Geotechnical Conditions at Sydney Desalination Plant

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ABSTRACT
This paper presents the geotechnical conditions surrounding the development of the Sydney Desalination Plant located at Kurnell, New South Wales, Australia. The development comprised a plant site covering an area of about 45 hectares with water inlet and outlet tunnels about 2.5 km long. Each tunnel is connected to riser structures located about 300 m offshore, beneath the Tasman Sea. Key geotechnical issues for the site include the identification of the sandstone profile buried beneath dune sands along the tunnel alignments and the assessment of the quality of the sandstone cover for the offshore portion of the tunnels and the riser construction. The site is adjacent to sensitive and restricted areas including wetlands and a National Park where only low environmental impact site investigation techniques were permitted. Significant features including dykes, a paleochannel and joint swarms were present along the tunnel alignment. Particular challenges for the project were the investigation of a series of dykes and the assessment of the marine portion of the tunnels in the absence of borehole information.

RÉSUMÉ
Cet article présente les conditions géotechniques concernant la construction de l'Usine de Dessalement de Sydney située à Kurnell, Nouvelle-Galles du Sud, Australie. Le projet est composé d'un terrain d'implantation couvrant une aire d'environ 45 hectares et des tunnels d'admission et de sortie d'eau d'environ 2.5 kilomètres de long. Chaque tunnel est relié aux structures de canalisations verticales situées à environ 300 m des bords de la mer de Tasman. Les problèmes géotechniques clés relatifs au site comprennent la reconnaissance géologique des terrains gréseux sous les dunes de sables le long de l'alignement du tunnel et une évaluation de la qualité de la couverture de grés de la partie en mer du tunnel et des canalisations verticales. Le site jouxte une zone sensible et restreinte comprenant des zones humides et un Parc National où seules des techniques d'investigations de terrain à faibles impacts environnementaux sont autorisées. D'importantes structures telles que des dykes, un paléo-chenal et des essaims de fissures sont présentes dans l'alignement du tunnel. Les défis remarquables de ce projet ont été la reconnaissance d'une série de dykes et l'évaluation de la section marine des tunnels en l'absence d'informations provenant de trous de sondages.

1 INTRODUCTION

The Sydney Desalination Plant was built to provide up to 15 % of Sydney's water needs. The first stage of the plant has a capacity of 250 million litres per day which can be upgraded to supply 500 million litres per day. The plant is located at Kurnell, New South Wales, Australia, a suburb approximately 37 kms south east of the centre of Sydney.

The plant site occupies an area of about 45 hectares. Attached to the plant are the seawater inlet and wastewater outlet tunnels that are about 2.5 km long and connect to riser structures located 300 m offshore in the Tasman Sea.

Figure 1 presents the plan view of the plant, tunnel and offshore structures. The development is adjacent to wetlands and a National Park.

2 REGIONAL GEOLOGY

The site locality is generally underlain by fine to medium grained and very fine grained marine quartz sand associated with transgressive dunes and also peat, sandy peat and mud associated with back swamps. These soils overly Hawkesbury Sandstone, a medium and coarse grained quartz sandstone of the Triassic Period.

Dykes that trend approximately east-west can be seen in the cliff line on the coast. Geological mapping and observed surface features indicate that three dykes occur within the vicinity of the inlet and outlet tunnels.

3 SITE SURFACE CONDITIONS

The Kurnell Peninsula is characterised by undulating ground with a variable cover of transgressive dune sands and swamp deposits over the Hawkesbury Sandstone bedrock. Sandstone outcrops are visible at various localities within the peninsula, and sandstone cliff faces are present along the eastern perimeter of the peninsula. Dykes or the weathered remains of such are also visible along the coastal cliff line.

The desalination plant site, previously proposed for an industrial subdivision, was generally level and clear of vegetation with surface levels between about 3 m and 5 m above mean sea level.

A Conservation Area extends along the north western perimeter of the plant site, consisting of moderately to heavily vegetated ground.

Along the inlet and outlet tunnel alignments, the ground level gradually increases to the east of the plant site to between about 20 m and 30 m above sea level along the coastline. The terrain includes low lying wetlands, undulating dunes and then sandstone outcrop near the coastline. The coastal cliff line has near vertical faces about 20 m to 30 m high. The seabed level at the riser locations lies at between about 20 m and 25 m below sea level.

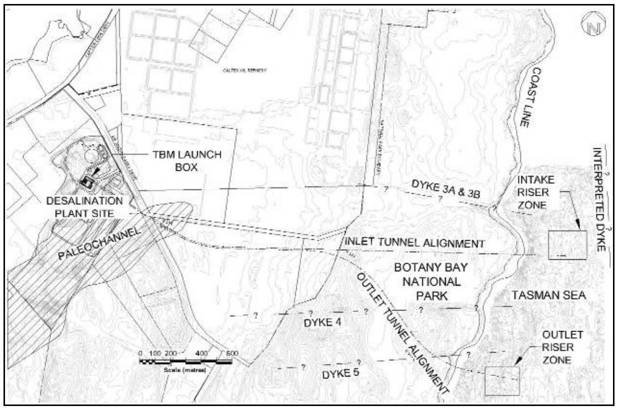

Figure 1. Site Plan

4 GEOTECHNICAL INVESTIGATION

Historical borehole data in the vicinity of the desalination site was included in the assessment of bedrock levels across the desalination site.

Several geotechnical investigation techniques were used to assess geotechnical conditions. Investigation technique such as conventional rotary borehole drilling and electronic cone penetration tests (CPTs) were used at accessible locations, which were mostly within the plant site. Over 40 boreholes were drilled and 70 CPTs were carried out.

Flat plate dilatometer tests, water pressure packer tests, RAAX imaging (a downhole imaging technique which provides a graphical interpretation of rock defects) and in situ rock stress tests were carried out in conjunction with the boreholes. Piezometers and groundwater monitoring wells were installed and pumping and infiltration tests were carried out to provide hydrogeological information.

A site gravity survey was carried out at the plant site to provide additional information on rock levels.

At the tunnel locations, only a relatively small portion of the tunnel length was accessible by a conventional drilling rig as the tunnels are located beneath a National Park. Access to and within the National Park was restricted to existing walking trails or areas where access was only permitted via helicopter.

Initially, less invasive geophysical investigations combined with coastal cliff geological mapping were carried out in restricted access areas. The geological mapping was conducted by a combination of walkover examination along the crest of the cliff face and offshore examination of the cliff face from a boat. The geological mapping identified dykes that may intersect the tunnel alignments.

At targeted locations, a drilling rig was transported into the National Park using a helicopter to drill boreholes along the tunnel alignment near the coastal cliff line. Inclined boreholes were used to investigate the dyke materials at the tunnel levels.

Airborne magnetic data were collected in the vicinity of the tunnel alignments to assess the extent of the dykes mapped in the cliff lines and to identify any other magnetic dykes which were not visible due to the heavy vegetation within the National Park. In addition, a ground magnetic test was also carried out to amplify the data collected from the airborne magnetic survey. Electromagnetic (EM) profiling and resistivity soundings were also carried out using handheld equipment to assess the thickness of the dune sands overlying the sandstone bedrock and to assess whether bedrock depressions exist along the tunnel alignments.

At the riser locations, no borehole drilling was carried out due to the prevailing rough sea conditions and the unavailability of a jack up barge in the time available for investigations. Geophysical investigation techniques were used in these areas. Airborne and marine magnetic data was collected in the vicinity of the riser locations. A bathymetric survey was carried out to produce a sea bed contour map.

An offshore video transect survey was carried out covering sections of the sea floor at the riser locations. Video footage was collected by divers and still images were extracted from the video and utilized to create a montage of images along the riser locations.

Laboratory testing carried out on the soil and rock samples obtained from the investigation included moisture contents, particle size distributions, uniaxial compressive strength (UCS), rock modulus, point load strength index, Brazilian tensile strength (Brazilian), petrographic analyses, and abrasivity tests.

5 GEOTECHNICAL CONDITIONS

5.1 Overview

The plant site is generally underlain by varying thicknesses of fill and natural sand deposits over Hawkesbury Sandstone bedrock. At the north of the plant site, the rock level is shallowest and this was the location of the tunnel boring machine (TBM) launch box for the construction of the inlet and outlet tunnels. A rock contour plan for the site is shown in Figure 2.

The tunnels and the riser structures were constructed within Hawkesbury Sandstone. Two dykes were inferred to cross the tunnel alignment. Figures 3 and 4 present the interpreted long section for the inlet and outlet tunnels, respectively.

5.2 Soil Profile

The depth of fill and natural sand deposits varies across the plant site from 1.2 m to 26 m. The fill varied to 3.5 m thick and generally comprised clayey sand with sandstone gravel, cobbles and boulders and shale gravel fragments. The natural sand deposits were of aeolian or sedimentary origin, varying from loose to very dense, but typically medium dense. The sands contain bands of estuarine/swamp deposits comprising clays and silts. The boreholes indicated that peat layers, ranging from 0.4 m to 3.3 m thick, occur on the north western perimeter of the plant site adjacent to the conservation area.

The bedrock, as shown by the bedrock depths in Figure 2, rises to the north across the plant site, with the southern part of the plant site located within a paleochannel. The floor level of the paleochannel ranges from about 14 m to 22 m below sea level, deepening towards the western extent of the plant site. The paleochannel is likely to combine with a deeper paleochannel network known to exist between the Kurnell Peninsula and Cronulla, extending west out through Bate Bay.

Rock contours indicated that the paleochannel is located in an area about 400 m from the TBM launch box for the inlet and outlet tunnels. This location was of critical importance for design of the vertical alignment of the tunnel due to the limited sandstone cover. A series of CPTs were carried out in this area to assess the deepest rock level and it was found to be 20 m below the ground surface or 14 m below sea level.

Within the National Park, the EM profiling and resistivity sounding combined with a limited number of boreholes did not find any evidence of deepening of the bedrock along the tunnel alignments. Sand dunes up to 17 m high were found above the sandstone bedrock.

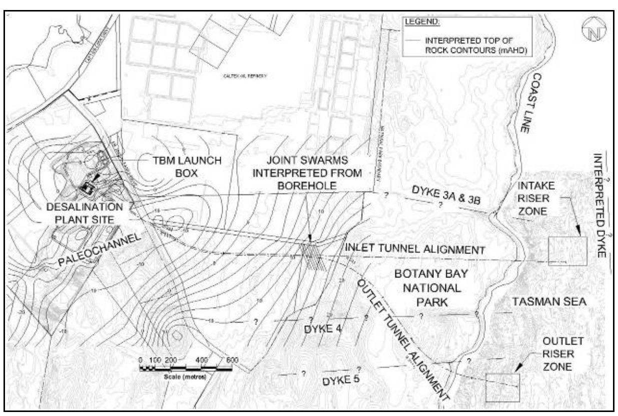

Figure 2. Rock Contour Plan

5.3 Rock Profile

The tunnels and riser structures are constructed within the Hawkesbury Sandstone. The investigations indicated that the tunnels have rock cover of at least 3 m, gradually increasing to the east toward the coastal cliff line. The 3 m minimum rock cover is located at about 400 m away from the launch box where the paleochannel intersects the tunnel alignment. Based on the topographic and bathymetric contours, limited borehole data, geophysical investigations and the appearance of the sea bed in the photographic record, rock cover over the bulk of the on-shore portion of the tunnels beyond 1,000 m from the launch box is greater than 25 m and for the off-shore portions of the tunnels is greater than 17 m.

The video transect survey indicated that the sea floor at the riser locations comprised Hawkesbury Sandstone outcrops with thin sand cover. Large areas were characterised by relatively flat or undulating rock benches with scattered boulders. Boulders and cobbles were evident at various locations, with notable accumulations at the toe of rock faces. The profile of the sea bed is stepped, reflecting weathering along the widely spaced horizontal bedding planes. The surface condition of the sandstone exposed in the sea floor was of similar nature to that observed in rock exposed along the cliff line.

5.3.1 Rock Description and Material Properties

The Hawkesbury Sandstone is predominantly medium to coarse grained quartzose sandstone deposited in 1 m to 3 m thick beds and lenses that exhibit either massive structure or foreset cross beds dipping at 20^o to 30^o. Erosive contacts are common between beds, and shale breccia channel lag type deposits are observed at the base of some beds. Shale interbeds make up a minor part of the sequence. The Hawkesbury Sandstone is inferred to represent alluvial sequences with massive beds grading to cross beds representing deposition from waning flood events. Shale interbeds represent overbank and swamp type deposits.

Petrographic analyses performed on the sandstone core samples recovered near or at the tunnel horizon described the Hawkesbury Sandstone as Quartz Arenite with an average grain size of 0.15 mm to 1.0 mm. The quartz percentage is in the range of 52 % to 60 % and the amount of clay matrix and micaceous minerals is in the range of 24 % to 30 %.

The rock strengths measured from UCS, Brazilian and point load strength index test carried out on the core samples are shown in Table 1.

Table 1. Rock Strength Test Results

Rock Strength	Range	Average
UCS (MPa)	10.8 – 75.6	38
Brazilian (MPa)	4 – 6.75	5.6
Axial Point Load Strength (MPa)	0.45 – 4.8	2
Diametral Point Load Strength (MPa)	0.21 – 5.04	1.77

UCS values of greater than 70 MPa were from:

- samples collected within 1 m of dykes and probably represent contact metamorphic impacts; and
- interlaminated sandstone and shale within the Hawkesbury Sandstone.

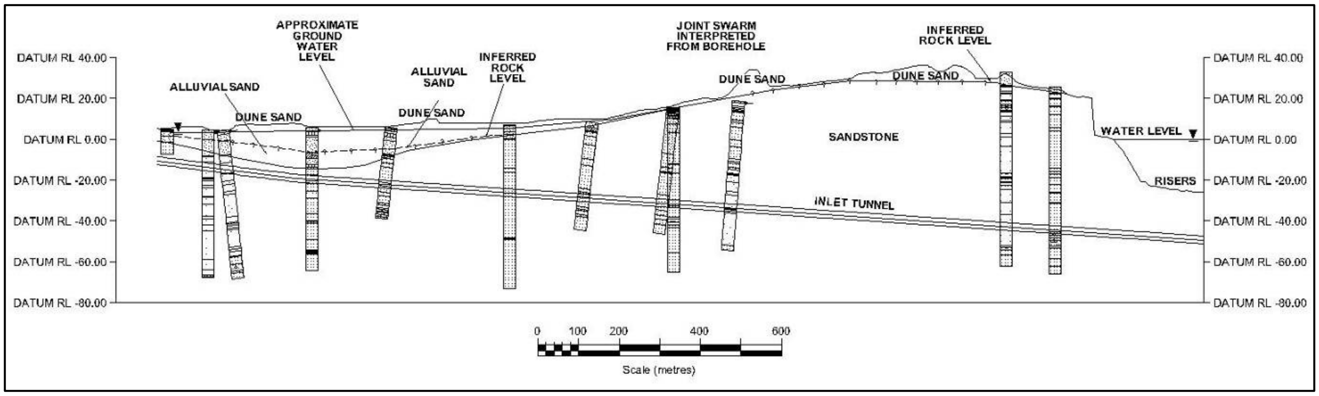

Figure 3. Inlet Tunnel Long Section

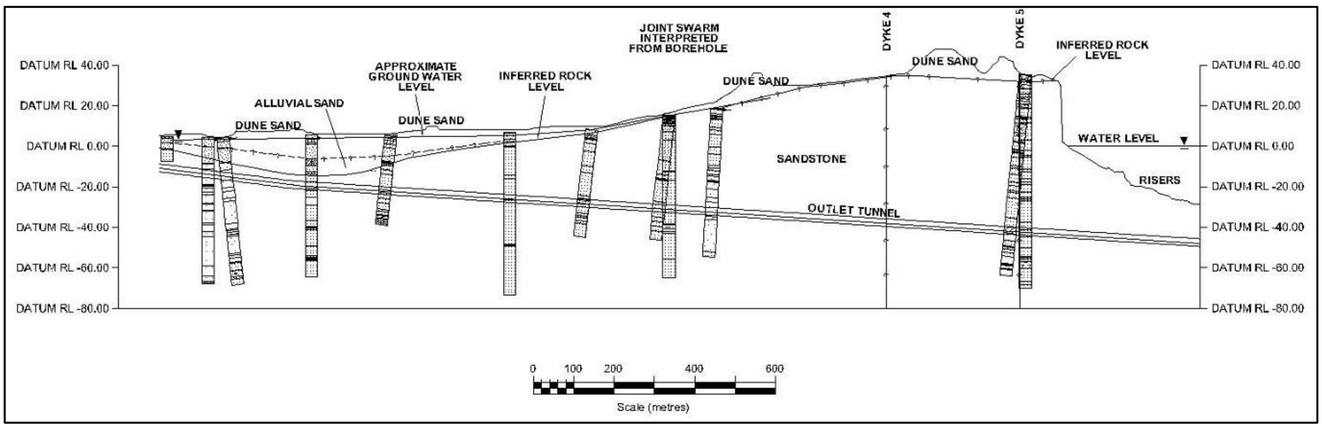

Figure 4. Outlet Tunnel Long Section

Similar to UCS test results, relatively higher point load strengths (3.44 MPa to 4.13 MPa axial and 3.48 MPa to 5.04 MPa diametral) were obtained from samples collected within 1 m of dykes.

Results of the UCS and Brazilian tests were compared to adjacent point load index strength test results and the ratios in Table 2 were calculated.

Table 2. Rock Strength Test Ratios

Ratio	Range	Average	Standard Deviation
UCS/Axial Point Load Strength	8.4 - 74.7	20.7	9.7
UCS/Diametral Point Load Strength	9.9 - 84.8	23.6	11.4
Brazilian/Axial Point Load Strength	1.3 - 3.9	2.9	0.7
Brazilian/Diametral Point Load Strength	1.9 - 4.7	3.3	0.6
UCS/Brazilian	3.1 - 9.4	6.1	1.6

The rock substance elastic modulus, values derived from the UCS tests, showed values ranging from 2 GPa to 27 GPa.

Structure in the Hawkesbury Sandstone of significance to the tunnelling operations include sub-horizontal bedding planes, cross bedding and laminations, sub-vertical jointing or joint swarms, faults, shear zones, and dykes. A joint swarm was interpreted from a borehole located at about 1,250 m from the launch box. Core photographs showed the presence of a series of sub-vertical joints approximately dipping 75° to 80° to the south west.

5.4 Dykes

The outlet tunnel crossed projections of two dykes (identified as Dykes 4 and 5) at approximately 1,800 m and 2,100 m from the launch box. The magnetic survey did not observe Dykes 4 and 5 due to their low magnetisation and/or possible deep weathering.

The dykes were of particular interest as at other locations in Sydney, igneous dykes have been associated with high groundwater inflows to tunnels during construction. In particular, high inflows have been recorded associated with the Great Sydney Dyke in the Sydney Central Business District during construction of service tunnels and rail tunnels.

At the boreholes drilled near the coastal cliff line, Dyke 5 was intersected at about 40 m below sea level where it was anticipated the tunnel would cross the dyke. The dyke varied from about 1.3 m to 2.7 m wide. Very high strength sandstone was observed within 1 m on either side of Dyke 5.

The dyke material encountered in the boreholes was highly to moderately weathered basalt, fine grained, massive to amygdaloidal. Scattered vesicles, some calcite infilled, 0.5 mm to 5 mm in size and silty clay seams up to 50 mm thick were also observed within the dyke material. RAAX imaging indicated that the dyke dips 70^o to 85^o to about 160^o magnetic direction. Several joints were noted within the dyke cores and shear zones up to about 200 mm thick were also observed.

The results of the point load index strength tests performed on intact rock mass of Dyke 5 ranged from 0.3 MPa to 3.06 MPa indicates typical strength ranging from medium to high strength. Samples from the dyke material disintegrated (typically breaking along pre-existing veins) during saturation prior to UCS testing. One sample was successfully subjected to UCS testing with stress/strain measurement and the results are shown in Table 3.

Table 3. Dyke Properties

Parameter	Value
UCS (MPa)	13.1 MPa
Young's Modulus (GPa)	4.71 (secant) 4.61 (tangent)
Poisson's Ratio	0.215 (secant), 0.233 (tangent)

The coastal cliff line mapping data indicated that Dyke 4 is 1.4 m wide, with material described as firm, grey orange brown, high plasticity clay. The mapping also indicated that fresh dolerite cobbles were observed at the coastal cliff base. No boreholes penetrated Dyke 4, hence the nature the dyke material such as the degree of weathering and strength remote from the exposure in the cliff line could not be assessed.

5.5 Abrasivity and Cuttability

The abrasivity and cuttability properties of the rock were important for the tunnelling operations. Tunnel construction experience in Sydney's Hawkesbury Sandstone has shown the rock to be highly abrasive to rock picks and cutter wheels. Assessment of the abrasivity and cuttability of the sandstone near the tunnel horizon for this project were carried out using Schimazek F value, Goodrich Tests, and Cerchar Abrasivity Tests.

Table 4. Abrasivity and Cuttability Characteristics

Characteristics	Sandstone	Sandstone within 1 m of Dyke	Dyke
Schimazek F value	0.31 – 1.49	no data	no data
Cerchar Abrasivity	1.55 – 4.55	3.15 - 3.75	0.6 – 1.25
Goodrich Wear Number	6.75 – 18.5	11.25 – 12.25	0.91 – 1.16
Goodrich Drillability	171 - 800	14 - 65	361 - 763
Goodrich Drillability/Wear Number	16.1 – 85.2	1.2 – 6.5	317 - 852

The test results indicated medium to extreme abrasiveness for sandstone and slight to medium abrasiveness for the dyke materials. The dyke materials have higher drillability than the surrounding sandstone. The values of Goodrich drillability to wear number ratio that correlates to the ability of a roadheader to economically cut the rock indicated that the sandstone close to the dyke should be cuttable using a heavier machine compared to the rest of the sandstone and the dyke materials.

5.6 In-situ Stress

In-situ stress testing using hydrofracture and overcore methods was conducted within the project site. The testing yielded major horizontal stresses, σ_H of 1.8 MPa to 9.0 MPa and minor horizontal stresses, σ_h of 1.4 MPa to 6 MPa with the direction of the major stress generally to the north and north east. The measured in-situ stresses for the project site together with the stress data from a number of projects in Sydney, collated in Coffey (2001) were compared to the stress regimes in the Sydney Basin suggested by Enever et al (1990) and Pells (2002), for rocks to a depth 200 m and 150 m, respectively. The measured stresses were within the stress envelope recommended by Pells (2002).

5.7 Hydrogeological Conditions

The groundwater investigation at the plant site indicated groundwater levels ranging from 2.2 m to 4.0 m above sea level. The groundwater generally flows to the west and north west of the plant site. Pumping tests carried out in the plant site recorded hydraulic conductivities of the surface soils ranging from 7 m/day to 25 m/day indicating that there could be some anisotropy within the groundwater aquifer.

At the tunnel alignments, groundwater levels approximately 4.1 m to 4.7 m above sea level were measured in the paleochannel. The other boreholes drilled along the tunnel alignments indicated groundwater levels ranging from 0.6 m to 1.8 m below the ground surface, mainly within sand deposits. As noted elsewhere in Sydney, water table conditions in sand overlying sandstone bedrock tend to be unresponsive to tunnelling in the underlying bedrock. It is likely this is due to the presence of a comparatively low permeability weathered zone at the top of the sandstone.

Packer testing of the sandstone rock was carried out in boreholes located within the plant site and tunnel alignments. Lugeon values ranging from 0 uL to 700 uL were obtained from the packer tests. These Lugeon values equate to a permeability range from 0 to $700x10^{-7}$ m/s. About 70% of the packer test data indicates Lugeon values of equal or less than 1 uL, while 90 % of the data indicated Lugeon values of less than 10 uL.

The results of the packer testing were compared to the database of test results drawn from tunnelling projects in Sydney reported by Best and Parker (2005). The median Lugeon value obtained from project site tests was 0.5 uL, similar to the findings by Best and Parker (2005).

The database of Lugeon values indicated that high permeability values have been encountered in sandstone in the Sydney area. Values of 50 uL or higher have occurred at adverse geotechnical features including those associated with valley bulging and dykes. The overall frequency of such areas within Sydney sandstone in general may be over represented due to targeting of testing at higher risk areas. In the project site, Lugeon values of greater than 100 uL were recorded at greater than 10 m below the invert level of the tunnels and Lugeon values of 20 uL to 72 uL were recorded at greater than 6 m below the invert level of the tunnels or greater than 10 m above the crown level of the tunnels. Generally, values less than 1.5 uL were recorded at tunnel levels.

Tunnelling was carried out by using tunnel boring machines with installation of 2.8 m diameter waterproof segmental lining. During construction groundwater inflow was not controlled at the face. Pre-construction estimates of potential inflow based on analysis of drilling and packer testing records indicated that inflow would not exceed 2 L/s. Construction performance was consistent with this assessment and no significant groundwater inflows were reported.

5.6 Impacts on the design of the tunnels

The design of the horizontal and vertical tunnel alignments and the location of the TBM launch box were influenced by the results of the investigations.

The original alignments were different from those constructed. The most significant change was to the outlet alignment, which was originally planned to have a separate launch box at the southern end of the plant site. The southern part of the plant site is located within a paleochannel. A rock level about 14 m deep was identified at the original location of the outlet launch box compared to the north of the plant site where the rock level is shallower at 6 m deep. The design was changed to have a single launch box for inlet and outlet tunnels on the northern side of the plant site to take advantage of the shallower depth to rock.

The design of the vertical alignment of the tunnels was driven by the depth of the paleochannel intersecting the tunnels at about 400 m from the launch box. A minimum rock cover of 3 m was maintained at the paleochannel intersection.

Dykes identified in the vicinity of the tunnels are to cross the outlet tunnel alignment. The outlet tunnel was modified in the area of the intersection with the dykes so that it crossed the dykes over a shorter length and well away from the coastline.

6 CONCLUSIONS

The geotechnical investigation techniques used for the Sydney Desalination Project, provided valuable information for the designers, where significant geological features such as dykes, a paleochannel and joint swarms were present and had the potential to impact on major structures such as the inlet and outlet tunnels for the desalination plant.

Investigations were successfully carried out in environmentally sensitive areas and where access was restricted. Aside from conventional drilling and cone penetration testing, an innovative combination of investigation techniques including geophysical methods (i.e. airborne, marine and ground magnetic surveys, electromagnetic (EM) profiling and resistivity soundings) and video imaging using divers was used to investigate the tunnel route. The use of a helicopter to gain access to drilling locations within the National Park was important to provide information regarding dykes crossing the tunnel alignments.

As the project was constructed the geotechnical models developed from the geotechnical investigations were verified and the project was successfully completed.

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