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Sydney Metro site investigation for the Sydney Harbour tunnel crossing

N. J. C. Byrne[1], and D. J. Och[1,2].

[1]WSP|Parsons Brinckerhoff, Level 27, Ernst & Young Centre, 680 George Street, Sydney NSW 2000, Australia; PH +61 2 92725310; email: NByrne@pb.com.au
[2]School of Biological, Earth and Environmental Sciences, University of New South Wales, Australia email: DOch@pb.com.au

ABSTRACT

Sydney Metro is Australia's biggest public transport project. Stage 2 of the program, the Sydney Metro City & Southwest project, will extend metro rail from Sydney's North West, under Sydney Harbour, through new underground CBD stations and beyond to the South West. A critical element of this project is tunnelling beneath Sydney Harbour. At the commencement of the concept design development, very little geophysical, geological and geotechnical information was available that covered the area of interest in Sydney Harbour. The harbour geology was therefore identified as a critical design risk, and geological information was urgently required to inform the tunnel and track alignment designs. The metro alignment and tunnelling approach were progressively refined during the site investigation stages, as the geological model was developed. This paper summarises the site investigation stages (desktop analysis, geophysical testing, cone penetration testing and boreholes with HQ coring) and describes the implications for the design development of both the tunnel alignment and metro stations, as the harbour geological model was established and refined. It highlights the importance of good coordination between all design disciplines and the geotechnical team during the site investigation process, to ensure that both the site investigation is adequate for the design and that the design can capture and guide the site investigation.

Keywords: Sydney Harbour, site investigation, geophysics, paleovalley

1 INTRODUCTION

The Sydney Metro City & Southwest will consist of two 15.5 km rail tunnels running from Chatswood to Sydenham. At the commencement of the Scoping Design phase for Sydney Metro City & Southwest, it was anticipated that the tunnels would be driven through rock using tunnel boring machines. A critical element of this project is the Sydney Harbour crossing, between Blues Point, on the North Shore and Walsh Bay at the north of the Sydney CBD (Figure 1).

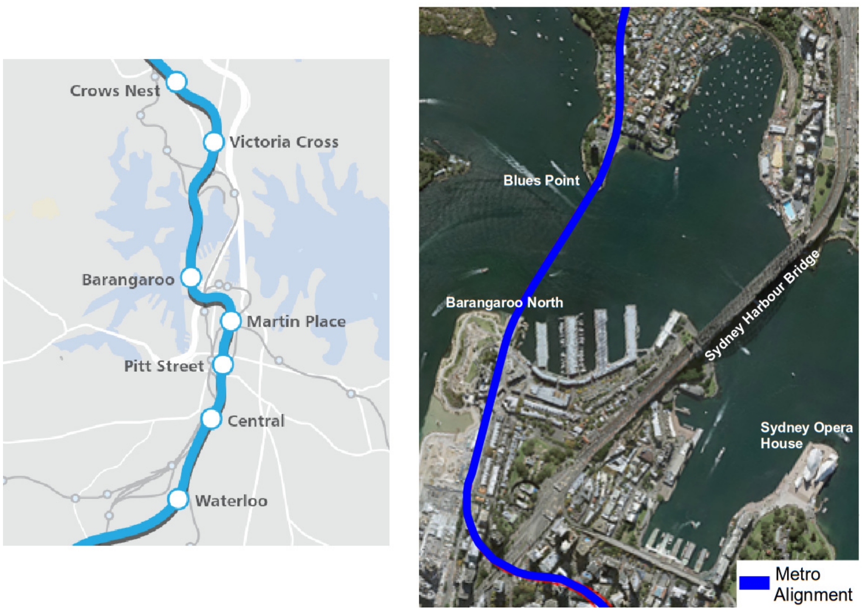

Figure 1. Location plans: City section of Sydney Metro tunnel alignment & harbour crossing alignment between Barangaroo North and Blues Point.

Parsons Brinckerhoff and Aecom formed a design joint venture (PBAJV) and were engaged as the technical advisors for Transport for New South Wales (TfNSW) on the Sydney Metro City & Southwest project in 2014. The objective was to develop a Scoping, Definition and finally a Reference Design for the Sydney Metro City & Southwest, connecting to Sydney Metro Northwest at Chatswood

At the commencement of the Scoping Design, the Desktop Study highlighted a lack in previous geotechnical data that covered this part of Sydney Harbour, and therefore identified the need for a phased geotechnical investigation to adequately inform the Sydney Metro Design. One stage of geophysical testing and one stage of over water borehole drilling was planned for the harbour area in order to develop a geological model to inform the scoping/reference design.

This paper presents the development of the geological model for the tunnel alignment beneath Sydney Harbour as additional geotechnical investigation stages were performed. A series of potential alignments were investigated that attempted to take best advantage of the sea bed and bedrock profiles in order to minimise the depth of the running tunnel alignment level, to ensure that the station platforms could be located as shallow as possible. This paper reflects on how the progressive site investigation results allowed continued refinement of the geological model, and how the tunnel alignment design was refined to accommodate the development of the geological model. Furthermore it discusses how continual design re-assessments and constant communication between the geotechnical and track/tunnel design teams was required during the site investigation to relocate and refine borehole test locations to ensure an adequate site classification was achieved.

2 STAGES OF SITE INVESTIGATION AND DESIGN IMPLICATIONS

2.1 Scoping design stage

A key design objective for the project was to minimise the station platform depths below street level as the depth of platform impacts on the total passenger travel time from street to platform. A general principal for the station design was that a concourse level deeper than 35 to 40 metres below street level would reduce ease of use of the station for the customer.

An existing design constraint that influenced the station depth at Victoria Cross Station (North Sydney) was the rapid topography level change between Sydney Harbour and North Sydney (Figure 2), rising approximately 70 to 80 metres above sea level at North Sydney. The metro trains are designed to operate at a maximum gradient of 4.5%, which limited the vertical change that could be achieved over a specific length of track, (note that in comparison Sydney Trains rolling stock are typically limited to an ultimate maximum gradient of 3.3%).

As the preferred location for Victoria Cross Station had been identified, and the distance between the tunnel’s inflection point (deepest point) beneath the harbour and the Victoria Cross station was fixed (approximately 2.5 km), the tunnel’s deepest point beneath the harbour would directly impact on the Victoria Cross Station depth, as depicted in Figure 2.

The following criteria governed the vertical alignment for the Sydney Metro tunnels:

- A maximum grade of 4.5% on straight track and compensated horizontal curvature (i.e. flatter grade for a tighter horizontal curve).
- Minimum total cover above tunnel crown (rock + sediments) of 1.5 tunnel diameters (i.e. 11.0 m).
- Minimum rock cover above crown of 1.0m.
- 7.0 m diameter tunnel with tunnel crown 5.5 m above rail level.

The initial design study that assessed the harbour crossing, had a direct route from Martin Place Station to Victoria Cross Station, and was based on an initial geophysical survey of Sydney Harbour by Lean (1973) which was refined by Harris et al. (2001). It also referenced sections that profiled areas in Sydney Harbour in the Sydney 1:100,000 scale Geological Sheet Explanatory Notes of Herbert (1983).

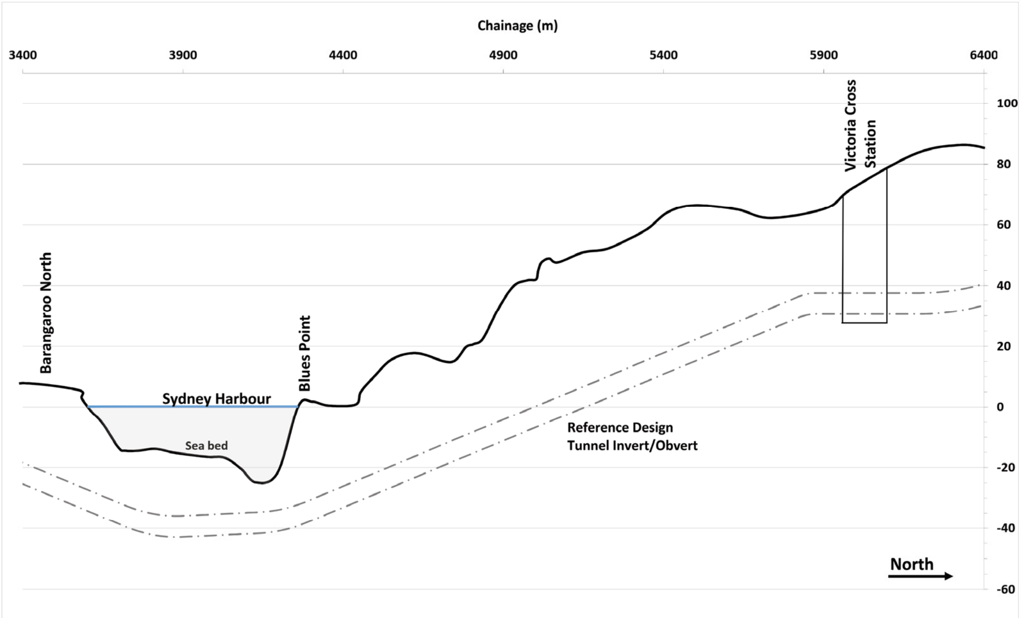

Figure 2. Section between Barangaroo and North Sydney which shows the substantial ground level change between Sydney Harbour and the Victoria Cross Station (North Sydney).

A top of rock contour model was developed from the Lean (1973) information and geological long sections were cut from this model. These sections were used to develop an early version of the Scoping Design tunnel vertical alignment. The deepest rock level, along the proposed alignment, inferred from the Lean (1973) data was approximately RL -34.5m AHD. The tunnel alignment which maintained the required rock cover resulted in the Victoria Cross Station platform level being located some 35 metres below street level.

During the Scoping Design in 2014, the Sydney Metro design technical advisor coordinated a project specific geophysical investigation to refine the available geophysical information. This geophysical survey covered an extended zone reaching from the Sydney Harbour Bridge in the east, to Goat Island in the west. The large area was surveyed to allow for the assessment of multiple alignment options to find the most suitable tunnel alignment.

The initial geophysical survey included:

- Echo sounding/bathymetric survey to provide a map of sea bed levels, and to provide accurate sea bed levels for the seismic survey results
- Side scan sonar survey to map sea bed features
- Marine magnetometer survey to locate ferrous objects over the investigation area and to attempt to delineate geological features such as faults or dykes
- Seismic reflection profiling survey to map subsurface layers across the site to assess geological conditions, in particular the depth to top of rock, and allow spatial coverage to produce a bedrock contour plan
- Seismic refraction survey focused on Scoping Design alignment to map the subsurface seismic velocity distribution to confirm the depth to rock and identify any significant variations in seismic velocity to at least 20 m below top of rock.

The geophysical investigation defined the palaeogeographical rock surface (2014 inferred rock level) and identified the existence of a NW to SE trending palaeovalley crossing the scoping design alignment approximately 11 metres deeper than indicated by the earlier geophysical data. Thus, in order to maintain the 7 metre rock cover for the tunnel crown, as required by the design criteria, the Scoping Design vertical alignment would have to be lowered by 11 metres. The Victoria Cross platform level would have to be lowered by a similar amount.

The project team was encouraged to investigate alignments that would maximise customer outcomes and reduce the depth of the station platform depth approximately 45 m below street level back to the target station depth.

In an attempt to restore the Victoria Cross station depth to the original design level, the geotechnical and track design teams investigated approximately 12 different tunnel alignments based on the revised palaeogeographical rock profile yielded by the geophysical investigation. An additional station at Barangaroo was also included in the project at this stage and hence the tunnel alignment was adjusted to incorporate this new station.

An alignment option slightly further west than the Scoping Design alignment focused on an inferred palaeogeographical rock surface which was approximately 2 m shallower than along the original alignment. Other tunnel alignment changes were also incorporated to reduce the Victoria Cross station depth which included increasing the tunnel length with a sweeping curve north of the harbour and moving the Victoria Cross station 150 metres north. The adoption of these opportunities and focusing on the alignment option with shallower rock allowed the platform depth at Victoria Cross to be lifted to approximately 40 m below street level.

2.2 Definition design geotechnical investigation

Following the Scoping Design, the Sydney Metro design team began the Definition Design and coordinated the development of a geotechnical investigation which included a suite of marine borehole investigations, which were commenced in April 2015. The marine investigation incorporated the revised tunnel alignment and the borehole locations were planned to target geophysical refraction velocity anomalies observed in the inferred rock contours.

The initial boreholes close to the shore on both the southern and the northern side of the harbour crossing correlated well with the geophysical investigation, with encountered rock levels very closely matching the rock levels predicted from the geophysical investigation. Surprisingly some of the boreholes located in the area of the identified palaeovalley encountered rock substantially deeper than anticipated from the geophysical model.

The boreholes encountered rock between 5 and 10 metres deeper than inferred on the geophysical interpreted palaeogeographical surface. The results led to the postulation that an incised valley existed within the palaeovalley perpendicular to the design alignment, which accounted for the substantial rock depth change observed. Such a structure was comparable to upstream valleys formed within Hawkesbury Sandstone rock materials that are currently visible across the Sydney region today.

Due to the unexpected borehole results, regular discussions between the site investigation and geotechnical design teams were required. As each borehole result became available, the information was incorporated by the geotechnical design team into the developing geotechnical model. Each additional result was used to inform and refine the selection of the remaining test locations to ensure a thorough and optimised site investigation was completed.

As a result of rock levels encountered in the marine boreholes being deeper than inferred in the geophysical palaeogeographical surface, an additional geophysical seismic reflection survey was carried out in May 2015 and focused on characterising the region of the deeper palaeovalley along the new alignment. The results of this geophysical survey is shown in Figure 3.

The borehole and additional geophysical investigation identified that the palaeovalley contains a deeper incised valley approximately 20 m wide and an additional 10 m deeper than anticipated. The identification of this incised rock valley lowered the minimum level of the geological rock profile an additional 10 m from the Scoping Design rock level assumptions, totalling approximately 21 m reduction from the initial rock level assumption. To comply with the design criteria of maintaining a one tunnel diameter rock cover above the tunnel crown, such results would mean that the tunnel would have to be lowered a further 10 metres. Consequently the Victoria Cross Station would further deepen to approximately 50 metres below street level.

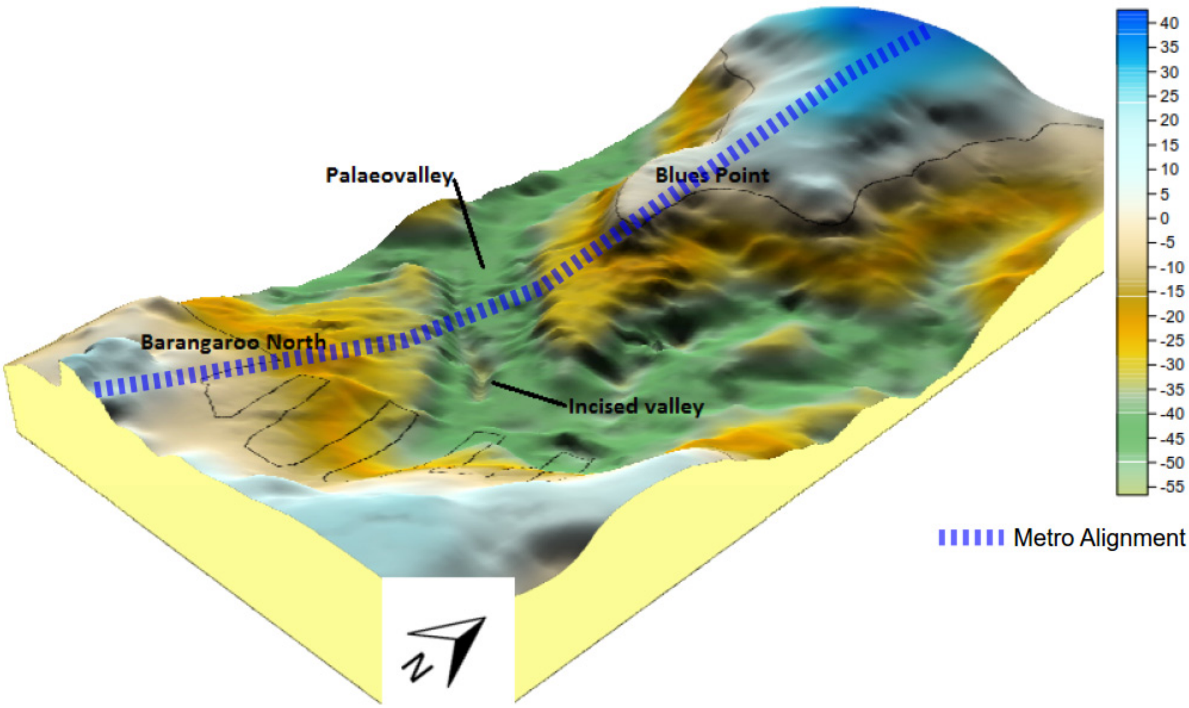

Figure 3. This 3D projection illustrates the palaeogeographical surface (top of rock) that defines the palaeovalley between Barangaroo North and Blues Point.

Discussion with the architectural and product teams concluded that a station at this depth could potentially reduce ease of use of the station for the customer and that alternative vertical alignments should be considered.

Due to the deeply incised palaeovalley crossing the proposed tunnel alignment, it was proposed that instead of lowering the tunnel alignment to keep the tunnel within rock, a tunnel alignment that passed through the soils that had infilled the palaeovalley be adopted. An alignment through soil, would introduce new tunnelling risks such as the potential need for cutter head interventions (manual replacement of drill bits) during the transition between rock and soil, and tunnelling through soil materials where tunnel blow-outs (tunnel boring machine pressure balance failures) could occur. However, it was agreed that the provision of such an alignment which would result in an ideal Victoria Cross Station depth, and thereby greatly improve the product outcome for the commuter.

To inform the tunnel design and help quantify the risks associated with construction through the soil materials, additional geotechnical investigations were performed to refine the geological model for the harbour sediments. A third seismic refraction investigation was performed along the preferred alignment and Cone Penetration Tests (CPTs) and Denison Sampler coring were also performed.

With reference to the refined geotechnical model, the tunnel alignment was adjusted to be aligned roughly perpendicular to the main axis of the palaeovalley. This minimised the distance the tunnels would be required to be bored through both soils and mixed face consitions (where the top portion of the cutter head is in soil and the bottom portion is cutting through rock).

At the completion of the harbour crossing site investigation program: 22 boreholes, 30 CPTs, 1 cross hole seismic survey, and 3 rounds of geophysical testing had been performed. The finalised tunnel alignment proposed for the project’s Reference Design contained approximately 150 metres portion of tunnel through harbour sediments and located the Victoria Cross station approximately 30 metres below the entrance street level. Figure 4 presents a long section through the Sydney Harbour crossing, and details the inferred palaeogeographical profile interpreted at the various stages of the design / site investigation.

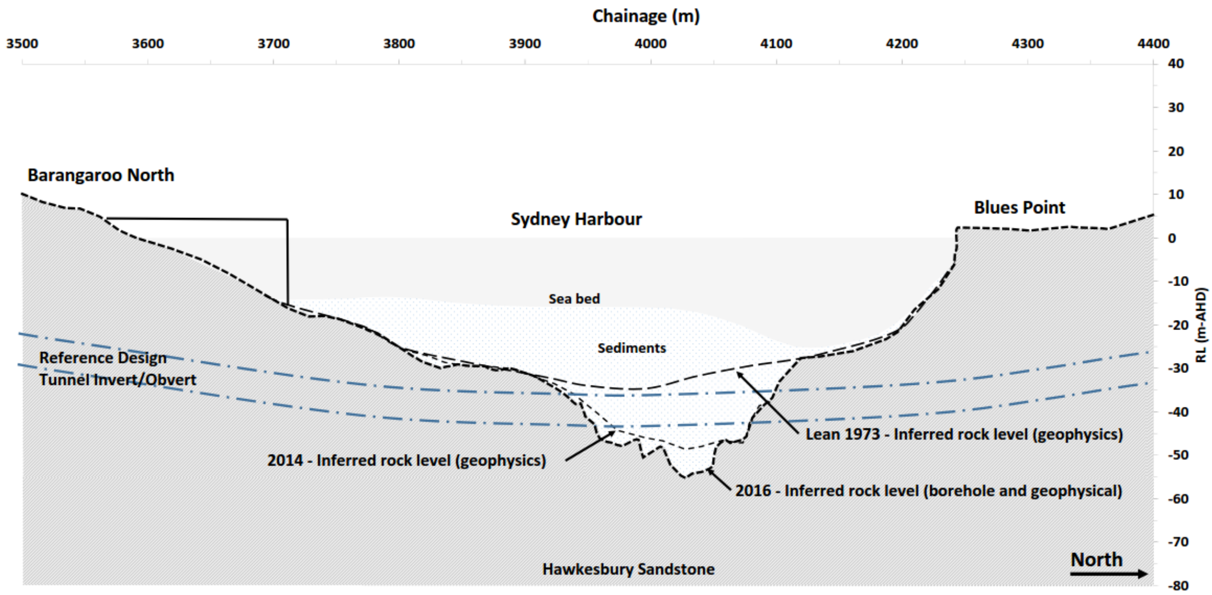

Figure 4. Geological section through Sydney Harbour, showing the inferred top of rock profile based on the initial information (Lean 1973), the 2014 geophysical investigation and the 2016 geotechnical investigation results.

3 CONCLUSION

This paper has summarised the steps taken during the site investigation for the Sydney Harbour crossing of the Sydney Metro City & Southwest project. Multiple stages of alignment redesign were performed as the geological model was developed. The close interactions between the track design, tunnel design and geotechnical teams ensured that the site investigation was able to prepare a geological model suitable for the tunnel alignment and tunnel structural design. The geological section was constantly revised upon receipt of each additional borehole log, and was used to inform the design teams and alter the locations of the remaining site investigations. The design teams worked closely together sharing draft sections and models to speed up design assessment and ensure the site investigation program was not delayed.

This paper has demonstrated the value of communication and interaction between the site investigation team, the geotechnical design team and the project design teams, so that impacts of an evolving geological profile can be appropriately assessed and addressed. This communication and interaction identified the likely negative outcome of a deep station and instigated the change to a construction method to allow for a tunnel alignment through both rock and soils.

Finally it is noted that the site investigation during this program was more extensive than originally planned. However the comprehensive geological model prepared from the site investigation is expected to greatly reduce the construction risks for the tunneling contractor.

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