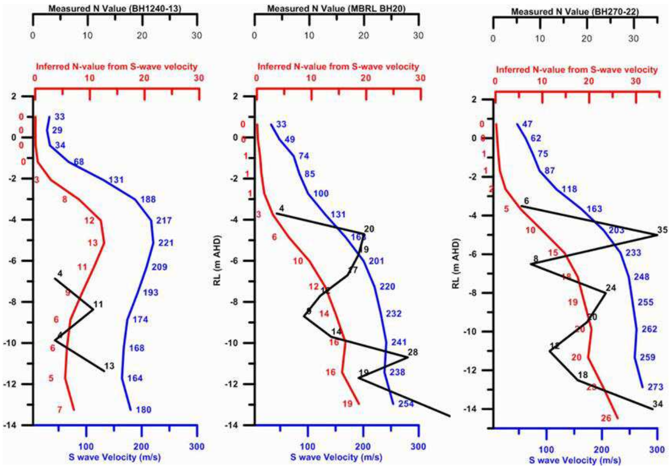

Figure 6. Inferred N-SPT values for Boreholes BH1240-13, BH20 and BH270-22

11 AS CONTRUCTED PILE TOE ELEVATIONS

The design considered that variations in founding level between predicted and as-built of around 2 m were possible, due to localised ground variations across the pier footprint. An overdrive allowance of 2 m was therefore provided for in pile lengths to account for this potential variation.

In general terms the as-built pile toe elevations were close to design pile toe elevations. Piers with a borehole at the pier location displayed a similar range of variation between design and as-built toe elevations, compared to those assessed using geophysical surveys.

Increased (however not significant) pile depth discrepancies were mainly noted in piles installed around the Saltwater Creek watercourse (Figure 7), where both conventional geotechnical boreholes and geophysical investigations were necessarily limited due to the presence of mangrove vegetation and narrow creek access.

The as-built pile records indicated that the actual pile toe levels are generally within ± 2 m of the design pile toe levels. Only at some pier locations, the actual pile toe levels deviate up to – 4 m. Considering the actual pile records, it is considered that the interpretation of geophysical surveys was quite successful and could provide meaningful geotechnical information for the design purposes.

12 CONCLUSIONS

The adopted site investigation technique using geophysical surveys and minimum borehole for the 325 m long Saltwater Creek bridges is the first site investigation approach undertaken in Queensland and probably in Australia. The use of geophysical investigation techniques in combination with a reduced number of 'conventional' geotechnical boreholes was effective in confirming ground conditions that allowed a satisfactory assessment of design pile toe elevations and pile capacity, for the ground conditions present at this site. As-built pile toe elevations were close to design pile toe elevations at each pier location for each bridge.

Figure 7. Saltwater Creek Rail Bridge and Shared Path Bridge - Piling.

The proposed site investigation methodology in combination with the proposed risk mitigations have been applied and have demonstrated the following key project aspects:

- A robust design process for the bridge driven pile foundation;
- A successful methodology to avoid the construction delay due the access issues; and
- A successful methodology to be more cost effective for the site investigation.

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