Sydney Metro - Site Investigation and Ground Characterisation for the Sydney Harbour Crossing.

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ABSTRACT: Sydney Metro is Australia's largest public transport project, extending 65 km from the northwest of Sydney, under the iconic Sydney Harbour, through the CBD and then towards Bankstown to the west. The harbour crossing is a key element of Sydney Metro. Limited geotechnical information existed prior to the project. As such, detailed geophysical and geotechnical investigations to facilitate early planning and design work were undertaken for three harbour tunnel alignment options, which would involve either full rock face excavation by Tunnel Boring Machine, mixed face Tunnel Boring Machine excavation or the installation of immersed tubes. Following best practice, extensive geophysical and geotechnical data has been collected to characterise the ground below the harbour floor, identifying possible geotechnical risks in tunnelling beneath the harbour.

1 INTRODUCTION

The Sydney Harbour crossing is a key element of Sydney Metro City & Southwest (Figure 1), which includes 15.5 km of twin tube running tunnels extending from Chatswood at the north through to Sydenham, south of the CBD. Limited geotechnical information existed about the harbour prior to commencement of the concept design. As such, detailed geophysical and geotechnical investigations to facilitate early planning and design work were undertaken on behalf of Transport for New South Wales (TfNSW).

The scoping, delivery management and interpretation of the ground investigation and the development of the tunnel alignment concept design was undertaken by the Technical Advisor (PB AECOM design joint venture) in collaboration with TfNSW over a number of stages, namely the Scoping Design, Definition Design and Reference Design. Three vertical design options were considered for the harbour crossing. These were predicated on full rock face excavation by Tunnel Boring Machine (TBM), mixed face TBM excavation or the use of Immersed Tube (IMT) technology.

Staged site investigations were conducted concurrently with the concept design phases, which allowed for their adjustment as the geological interpretation and concept design developed. The investigations included the use of both intrusive and geophysical techniques and were planned to characterise both the soil and rock formations below the harbour floor, assisting with their classification into geotechnical units. The interpretation of these units was critical to design development and the identification of the geotechnical risks that could be realised whilst tunnelling below the harbour.

The marine intrusive investigations included cored boreholes and cone penetration testing (CPT) completed from jack-up barges. Continuous sediment sampling, water pressure testing and in-situ stress testing within the rock mass were undertaken. Down-hole optical and acoustic televiewer and high-resolution scanning of recovered core were completed.

Marine geophysical investigation included staged seismic refraction and reflection surveys, magnetometer and side-scan sonar surveys, cross-hole tomography and resistivity survey.

This paper describes the site investigation and then discusses how the sampling was used to inform and influence the design development.

2 HISTORY OF TUNNELLING BELOW SYDNEY HARBOUR

Despite intense surrounding development, there are few tunnels beneath Sydney Harbour and Parramatta River.

The earliest recorded excavation below Sydney Harbour was associated with coal mining at Balmain (Figure 2). Mining commenced in 1897 with the excavation of a deep shaft to a depth of 895 m below sea level (bsl). From this shaft, excavation progressed east in order to mine the 1.5 m thick Permian Bulli Seam. Difficult ground conditions were encountered as a consequence of “creep conditions” (NSW Mines Report, 1970) and high groundwater ingress. Mining operations ceased in 1931 after which the site was converted to allow methane gas extraction. Following an explosion in 1945, the shafts were completely backfilled by 1957 with fly-ash from the nearby power plant.

Construction of a cable-tunnel across the harbour commenced in 1913. Situated 2.4 km west of the Sydney Harbour Bridge (Figure 2), this tunnel is around 550 m in length and was built to carry the cables that supplied power to Sydney’s northern network of tramways and railways. Construction of this tunnel was based on an investigation that consisted of only three marine boreholes.

The information gathered from one of these boreholes, drilled centrally within the harbour, is likely to have misled the designers into believing the rock level at that location was 25 m bsl. Subsequent boreholes confirmed that the rock depth was in fact 46 m bsl.

During the drill and blast construction of this tunnel, a “fissure” was encountered mid-way along the alignment. The fissure acted as a conduit to convey water and marine sediments to the tunnel heading. After many failed attempts to grout the fissure and stem the inflow, the central portion of the tunnel was abandoned and excavation of a new heading commenced in 1917. This new heading ended up being excavated some 15 m deeper than the lowest point of the previous failed heading.

Tunnelling was further delayed at two locations when significant geological structures and high groundwater flows were encountered. These features were eventually sealed allowing construction of the tunnel to be completed in 1922 with a 10 fold cost overrun (after Foster, 1985).

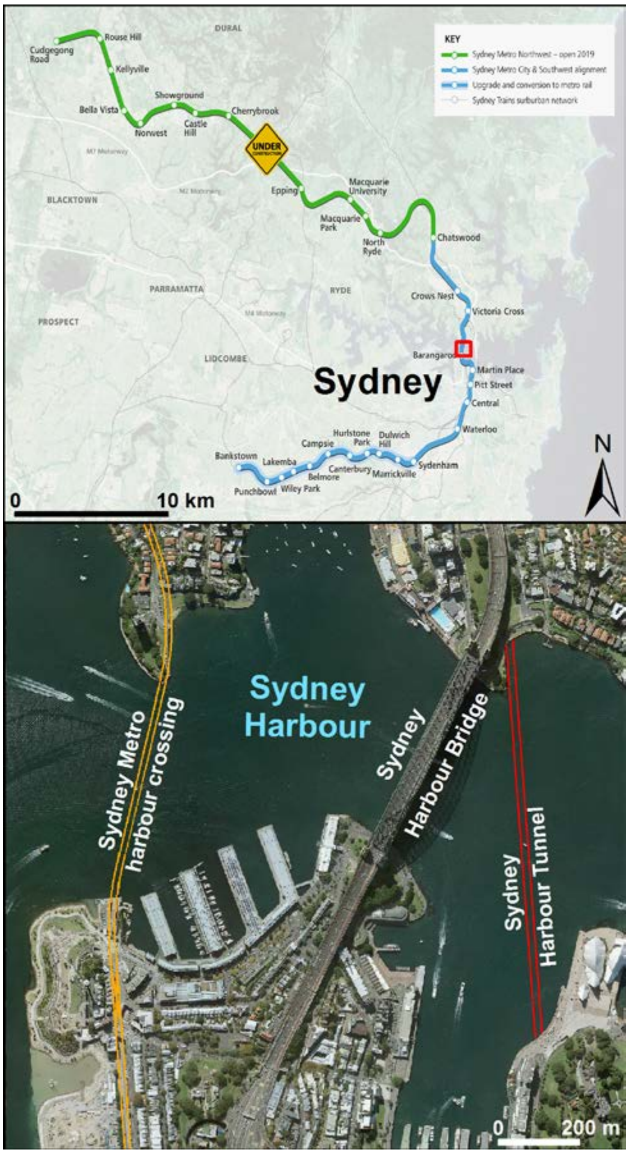

Figure 1. Sydney Metro alignment and harbour crossing plan

The landmark Sydney Harbour Tunnel is the only submarine tunnel below the harbour still in operation. This road tunnel crosses the harbour to the east of the Sydney Harbour Bridge (Figure 2) and was constructed as an “in-harbour” (Foster, 1985) IMT, which involved dredging of estuarine sediments to create a trench in which the precast tunnel elements were submerged and placed. This approach was selected to avoid issues associated with connecting to a bored tunnel that could have potentially been constructed to depths greater than 45 m below “sea level”, as well as avoid geological unknowns (Gomes, 1991).

3 REGIONAL GEOLOGY

The project area lies within the geological region known as the Sydney Basin. During the Permian and Triassic Periods (298 to 200 million years ago), the Sydney Basin was infilled with a thick sequence of sediments deposited in both fluvial and marine conditions.

The minor deformation and warping of the basin that occurred at the end of the Late Triassic and a period of tectonic activity from Jurassic to the Palaeogene, contributed to the formation of joints and faults and the intrusion of igneous dykes (Och *et al.*, 2009).

Major river systems eroded these structural weaknesses to form deeply incised valleys through the uplifted eastern margin of the basin. Sea level rise in the Pleistocene resulted in sediment infilling these valleys.

A second period of lower sea levels resulted in the erosion of most of the Pleistocene valley infill, apart from the upper portions of the valleys.

The last Holocene sea level rise resulted in the infilling of the valleys with Holocene sediments. These sediments are underlain by Pleistocene sediments.

The dominant geological units present along the intended Sydney Metro harbour crossing are shown in Figure 2 and comprise the following (Herbert, 1983): anthropogenic fill (reclaimed areas generally adjacent to the harbour), Holocene sediments, Pleistocene sediments, residual soils and Hawkesbury Sandstone (medium to coarse grained quartz sandstone).

3.1 *Local geological conditions*

The first geological publication about Sydney Harbour was by Laseron (1947), who completed a study on the dredged sediments within the eastern part of Sydney Harbour and established a faunal association within dredged sediments.

Lean (1973, 1976 and 1978) carried out the earliest geophysical survey of the western side of Sydney Harbour Bridge, including Darling Harbour and Garden Island Naval Dockyard. Notably, this survey was not correlated with overwater boreholes.

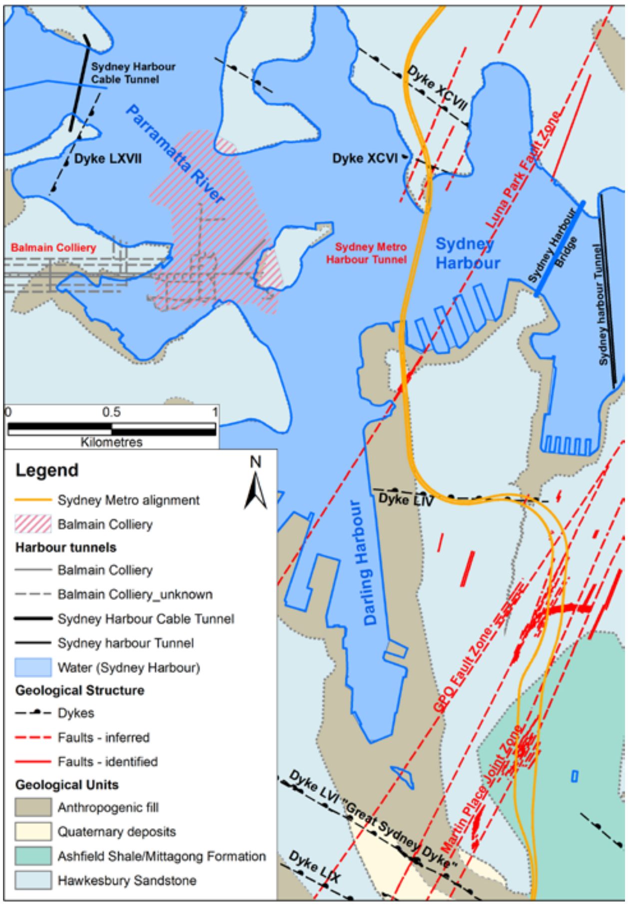

Figure 2. Sydney Harbour geological map (after Herbert, 1983) indicating under harbour crossings.

Roy (1983) carried out a high level review of the entire Sydney Harbour for the Sydney Geological Sheet Explanatory Notes (Herbert, 1983) and produced many geological sections of Sydney Harbour. These sections included information at Gladesville, Iron Cove and Garden Island. The geological section between Millers Point and Blues Point, relevant to the proposed Sydney Metro tunnel alignments, was based on the geophysical reflection survey of Lean (1973).

A description of the sedimentary sequence within the Port Jackson area of the Sydney Harbour is provided by Roy (1983).

Pleistocene sediments were only encountered within the harbour palaeovalleys. These sediments generally comprise stiff clay, sandy clays and minor sand, shell hash, peat and charcoal layers, and are generally over-consolidated (identified as Units 3, 4 and 5 in this paper). A thin crust of desiccated sediments may also be present at the interface with the overlying Holocene sediments.

Roy (1983) notes that Holocene reworking of southern Pleistocene aeolian sand deposits, may be associated with 15 m to 20 m thick deposits of muddy sand, on the southern side of Sydney Harbour, east of the Sydney Harbour Bridge.

Holocene sediments are present in the palaeovalleys and form the upper bulk of the known valley fill comprising mainly sandy sediments, with mud (clay and silt) layers and abundant shells, overlain by a surface layer of fine grained sediments (identified as Unit 1 in this paper).

Harris *et al.* (2001), as part of a greater harbour study, compiled the work of Lean (1973) with other geophysical data and presented an interpretation of the rock levels below Sydney Harbour (Figure 3).

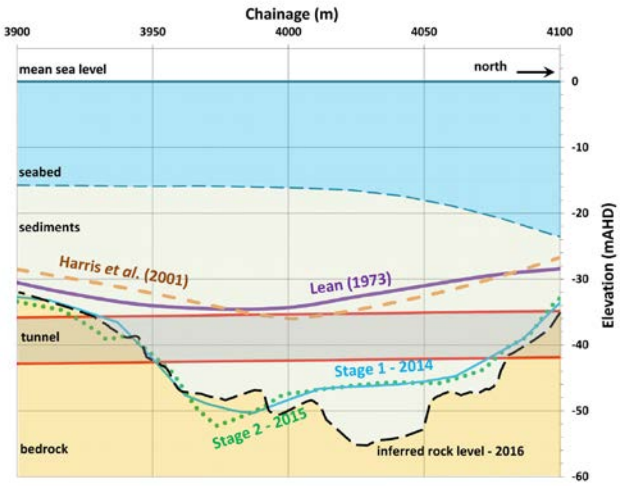

Figure 3. Rock level interpretation below Sydney Harbour

As part of the Sydney Harbour Tunnel project, 15 marine exploratory holes were completed east of Sydney Harbour Bridge. The results were interpreted by Pells and Wong (1990). The sediments on the southern half of the crossing are described mainly as firm to stiff high plasticity clays (up to 20 m thick) overlain by stiff to very stiff low to medium plasticity clays and sandy clays (up to 5 m thick), inferred to date from the Pleistocene (correlating to Unit 3 as described in Section 3 of this paper). On the northern side, these sediments were interpreted to have undergone channel erosion, then been backfilled during the Holocene with sand, peaty sand and silty sand of variable density (identified as Unit 2 in this paper). These deposits are draped by up to 5 m of very loose muddy sands with shells (identified as Unit 1 in this paper). The top of the Hawkesbury Sandstone is interpreted to be at approximately 45 m below Australian Height Datum (AHD).

4 GEOTECHNICAL AND GEOPHYSICAL SCOPE

During the initial Scoping Design phase of the City & Southwest section of the Sydney Metro project, several harbour crossing running tunnel alignment options were developed. The vertical alignment of the tunnels was critical as it would potentially govern station depths north and south of the harbour and tunnelling methodology. Based on the rock levels inferred by Harris *et al*. (2001), initial options placed the tunnels entirely within sandstone (Figure 3). Consequently, the initial scope of the marine ground investigations focused on understanding the rock mass conditions (Table 1), which later was broadened to investigate the seabed sediments as described in the following sections.

Table 1.Scope of ground investigation below harbour

Stage	Expected Conditions	Scope
Scoping Design	Palaeovalley Hawkesbury Sandstone	12 cored boreholes Stage 1 geophysics
Definition through to Reference Design	Deeply incised palaeovalley	23 cored boreholes to -80 m AHD, in water depths of 14 m to 23 m 30 CPTs (7 followed by coring) 4 stages of geophysics Additional laboratory testing in sediments

4.1 *Geophysical investigations*

The geophysical surveys completed at each stage are summarised in Table 2.

The bathymetric data suggest that the seabed floor is relatively flat, at a typical elevation of -16 m AHD, with the exception of a channel to -26 m AHD north of the harbour, which connects with a -48 m AHD deep depression feature east of the alignment. This feature was identified in 2014 by the Port Authority of New South Wales during a multibeam echosounder survey.

Stage 1 reflection survey results suggested a 150 m wide north-east trending palaeovalley to a depth of -50 m AHD, overlain by 30 m of marine sediments (Figure 3). This valley appears to be steep to the north and gently sloping to the south. Boreholes were located to target this channel, one of which revealed the rock level to be at -60 m AHD east of the proposed tunnel alignments (Figure 3).

Based on an evolving understanding of the rock level below the harbour, the design team needed to re-evaluate the alignment design concept through the harbour. It became apparent that an alignment that remained in rock would drive deeper station depths both sides of the harbour, detrimentally impacting on station operational performance.

Table 2. Summary of harbour geophysical surveys

Stage	Date	Method
1	Dec 2014	Bathymetric survey, Side-scan sonar, seismic reflection (50 m line spacing), seismic refraction (30 m line spacing), magnetometer survey
2	May 2015	Additional seismic reflection (15 m line spacing)
3	June 2015	Down-the-hole tomography
4	August 2015	Additional seismic refraction (20 m line spacing)
5	June 2016	Resistivity survey and digital integrated ground model

Therefore, shallower alternative alignments were considered that would either require a short section of tunnelling through marine sediments with sections of mixed face conditions or an IMT placed on the harbour floor.

Consequently, three additional rounds of geophysical surveys (Stages 2, 3 and 4) were undertaken to focus on areas where the rock level was interpreted to be deeper than expected, based on the results from the Stage 1 geophysical and initial boreholes (Figure 3 and Figure 4). Refraction data from Stage 1 was reinterpreted to provide more information on the soft/loose surface sediments.

The Stage 3 geophysical survey consisted of cross-hole seismic tomography between two boreholes that staggered the alignment, to better define the underlying geological structure and the morphology of the buried palaeovalley.

By the Definition Design stage, the decision had been reached, for reasons of operational performance, to align the tunnels through the marine sediments. The reasons for this selection are discussed in further detail in Section 7 of this paper.

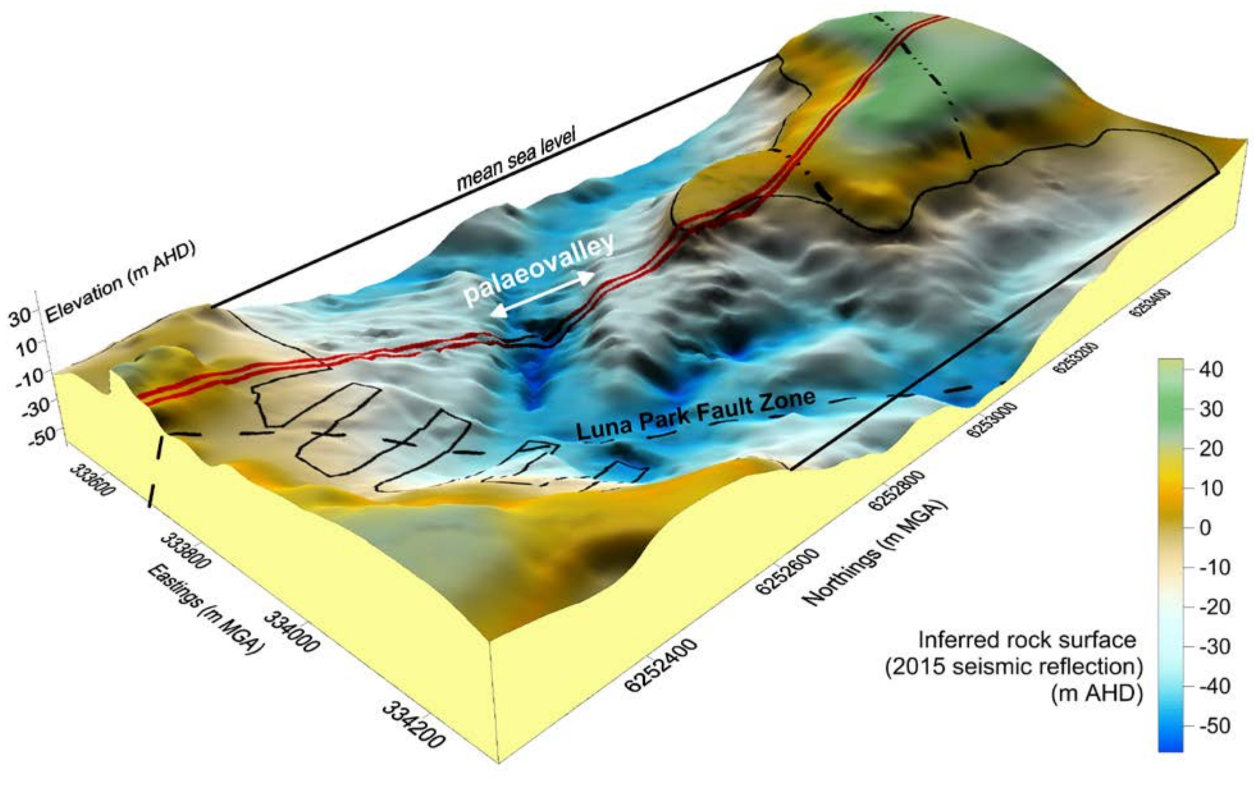

Figure 4. Palaeogeographical rock surface from Stage 2 Seismic Reflection Survey (projected alignment in red)

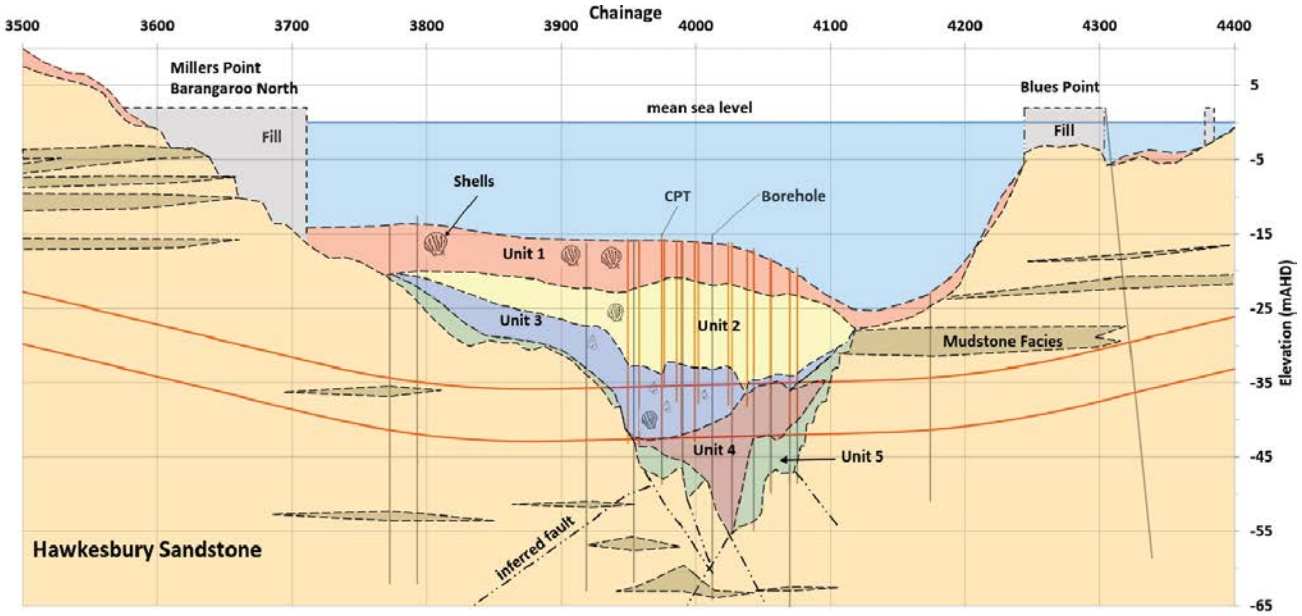

Figure 5. Interpretative geological long section of the conditions along the proposed harbour crossing

The Stage 4 seismic refraction survey was undertaken at a reduced line spacing based on the selected final alignment and the reflection data was reinterpreted using the additional CPT and borehole data.

Additionally, a resistivity survey (Stage 5) was carried out along the finalised alignment and at the soil/rock interface with a long and short cable.

The data was combined to create an integrated ground model. The southern extent was found to match earlier models (Figure 3). However, to the north the rock profile is interpreted to be deeper.

4.2 *Geotechnical investigations*

The geotechnical investigations completed for the project are summarised in Table 1. The location of the boreholes and CPTs were largely selected to correlate the results from the geophysical survey. When it became apparent that the running tunnels would need to align through the marine sediments, the focus of the intrusive testing was widened to encompass a greater range of testing within the marine sediments. In particular the information from this testing would be critical in assessing the feasibility of excavation by TBM through the marine deposits.

The boreholes and the CPTs were carried out from two jack-up barges, down to -80 m AHD. The position of the completed boreholes and CPTs were severely constrained by the combination of the marine traffic, water depths, thickness of soft/loose sediments and the length of the jack-up legs.

The following in-situ testing was carried out within the sediment:

- Standard Penetration Tests (SPTs);
- continuous sampling with a Denison Sampler (double-core barrel) in four boreholes; and
- dissipation tests in some of the CPTs.

5 HARBOUR GEOLOGICAL MODEL

5.1 *Palaeovalley Description*

The deeply incised palaeovalley (Figure 4) discovered during the geophysical and geotechnical survey is interpreted to have the following characteristics close to the proposed tunnel alignment:

- north-west to south-east axis orientation;
- maximum width of approximately 160 m;
- maximum depth of around - 56 m AHD; and
- deepest infill thickness of 38 m.

5.2 *Unit Summary*

For the purpose of developing the concept design, the sediments have been characterised into five distinctive units. These units are summarised in Table 3 along with the corresponding radiometric ages in Table 4.

Table 3. Summary of sediment units

Unit	Depth below seabed (m)	Maximum Thickness (m)	Description
1	0.0	12.5	Loose sands and soft silty clays with shells
2	2.7-10.6	15.0	Well-sorted sand, some silty interbeds with shells.
3	1.6-17.5	18.0	Clays/silty clays with shells.
4	16.3-33.0	15.0	Interbedded silty sands and silty clays.
5	10.5-42.0	5.0	Colluvium

Table 4. Radiometric ^{14}C age dating

Unit	Elevation (mAHD)	^{14}C Age Dating
1	-20.0	39 Ka
2	-23.5	22 Ka
3	-34.5	24 Ka to 50 Ka
4/5	-41.0 and -50.0	30 Ka to 63 Ka

5.3 *Unit Distribution*

Figure 5 presents the interpreted longitudinal section along the running tunnel alignment.

Figure 6 below shows the number of Sydney Metro boreholes and CPTs that encountered each of the defined soil units plotted against elevation at intervals of one metre.

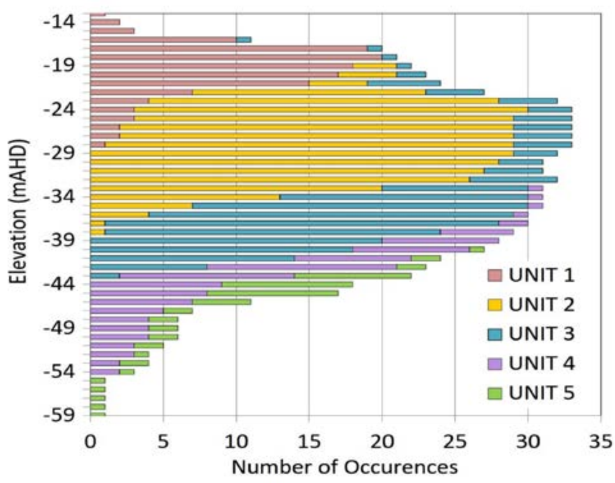

Figure 6. Number of borehole and CPT per unit against depth

5.4 *Unit descriptions*

The soil encountered during the site investigation has been divided into five geotechnical units, which are described below.

Unit 1 forms the present seafloor to a depth of 11 m and covers all the sediments along the alignment. This loose/soft layer consists of clayey silt (50%) interbedded with fine to medium silty sand (50%) with shells. They are considered as Holocene; the age dating would then be indicative of disturbance (Table 4).

Unit 2 consists of medium dense to dense, medium grained sand (70%) that is relatively clean and well sorted (Figure 7). There are several shell hash horizons, trace fine quartz gravels, charcoal and organic matter. This unit is up to 17 m in thickness, thinning out towards the north. Based on age dating, deposition occurred during the Pleistocene (Table 4) in an estuarine environment.

Unit 3 consists of a firm to very stiff clay and silty clay (80%) with some interbeds of sandy fines and shells (Figure 7). This unit is up to 18 m thick and thins out at the northern part of the alignment. Age dating indicates, deposition occurred over an extended time during the Pleistocene (Table 4) in an estuarine environment.

Unit 4 consists of silty sand (70%) with interbeds of silty clay (20%) and includes sub-rounded gravels, charcoal layers and wood fragments (Figure 7). This composition suggests that the depositional environment could be a fluvial system along the ancient Parramatta River during the Pleistocene, with some sediments of colluvial origin from the upper slopes of the incised valley (Table 4). From the CPT data, the sand is interpreted to be typically dense to very dense interbedded with stiff to very stiff clay as defined in Figure 8.

Unit 5 is interpreted as colluvium, deposited over an extended time during the Pleistocene (Table 4 and Figure 7). This layer is composed of cohesive “dirty” sands (70%) interbedded with fines (30%) and with sub-rounded to angular cobbles and boulders of sandstone, charcoal and wood fragments. CPT and laboratory classification results indicate the soil component to be similar to Unit 4. The occasional residual soils are incorporated in Unit 5 material.

6 UNIT CHARACTERISATION

The separation of the sediments into the five units was largely based on the following information: geological logs, sample descriptions, presence of shell and organic matter, Denison Sampler log descriptions and photos, CPT Soil Behaviour Types, seismic refraction velocities, laboratory classification testing and advanced laboratory testing (i.e. ^{14}C radiometric dating, Multisensor Core Logger, HyLogger, X-Ray diffraction).

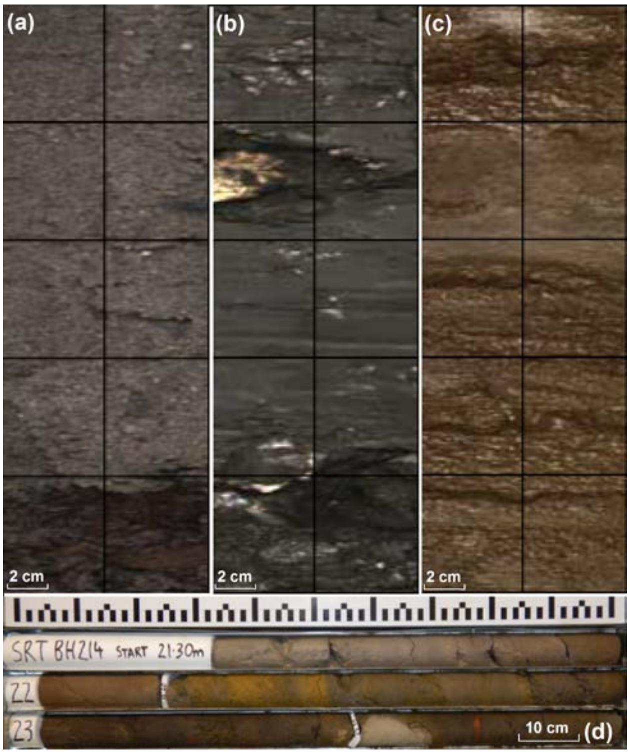

Figure 7. (a) Unit 2 with organic matter at bottom (b) Unit 3 with shells (c) Unit 4 (d) Unit 5 with a sandstone cobble at 23.6 m

6.1 *Geophysical characterisation*

The very soft silt and thicker silty clay beds define a seismic refraction velocity boundary of <1600 ms^{-1} for Unit 1. The overall interpreted sand horizon of Unit 2 was characterised with seismic velocities of 1600 ms^{-1} to 1800 ms^{-1}.

6.2 *Laboratory soil classification testing*

For sediment classification purposes, the Particle Size Distribution and Atterberg Limits were determined.

Grading curves were determined on 82 samples with a combination of sieving and hydrometer (for particles passing the 0.075 mm sieve) (Figure 8). These are shown for Units 3, 4 and 5, and on a ternary diagram below (Figure 9).

The Atterberg Limits (Figure 10) tend to show that Unit 1 and 3 materials generally have medium to high plasticity. Some low plasticity values were recorded, but these are likely to be due to some sandy layers within the unit. This high plasticity is consistent with the presence of clay minerals identified by X-Ray diffraction. Unit 4 and Unit 5 were grouped due to their similarity and the limited data associated with each unit. These units are typically low to medium plasticity.

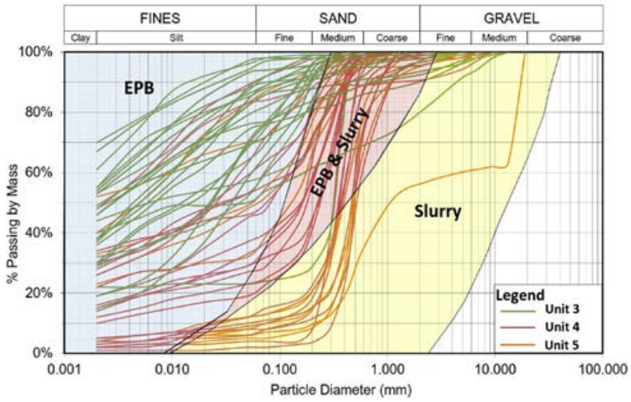

Figure 8. Particle size distribution plot for Closed Face TBMs (*after* Pennington, 2011)

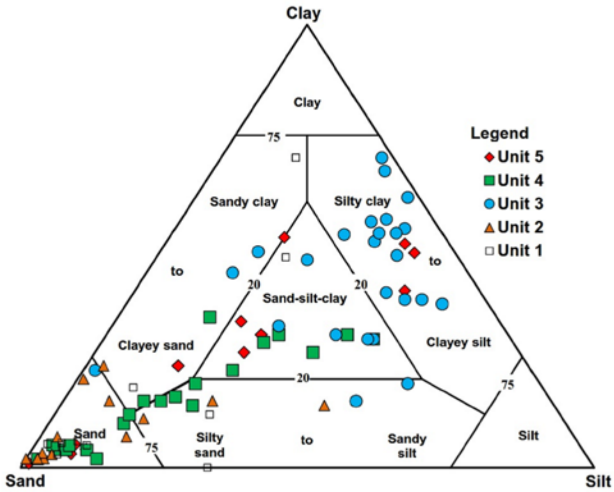

Figure 9. Clay-Sand-Silt Ternary Diagram per unit

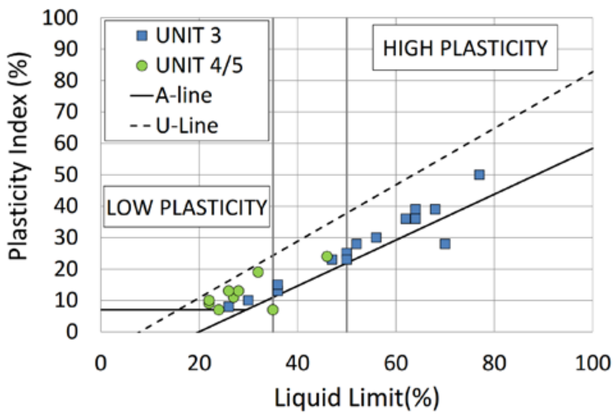

Figure 10. Atterberg Limits

6.3 *Cone Penetration Testing*

The cone penetration resistance and friction resistance were correlated with the boreholes.

The normalised Soil Behaviour Type (SBTn) plots developed by Robertson (2010) were then used to classify the CPT data. The distribution of SBTn for each of the units is showed on Figure 11 and Table 5. This classification suggest that Unit 1 will behave predominantly as sand and silt mixtures, Unit 2 as a sand, Unit 3 as a cohesive material and Units 4/5 as sand and sand mixtures.

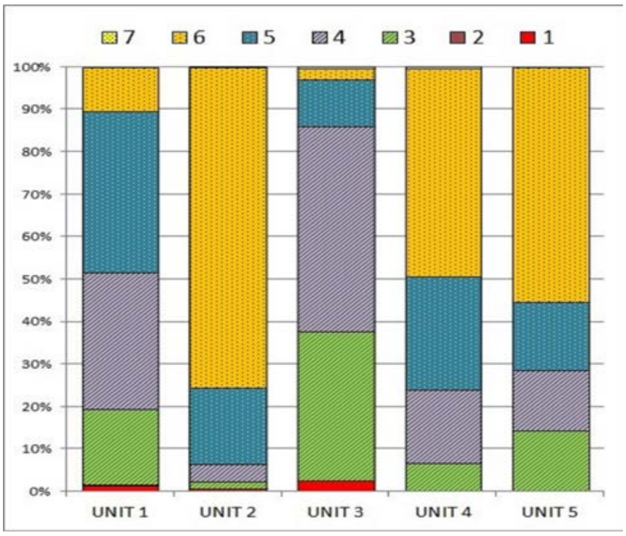

Figure 11. Normalised Soil Behaviour Types per Unit

Table 5.Soil Behaviour Types (Robertson, 2010)

SBT	Description of behaviour
1	Sensitive fine-grained material
2	Organic soils - PEAT
3	CLAY: CLAY to silty CLAY
4	SILT mixtures: Clayey SILT to silty CLAY
5	SAND mixtures: Silty SAND to sandy SILT
6	SAND: Clean SAND to silty SAND
7	Gravelly SAND to dense SAND

7 IMPACT OF HARBOUR GROUND CONDITIONS ON ALIGNMENT DESIGN

During the assessment of the three tunnelling strategies for the harbour crossing, the following issues were given consideration.

7.1 *Immersed Tunnel option (IMT)*

The adoption of an IMT approach offered the opportunity of a shallow rail alignment, which would introduce a number of rail and station operational benefits. However, as the station design progressed at Barangaroo and North Sydney, it became apparent that factors (e.g. rock cover and the provision of space for plant and equipment) other than tunnel grade, were dictating station depths.

Further, the results of contamination testing revealed the presence of raised levels of mercury within the upper marine sediments. These would be disturbed by the dredging works associated with an IMT approach. Factoring in the construction cost differential associated with IMT in addition to the described issues ultimately led to the decision to discard this IMT solution.

7.2 *Deep TBM alignment entirely through rock*

The option to select a TBM alignment entirely through Hawkesbury Sandstone would force the future stations at Barangaroo and North Sydney to be deeper than necessary due to the grade of the rail track alignment. It was judged that the only key advantage of a deep alignment option would be a simplification of tunnel construction, as it could introduce opportunity to use an open face type of TBM. However, based on the geotechnical model developed, it is expected that even a comparatively deep alignment through rock would encounter highly fractured fault zones (Figure 5) below the palaeovalley with possible hydraulic connectivity to the harbour, potentially necessitating closed face TBM technology regardless. The TBM would possibly require treating the ground ahead of the advancing face. Given the impacts to the final operational performance of the metro and the limited benefits to construction this option was discarded.

7.3 *Shallow TBM alignment through rock and marine sediments*

The selection of this option would involve tunnelling predominately through sandstone, with soft ground and mixed face tunnelling over a comparatively short section of the alignment. This will require TBM technology that can cope with both rock and soil conditions. An assessment of the results from ground investigation, anticipated groundwater pressures and review of the developed geotechnical model (in particular the classification of the marine deposits - Figure 8) led the design team to conclude that the use of a closed face slurry TBM would be feasible.

Furthermore, the selection of a mixshield type TBM that uses 'air bubble' technology within the slurry mix could allow accurate face pressure control through the expected marine sediments. Given that this option would permit the selection of the optimum rail alignment with no detrimental impact on station depth, this option has been selected to form the basis for the finalised concept design and the mandated final alignment. The selection of this option also took into consideration issues such as TBM drive strategy, program and site availability.

The risks associated with tunnelling through soft sediments and transition mixed face zones are considered to be manageable. Nonetheless, a number of construction risks identified by the Technical Advisor will need further consideration beyond the concept design stage. These include the following:

- management of face pressures through marine sediments to prevent a TBM blow-out condition being realised;
- management of TBM cutters resulting from their accelerated wear through mixed face conditions;
- confirmation of rock cover above cross passages between running tunnels to enable their mined excavation; and
- potential need for ground treatment to mitigate geological risk.

8 CONCLUSION

A staged approach towards undertaking intrusive and geophysical ground investigation of the harbour provided the opportunity to best tailor the investigation to suit an evolving understanding of the geotechnical model and consequential changes to the design development. Moreover, the establishment of an integrated design team with the combined responsibility of managing the ground investigation and undertaking the design ensured that the adjusted alignment design drove the investigation requirements and that the ground investigation yielded information that was critical to undertaking constructability assessments.

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