HYDROGEOLOGICAL PROPERTIES OF HAWKESBURY SANDSTONE IN THE SYDNEY REGION

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ABSTRACT

Geotechnical and hydrogeological data obtained from investigations for the design of tunnels in Sydney have created a large database that describes the hydrogeological properties of the Sydney Hawkesbury Sandstone, providing an insight into its hydraulic behaviour. Investigations for the Epping to Chatswood Rail Line and another tunnel project in Sydney included drilling of over 150 boreholes and execution of over 450 packer (water pressure) tests within these boreholes. For the Epping to Chatswood Rail Line, a 48-hour pumping test was conducted at two separate locations and acoustic borehole imaging was conducted in 20 boreholes to provide information on subsurface defect characteristics, essential to understanding hydraulic behaviour. This paper presents the results of a statistical analysis of packer test results and borehole imaging data, a comparison to pumping test results, and compares measured groundwater inflow rates from the tunnels with estimates from numerical modelling. Data analyses show the depth-dependence of the hydraulic conductivity of the Hawkesbury Sandstone, show a relationship between hydraulic conductivity and defect distribution, and demonstrate the requirement to address scale effects when using packer test results to assess groundwater inflow to underground excavations.

1 INTRODUCTION

Sydney is currently the scene of several major transportation tunnelling projects. In this paper, data from the Epping to Chatswood Rail Line (ECRL, formerly known as the Parramatta Rail Link but now reduced in length with the cancellation or postponement of the previously planned Epping to Parramatta Section) and another ongoing project in the northern Sydney area have required geotechnical and hydrogeological input for design. Both tunnels are being excavated at depths of between 15 m and 60 m mainly in the Triassic Hawkesbury Sandstone, which underlies most of Sydney.

The pre-tender and detailed design phases for these tunnels required significant investigations of the geotechnical and hydraulic properties of the lithologies to be excavated. The database used for this paper was collated from results of these investigations, covering an area of around 20 km^2 between Epping and Artarmon (Figure 1).

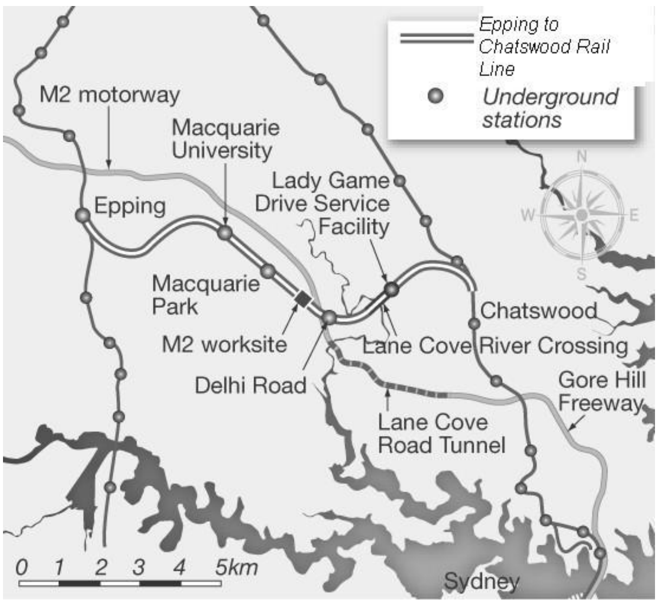


Figure 1: Location of the investigation area

The database consists of interpreted results of packer (water pressure) tests and pumping tests, and logs from borehole acoustic imaging. This paper focuses on analysis of the hydraulic conductivity results from the hydraulic tests, and defects logged from borehole imaging. The objective was to develop a detailed understanding of the spatial variation of the hydraulic properties of the Hawkesbury Sandstone.

For the ECRL, one of the design objectives was to evaluate the magnitude of groundwater inflows to the running tunnels and then identify segments of the tunnels where the advance of the tunnel boring machine (TBM) might be impeded by high groundwater inflows. Major project issues included groundwater control to limit groundwater level drawdown and surface settlement, and reduce discharge quantities of excess water to treatment facilities and the environment. In addition, the owner placed limits on the acceptable long-term groundwater inflows to the running tunnels and station cavern excavations, and limits on settlement. The maximum inflow criteria were stipulated as 0.1 L/s into any continuous 100 m length of single-track tunnel, and 0.75 L/s for each 10000 m^2 excavated area of a station cavern. This required numerical simulation to identify the segments of the tunnels and parts of the caverns where ground treatment would be required to meet the design criteria.

Considering the ECRL tunnel geometry and regional groundwater levels, the inflow limit for the running tunnels would generally be caused by a bulk (depth-averaged) hydraulic conductivity of approximately 0.05 m/day. Packer test results are usually reported in Lugeons (Lu). The Lugeon is a unit of transmissivity and is dependent on borehole diameter. For practical purposes, and to relate information to packer test flows, one Lugeon is generally taken to represent a hydraulic conductivity of 1 x 10^{-7} m/s (approximately 0.01 m/day) in a homogeneous, isotropic medium. A hydraulic conductivity of 0.05 m/day is thus assumed to be approximately 5Lu.

1.1 REGIONAL STRATIGRAPHY

The investigation area is located on lithology of the Sydney Basin. Lithologies comprise (down the stratigraphic sequence):

- Unlithified sediments of varying thickness (usually a few metres but known to reach 10 m or more) mainly comprising residual soils. Alluvium and/or colluvium also occur in some creek channels and river valleys (such as the Lane Cove River valley on the ECRL alignment). Residual soils host disjointed zones of perennial saturation, but alluvial bodies may create more extensive zones.
- Ashfield Shale (of the Wianamatta Group), occurring as bodies of limited thickness on higher ground at Epping, Marsfield, North Ryde, and Chatswood. It is known to maintain saturation as a separate aquifer at Epping and Chatswood.
- Mittagong Formation, consisting of interlayered shale and sandstone forming a thin transition zone between the Ashfield Shale and underlying Hawkesbury Sandstone. Packer test results and geophysical logs from the investigations suggest it behaves similarly to the overlying shale.
- Hawkesbury Sandstone, of maximum thickness 290 m (Pells, 2002). This sandstone hosts the majority of the excavated portions of the tunnels and is the uppermost lithology that hosts a perennially saturated extensive aquifer. Both tunnels are stratigraphically located in the upper 80 m of the sandstone.
- The Narrabeen Group.

Bulletin 26 issued by the Geological Survey of NSW (1980) provides detailed geological descriptions of these lithologies. The stratigraphy along the ECRL is shown in Figure 2. In the Hawkesbury Sandstone, which is the focus of this paper, it is well known that there is a horizontal stress field that can contain a significant tectonic component which can influence civil engineering works such as tunnels and basement excavations. The geology and stratigraphy of the Hawkesbury Sandstone have been described in detail by others (for example, Conaghan, 1980).

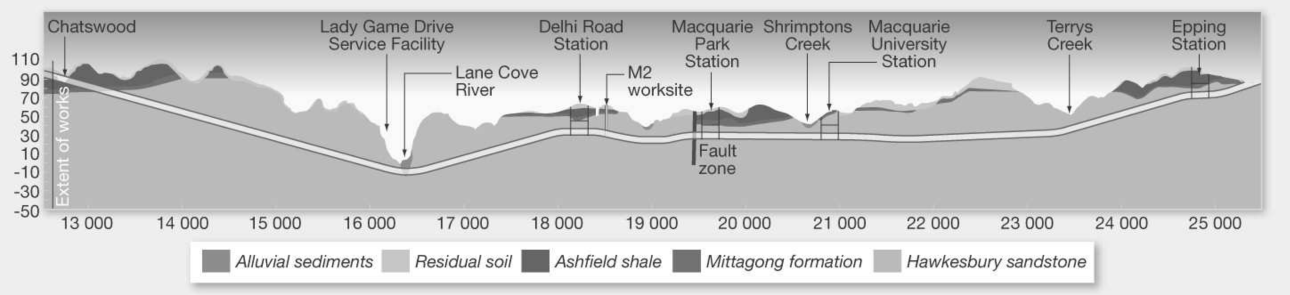


Figure 2: Stratigraphic cross-section along the Epping to Chatswood Rail Line.

1.2 SUBSURFACE INVESTIGATIONS

From a hydrogeological perspective, critical information was collected from the hydraulic testing and borehole imaging components of the subsurface investigations.

1.2.1 Hydraulic Testing

Investigations were conducted by several organisations during the pre-tender and detailed design phases of both tunnels with the majority of the tests being conducted along the ECRL alignment. Packer tests were conducted with an average vertical spacing of 6.3 m, but varying between 2 m and 20 m. The aerial distribution of boreholes in which packer tests were conducted was concentrated around the underground stations, however good coverage was also achieved along the rest of the ECRL alignment. A typical result sheet from a borehole packer test is given in Figure 3.

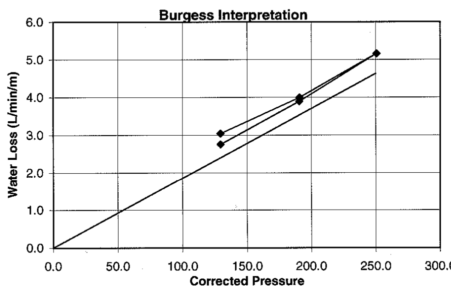
BOREHOLE WATER PRESSURE TEST

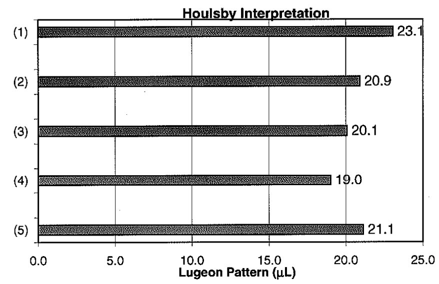
Job No: **2110080A** Office: **SYD**

Client: **Thiess Hochtief JV** Location: **Lady Game Dr Service Facility** Reduced By: **DCG** Borehole no: **LGD103**
Project: **Parramatta Rail Link** Test Date: **3-Dec-02** Checked By: EDG

Test Details: Packer Type: **Pneumatic** Borehole Diameter: **76mm** Depth from: **18.60 m**
Type of Pump: **Silvan AZ71** Borehole Inclination: **-90deg** Depth to: **24.92 m**
Pressure Gauge & Serial No: **Wise (0-250kPa)** Borehole Azimuth: **N/A** Test Depth Interval: **6.32 m**
Pressure gauge height: **1.7 m** Depth to g'water **5.3 m** Static Pressure: **68.7 kPa** Test Midpoint (m): **21.76 m**

Time Interval (minutes)	Gauge Pressure (kPa)	Water Loss (litres - from flow meter) Start (L)	Finish (L)	Total (L)	Flow Rate (Litres/minute)	Head Loss (kPa)	Corrected Pressure (kPa)	Water Loss Rate (L/min/m)
5	61	10374	10470	96	19.20	0.0	129.7	3.04
5	61	10470	10563	93	18.60	0.0	129.7	2.94
5	122	10590	10716	126	25.20	0.0	190.7	3.99
5	122	10716	10842	126	25.20	0.0	190.7	3.99
5	182	10842	11005	163	32.60	0.0	250.7	5.16
5	182	11005	11160	155	31.00	0.0	250.7	4.91
5	122	11181	11304	123	24.60	0.0	190.7	3.89
5	122	11498	11604	106	21.20	0.0	190.7	3.35
5	61	11612	11699	87	17.40	0.0	129.7	2.75
5	61	11699	11785	86	17.20	0.0	129.7	2.72





Interpreted Burgess Permeability : 18.5 µL
Based on Burgess, 1983

Interpreted Houlsby Permeability : 19.0 µL
Based on Houlsby, 1976

Packer Test Results - Type - Rev 1

Figure 3: Typical packer test results sheet.

Two 48-hour pumping tests were conducted at specific locations on the ECRL alignment to provide hydraulic conductivity values over a larger volume of aquifer at two critical locations, and to allow an estimate to be made of the applicability and reliability of packer test results for numerical simulation. One pumping test using observation wells was conducted at the Macquarie Park Station cavern site and the other at the Lane Cove River crossing (see Figures 1 and 2). At each of these locations, numerous packer tests had been previously conducted in surrounding boreholes, and a significant packer test results database was available. Each pumping test was conducted at flow rates of between 1.5 and 2.5 L/s.

1.2.2 Acoustic Borehole Imaging

In acoustic borehole imaging, a tool that emits sound waves is lowered down the borehole. The tool also receives the sound waves as they are reflected from the borehole wall. Synchronization of emitted and received waveforms provides an acoustic image of the borehole wall. The acoustic image is processed to provide a visual image of the entire logged section of the borehole and is subsequently used for interpretation. Acoustic imaging was conducted in 20 boreholes along the ECRL alignment. In each borehole, both open and closed (tight/infilled) defects were logged. For eight boreholes, an indicative aperture size was also recorded for each open defect.

In this paper, defects are defined as open dislocations in the rock fabric that are of a large size compared to the typical size of intergranular voids present in intact fabric. These defects provide faster water transmission pathways than the rock matrix, and manifest themselves as sub-planar partings in the rock fabric (generally referred to as fractures, joints, or partings). In the Hawkesbury Sandstone they occur mainly as sub-vertical fractures, open bedding planes, and open cross-bedding planes. Although known by various names, the defects generally fall into two main groups:

- defects with dips less than or equal to 45 degrees (sub-horizontal defects). These typically have dips less than 30 degrees and comprise open bedding and cross-bedding planes. Apertures for these defects can be large near ground surface or in areas where stress relief is significant (such as at the Lane Cove River valley).
- defects with dips greater than 45 degrees (sub-vertical). These typically have dips greater than 60 degrees, and comprise sub-vertical fractures or other openings.

Preliminary analysis of borehole imaging data for the ECRL alignment indicated that the dips of the defects were strongly grouped into sub-horizontal and sub-vertical defects. The defect sample set was therefore split into these two groupings. Defect data were analysed for relative defect proportions, spacing and density, and mode of occurrence. The data from borehole imaging were combined with surface defect mapping data in evaluating defect orientation and continuity.

2 DEFECT CHARACTERISTICS

Defect analysis focused on the defects present in the Hawkesbury Sandstone, for the purpose of evaluating the way in which they influence the hydraulic conductivity and groundwater inflows.

2.1 RELATIVE PROPORTIONS

Figure 4 shows a rose diagram of unbiased (weighted) relative proportions of defect dips for the Hawkesbury Sandstone over the depth interval intersected by the boreholes, using arithmetic arcs. Sub-horizontal defects account for 75% of the total, and sub-vertical defects account for 25%. For a well-connected fracture system of sufficient density, the relative proportions of these defects allowing purely horizontal and purely vertical groundwater flow (over a large volume) are the trigonometric components for each recorded defect, and result in 66% for horizontal flow and 34% for vertical flow.

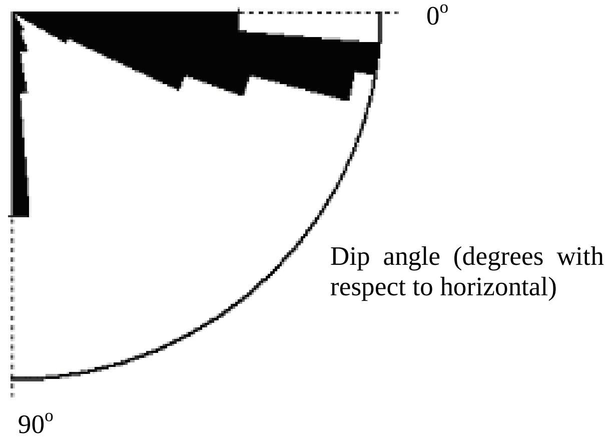


Figure 4: Unbiased (weighted) defect proportions over the depth interval of investigation.

2.2 ORIENTATION

Figures 5a to 5c show the strike of all defects logged from borehole imaging and mapping of surface outcrops and road cuts.

The strike of sub-vertical defects logged from borehole imaging (Figure 5b) shows strong primary peaks at 15 and 195 degrees with respect to grid north and a secondary peak at 125 degrees. The strike of sub-vertical defects logged from surface outcrop mapping (Figure 5a) agrees with the primary peaks from borehole imaging, but shows a much smaller secondary peak (possibly due to the bias arising from most outcrops in the area being generally oriented east-west), however there are 13 times more surface mapping data than imaging data. The main peak results from the horizontal stress field prevalent in the area (in a direction of 15 degrees with respect to grid north).

(a)

(b)

(c)

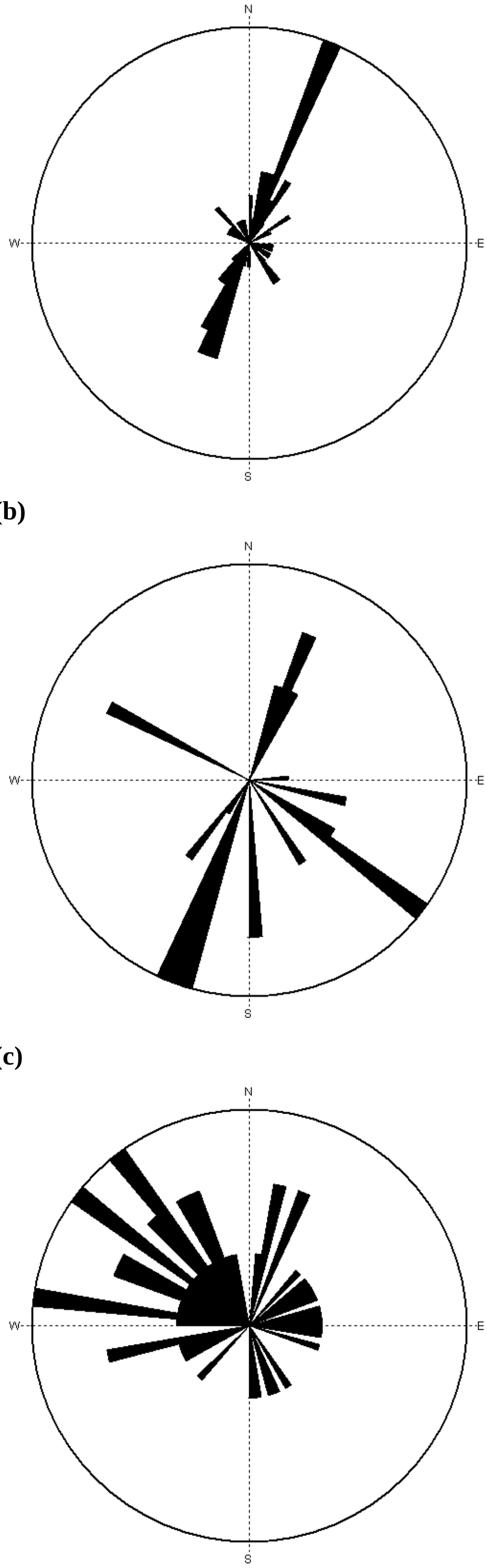


Figure 5: Strike orientation (with respect to the Australian Map Grid) of (a) sub-vertical defects logged from surface mapping (N=392), (b) sub-vertical defects logged from borehole imaging (N=35), and (c) sub-horizontal defects logged from borehole imaging (N=307).

The strike of sub-horizontal defects logged from borehole imaging (Figure 5c) shows a broad peak at about 315 degrees with respect to grid north which is consistent with a former surface water flow direction suggested by previous studies (Standard, 1964, 1968) which reported a vector mean of 34 degrees (probably measured with respect to magnetic north in the 1960s) from over 5000 measurements. The broadness of the distribution probably results from the generally curvilinear nature of cross-bed wave fronts in plan view (as observed in outcrops, with good examples presented pictorially in Conaghan, 1980).

2.3 SPATIAL DISTRIBUTION

2.3.1 Spacing and Density

Figures 6a and 6b show vertical spacing for the sub-horizontal defect group and horizontal spacing for the sub-vertical defect group respectively, as a function of vertical depth below ground level. Spacings shown in Figures 6a and 6b were calculated from borehole imaging data by first dividing the data sets for individual boreholes into sub-vertical and sub-horizontal defects, then calculating spacings between neighbouring defects of the same group in the same borehole. For individual boreholes, spacing follows a cyclic pattern.

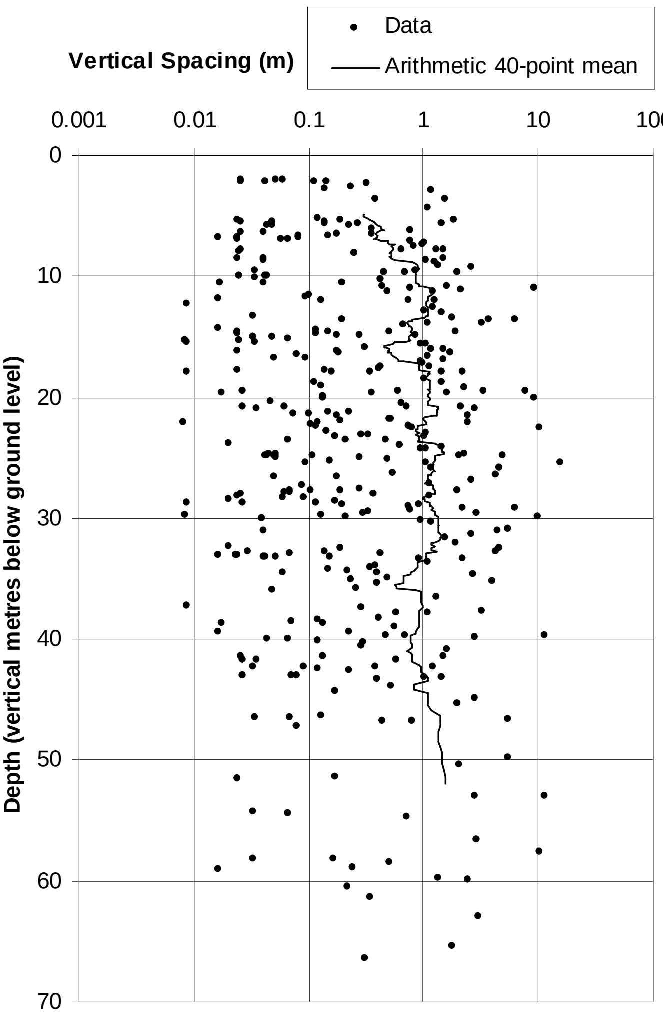


Figure 6a: Vertical spacing for sub-horizontal defects.

For the spacing distribution of each defect group, a 40-point arithmetic mean has been calculated down the profile; these averages are shown in Figures 6a and 6b. The average spacing for sub-horizontal defects over most of the profile is about 1 m but individual spacings can vary enormously (generally between 1 mm and 10 m).

Fewer data points are available for sub-vertical defect spacing. The average spacing for sub-vertical defects is similar to that for sub-horizontal defects, but note that the arithmetic 40-point mean distribution is short and suffers from end effects due to the limited number of points. The changing depth for horizontal spacing of defects in the same borehole also has an effect.

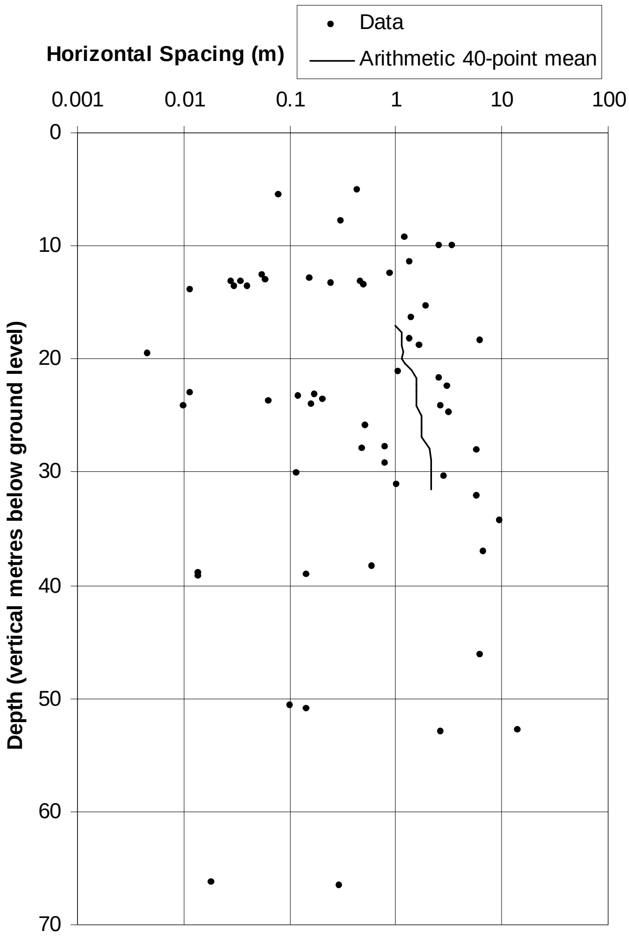


Figure 6b: Horizontal spacing for sub-vertical defects.

Defect density is defined as the inverse of spacing, in units of defects/metre. Figures 7a and 7b show the defect density distributions for sub-horizontal and sub-vertical defects respectively.

2.3.2 Continuity

Continuity of individual defects cannot be evaluated from imaging data from individual boreholes, and is difficult to evaluate between boreholes spaced even as little as 10 m apart. Mapping of surface outcrops in the investigation area has provided a database on continuities as a function of spacing, mostly for sub-vertical defects. The sub-horizontal defects dataset is small and covers the dip range 16 to 45 degrees (average of 35 degrees). A large proportion of sub-horizontal defects have dips consistent with cross-bedding planes. Conaghan (1980) provides estimates of the lateral extent of crossbed sets. He gives estimates of strike-length dimensions of around 40 m for a crossbed set thickness of around 1.5 m, and dimensions of between 0.5 m to 4 m for a crossbed set thickness of between 0.1 m and 0.4 m. These strike length estimates would probably be the upper bounds for horizontal continuity of sub-horizontal defects associated with cross-bedding plane partings.

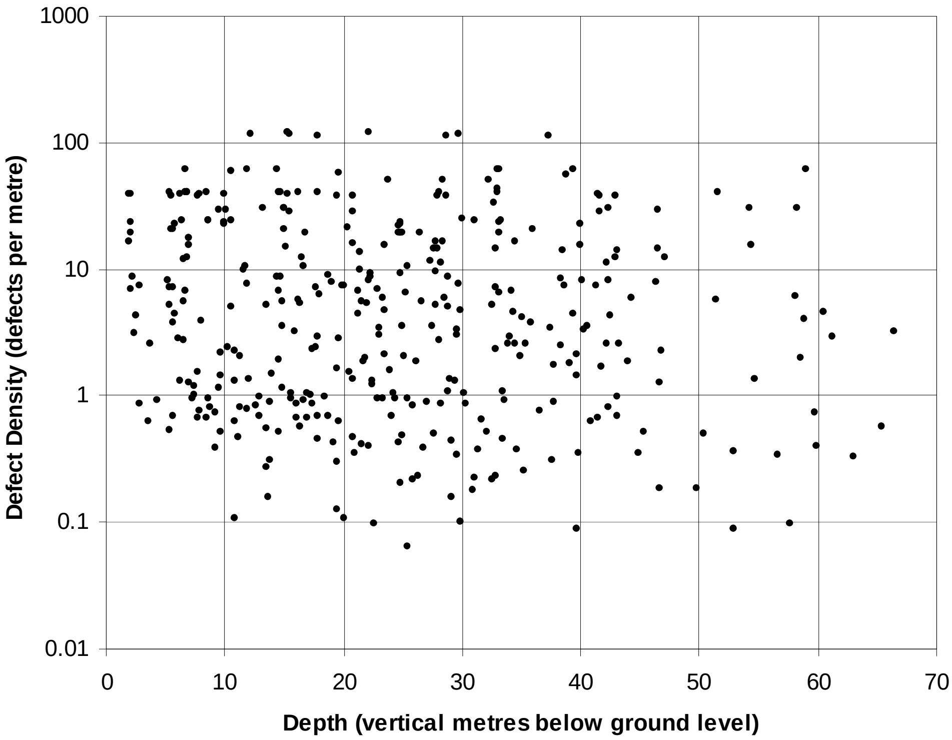


Figure 7a: Vertical density for sub-horizontal defects as a function of depth.

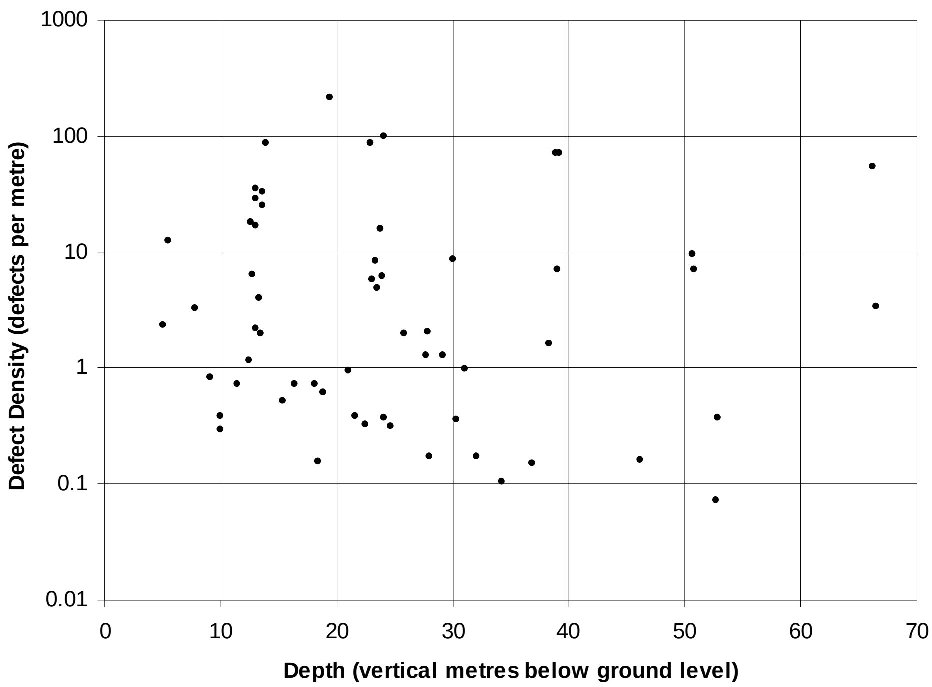


Figure 7b: Horizontal density for sub-vertical defects as a function of depth.

The surface mapping dataset for sub-vertical defects is much more extensive. Figures 8a and 8b show horizontal and vertical continuity respectively, as functions of lateral spacing. Horizontal continuity has no particular relationship with spacing, and continuities range between 0.2 m and 20 m. Vertical continuity appears to increase to some asymptote with increasing lateral spacing. The vertical continuity varies only between 1 m and 3 m over a much larger range of lateral spacing (0.1 m to 10 m), probably resulting from the propensity for these defects to terminate against sub-horizontal defects.

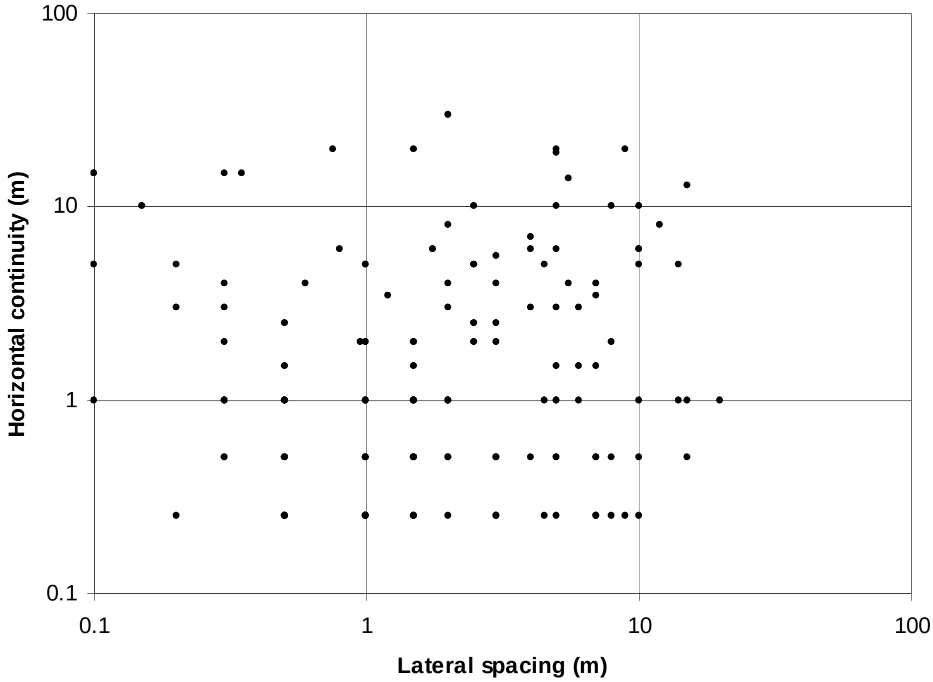


Figure 8a: Horizontal continuity of sub-vertical defects as a function of lateral spacing.

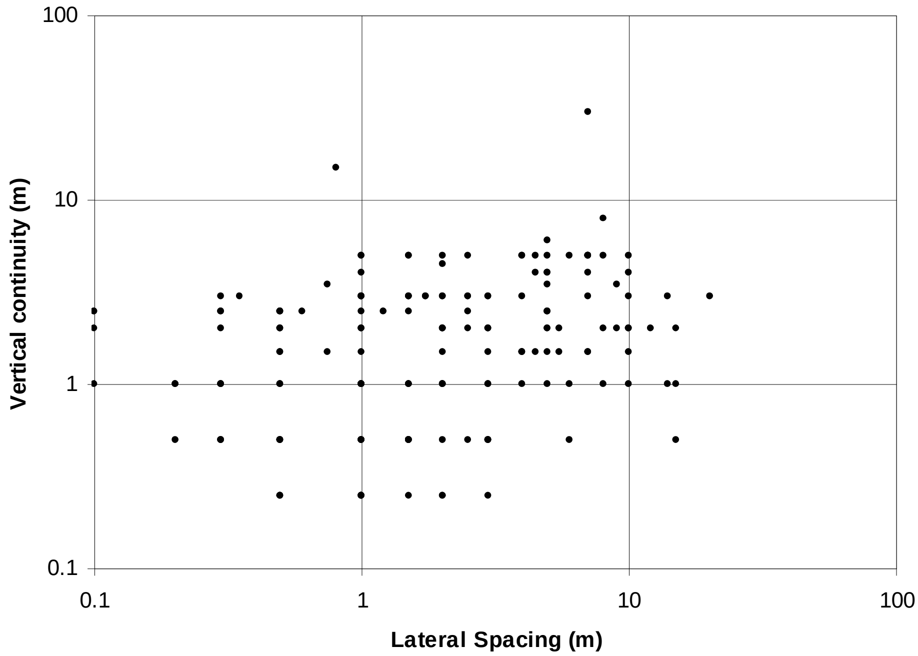


Figure 8b: Vertical continuity of sub-vertical defects as a function of lateral spacing.

2.3.3 Mode of Occurrence

The mode of occurrence of defects was investigated by analysing the location of each single defect down the profile. Fractal or frequency analyses are commonly conducted on defect data sets to test for the presence of a cyclic occurrence of defects in some spatial direction. Detailed frequency analysis indicates that sub-horizontal defects occur mainly in cycles ranging between 2 m and 10 m vertically, with cyclic defect patterns having a spatial wavelength of about 5 m being more common than others.

The typical lateral cycle for sub-vertical defects, based on limited data, is probably about 7 m (laterally), but observations in excavated caverns of the ECRL suggest a lateral cycle of about 10 m (or more) at 30 m depth.

2.4 APERTURE

Hydraulic conductivity of fractured rock is fundamentally related to defect aperture size. Figures 9a and 9b show the recorded apertures for sub-horizontal and sub-vertical defects respectively, from borehole imaging. Sub-horizontal defects included several fragmented zones where the aperture was defined as 5% of the thickness of the fragmented zone, based on a study of the imaging logs, rock cores, and surface outcrop. The logged aperture sizes were a minimum of 0.3 mm, although the imaging operators stressed that this is a lower limit and was assigned to defects of smaller aperture. Notwithstanding this limitation, the datasets are useful for evaluating the change in aperture with depth, and comparing aperture between defect groups.

Figure 9a shows how physical apertures for sub-horizontal defects vary widely, but decrease with depth. In contrast, apertures for sub-vertical defects (Figure 9b) change minimally, although far fewer data are available for this group.

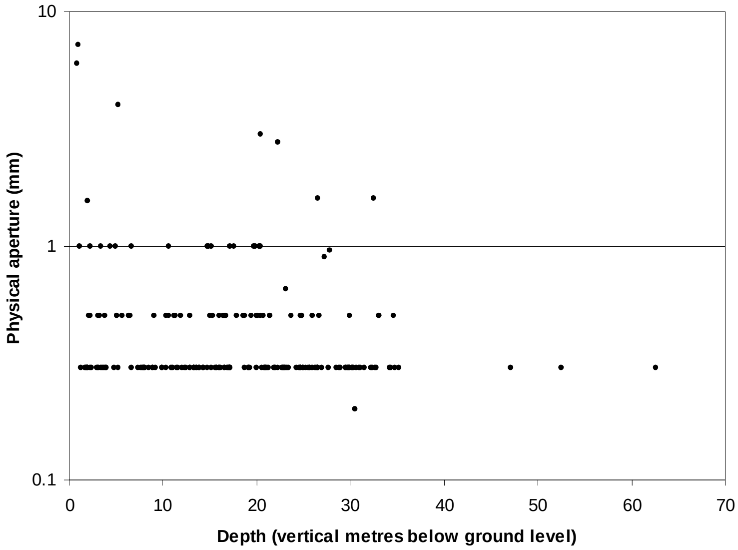


Figure 9a: Physical aperture for sub-horizontal defects as a function of depth.

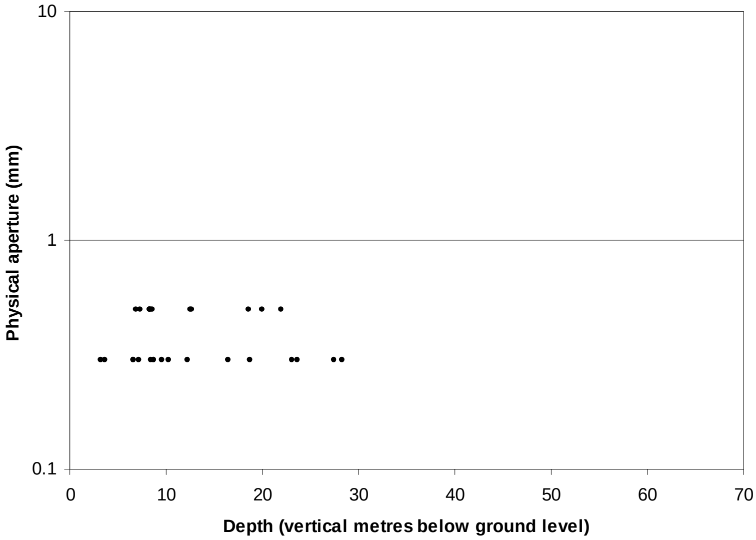


Figure 9b: Physical aperture for sub-vertical defects as a function of depth.

3 HYDRAULIC PROPERTIES

3.1 HYDRAULIC CONDUCTIVITY

3.1.1 Hydraulic Conductivity Interpreted from Packer Tests

The packer test database comprises 363 test results for the Hawkesbury Sandstone from 117 boreholes (representing about 2.4 km of tested borehole). The equipment used had limitations on measurable drill rod flow, and hydraulic conductivity results generally could not be defined outside the range of 0.001 m/day (0.1 Lu) to 1.7 m/day (170 Lu). Hydraulic conductivities reported as less than the range ("nil flow") were set to half the lower limit, and those reported above the range ("maximum flow") were set to double the upper limit. Nil flow results comprise 26% of the data set, maximum flow results comprise 2% of the data set, and measured values comprise 72% of the data set.

While not useful for spatial analysis, the probability distribution for hydraulic conductivity is useful for comparison to other datasets. Figure 10 shows the probability distribution for the dataset compared to other published datasets for the Hawkesbury Sandstone in the Sydney region. The distributions are similar, with differences being partly attributable to different average depths of investigation between datasets.

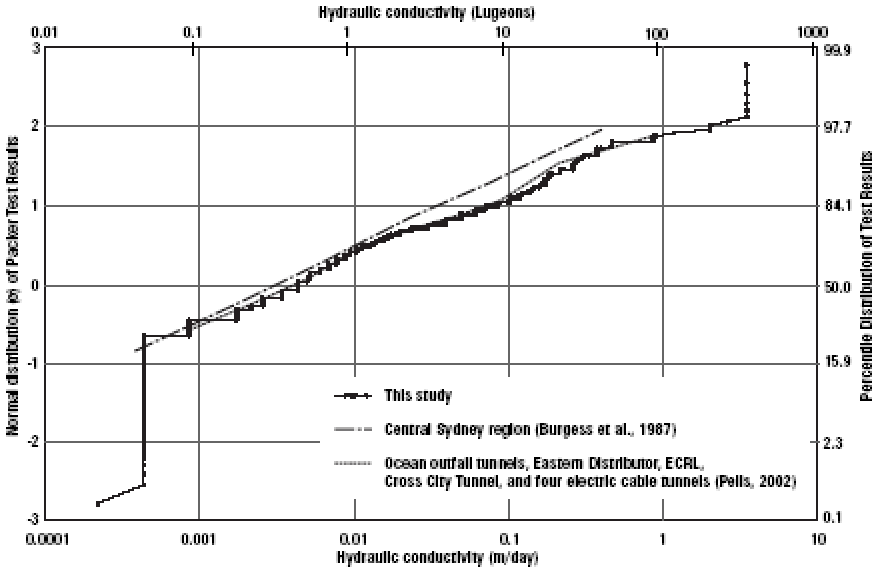


Figure 10: Probability distribution of hydraulic conductivity from packer test results for Hawkesbury Sandstone in the Sydney region.

Of greater value for spatial analysis is the distribution of hydraulic conductivity with depth, shown in Figure 11. The 40-point geometric mean of the results going down the profile is also shown. A clear overall trend of decreasing hydraulic conductivity with depth is evident. The log standard deviation in hydraulic conductivity over 5 m depth intervals is typically about 1 log cycle, and comparable to the log standard deviation of sub-horizontal defect spacing. This scatter is relatively large, but comparison of hydraulic conductivity and defect spacing over a small depth interval (discussed below) shows this scatter to be caused largely by the variation in defect spacing.

3.1.2 Hydraulic Conductivity of the Matrix

The geometric mean hydraulic conductivity of six cores of Hawkesbury Sandstone taken from two boreholes between depths of 8 m and 37 m below ground level (for a project unrelated to the tunnels), about 80 km north of the investigation area, was found to be 0.0019 m/day (2 x 10^{-8} m/s). This compares with a range of 10^{-9} to 10^{-11} m/s quoted in Pells (2002). This result for the rock cores was obtained from laboratory permeability experiments using water, and is useful as a representative estimate of the matrix permeability for the Hawkesbury Sandstone. At shallow depths matrix contribution is a negligible component of groundwater flow. At depths approaching 100 m the matrix may contribute in a more significant way.

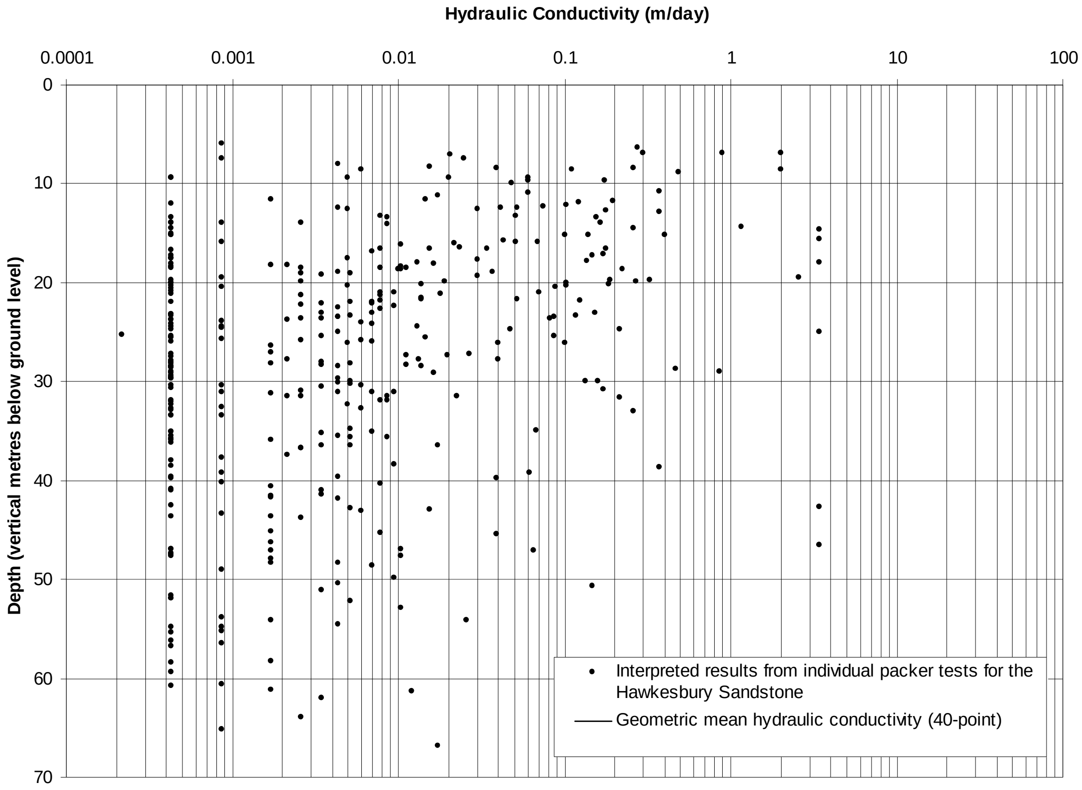


Figure 11: Hydraulic conductivity interpreted from packer tests.

3.2 RELATIONSHIP BETWEEN HYDRAULIC CONDUCTIVITY AND DEFECT DISTRIBUTION

3.2.1 Probabilistic Relationship

The relationship between hydraulic conductivity and defect distribution needs to be analysed over a depth interval with a length that is a trade off between:

- a small enough depth interval where the effect of overburden pressure and *in situ* stress, and any other factors related to depth that may affect defect aperture size and defect density, are largely constant and
- a large enough depth interval where the available defect information provides a probability distribution that is a valid, unbiased representation of the defect population at that depth.

The depth interval selected was 17.2 to 22.1 vertical metres below ground level, the interval containing the highest number of hydraulic conductivity results that is comparable to the most likely defect cycle occurrence in the sandstone, and where the variation in hydraulic conductivity with depth is minimal. Figure 12 shows the probability distributions for defect densities and hydraulic conductivity for this interval. The probability function of hydraulic conductivity is very similar in form (log-normality) and scatter (slope) to the function for sub-horizontal defects. If it is assumed that the overall mean of aperture size is constant for both defect groups over this small depth interval, the probability function for hydraulic conductivity may be a simple linear combination of the probability functions for sub-vertical and sub-horizontal defect density. Figure 11 shows that the low-end undefined packer test results were due to instances where very few or no defects were intersected by the packer interval.

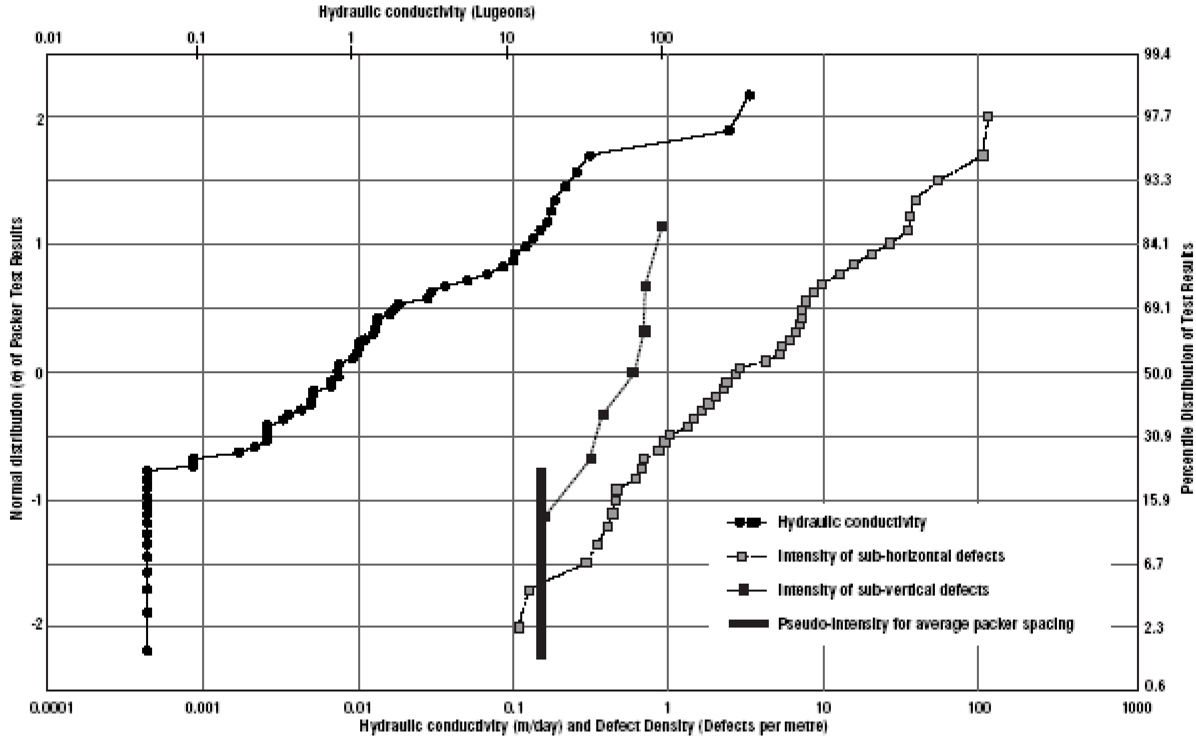


Figure 12: Comparison of hydraulic conductivity and defect density over the vertical depth interval 17.18m to 22.10m.

3.3 HYDRAULIC CONDUCTIVITY AND SCALE OF OBSERVATION

The presence of scale effects was investigated by comparing packer test results with the results from the two 48-hour pumping tests. Packer test results were compared to pumping test results by fitting 2nd degree polynomials to the log hydraulic conductivity versus depth distributions of the packer test results at both locations (so that no bias was introduced between interpolations) and integrating this function over the depth interval tested by the pumping tests. Equivalence in results was achieved by multiplying packer test results by a constant factor down the profile until the integration of the hydraulic conductivity function (equivalent to the transmissivity) equated the transmissivity assessed from pumping tests. Packer test results required upscaling by factors of 4.02 and 3.82 to match pumping test results for the Macquarie Park Station and Lane Cove River Valley sites respectively.

The tested volume of aquifer for each pump test was significantly greater than that for each packer test, and a comparison of the geometric mean hydraulic conductivity of packer tests and pumping tests reveals that the Hawkesbury Sandstone shows scale effects as reported in numerous other studies.

4 GROUNDWATER INFLOWS IN HAWKESBURY SANDSTONE

4.1 DRAINAGE

Some of the geotechnical factors generally considered in making the choice between drained and undrained design for basements and tunnels excavated in sandstone in the Sydney area include:

- discharge quantity and treatment of groundwater inflow;
- the effectiveness of ground treatment (eg grouting) in sealing transmissive zones;
- the effects of consolidation settlement due to groundwater table drawdown and
- the maximum likely groundwater level which would create uplift on the floor slab.

4.2 INFLOW

Measurements of water inflow have been made in several tunnels excavated in the Hawkesbury Sandstone in the Sydney Region. Measurements vary according to intersected lithology, the extent to which inflow has achieved equilibrium, depth of the tunnels, whether the tunnels are undrained or drained, climate effects, ventilation losses and the extent of ground treatment. Typical long-term extraction of water from the Eastern Distributor tunnel is reported to be approximately 1 L/s per kilometre of tunnel (PPK, 2000). Similar flows were predicted for the Cross City Tunnel (PPK, 2000; 2002). The average water egress the M5 East tunnels since the opening in December 2001 is 6-7 L/s for twin 4 km long tunnels, or between 0.75 L/s and 0.9 L/s per kilometre of single-tube tunnel.

To address inflows at localised features, there have been several instances of the use of microfine and/or ultrafine cements to reduce rock mass permeability to control groundwater inflow. These include:

- Northside Storage Tunnel beneath Middle Harbour (Gee et al., 2002);
- Sydney CBD and Sydney Park to Haymarket cable tunnels;
- Sydney LPG Gas Storage Cavern and
- ECRL at the Lane Cove River crossing and Macquarie Park fault zone.

Recently, several deep basements adjacent to the Harbour have been successfully constructed below groundwater level using a combination of bored pile walls and ground treatment using jet grouting techniques to control groundwater inflow, and thus permit design as a drained structure.

4.3 EPPING TO CHATSWOOD RAIL LINE

The ECRL is the NSW Government's largest publicly funded infrastructure project and among the most significant construction works currently being progressed in Australia. Construction has commenced on the Chatswood to Epping section of the route which is due to open in mid-2008. The major infrastructure components of the work currently underway include the construction of 13 km of twin rail tunnels (each of 7.2 m diameter) using TBMs, with four new underground railway stations. At the time of writing, TBM excavation is complete for the section from the M2 worksite to Epping.

The tunnels will be constructed mostly within the Hawkesbury Sandstone. The deeper parts of the sandstone aquifer generally behave in a semi-confined way. The caverns and tunnels for the ECRL will be fully lined, as the internal surfaces of the permanent linings require a complete absence of any leakage, seepage and damp patches. The caverns are designed as drained structures (that is, not subject to significant groundwater pressure). For the tunnels, the proposed delay period between tunnel boring and construction of the lining will be used to observe and monitor groundwater inflows. A combination of grouting works (targeted to intersect transmissive bedding horizons and near vertical defects) and undrained construction will be adopted in areas of high groundwater inflows to ensure that the inflows will satisfy the owner's requirements.

4.3.1 Running Tunnels

The economics of tunnel excavation using TBM equipment is predicated on rapid and uninterrupted machine advance. Large uncontrolled inflows and/or the stoppage or delay of tunnel drive for probe drilling and grouting are disadvantageous to TBM progress and performance. Therefore, one of the tasks undertaken during hydrogeological studies comprised the use of a numerical model for estimation of inflows to the entire alignment to identify the segments of the tunnels where the advance of the TBM might be impeded by groundwater inflows, where ground treatment would be required to meet the restrictive groundwater inflow criteria, and assess potential consolidation settlement.

For the numerical simulation of the ECRL alignment, the packer test hydraulic conductivity distribution for the Hawkesbury Sandstone was spatially partitioned into a number of zones, and upscaled by a factor of five. Anisotropy was incorporated as it played a major role due to the general azimuth of the alignment (almost normal to the major horizontal stress field). Inflows were quantified for tunnel lengths of not less than 100 m.

The inflow to the entire tunnel alignment from flow through sandstone (excluding large scale structural defects, the station caverns and the Lane Cove River) estimated from numerical simulation was 0.08 L/s per 100 m of twin tunnel. A recent pumping trial indicated an average groundwater inflow of between 0.075 and 0.1 L/s per 100 m of twin tunnel between Epping and the M2 work site (near Delhi Road Station – refer to Figure 2). However, this result included the inflow to the station caverns and inflow from large scale structural defects. When the additional estimated components of groundwater inflow to the station caverns and from large-scale structural defects are included, the predictive estimate is around 0.12 L/s per 100m. Thus the average measured inflow is between 63% and 83% of the numerical estimates, with the difference probably being accounted for by losses of groundwater to ventilation. It has also been observed that initial groundwater inflows encountered in the tunnels (for example at the excavation face) stabilise (reach equilibrium) in about four weeks from the time of encounter.

4.3.2 Lane Cove River Crossing

To assess inflow at the Lane Cove River crossing, a more detailed regional model was used to incorporate the significantly different conditions at the river crossing compared to the rest of the tunnel alignment. The Lane Cove River Valley where the cut-and-cover tunnel was constructed under the river is a palaeovalley comprising alluvial and estuarine sediments to depths of 17 m below ground level overlying fractured sandstone. High horizontal stresses have led to valley bulging and localised high permeability zones.

In this area, curtain grouting was adopted for the rock below the sheet piling of the perimeter coffer dam wall to limit inflows to the coffer dams. Pre-excavation grouting, using high early-strength ordinary Portland cement with plasticisers and micro-silica (“Grout Aid”) to improve the quality of the work, improve grouting efficiency and save time, was targeted to intersect the more transmissive features. The ground treatment was shown to be effective in reducing the log mean rock permeability from over 100 Lu to between 1 and 5 Lu, sufficient to address inflow criteria (further information can be obtained from Tunnels and Tunnelling International, Feb 2004, pp 14-18).

4.4 USE OF ANALYTICAL EQUATIONS

Heuer’s method (Heuer, 1995) is a semi-empirical method sometimes used to predict groundwater inflows to tunnels. This method uses the equation derived in Goodman et al. (1965) for steady-state inflow into a horizontal drain under the condition of a constant head boundary, and applies an empirical factor of 0.125 based on observations made in various projects by Heuer. This method is based on several major simplifying assumptions. A semi-numeric application of the method, using a probabilistic approach for hydraulic conductivity and a discretised approach for the elevation of the constant head boundary, has been proposed by Raymer (2001). This method is useful as a first approximation for expected inflows, and to assist decision making regarding waterproofing and ground treatment, based on conservative input parameters. However, more detailed estimates require the use of numerical methods due to the complexity in real spatial variations in hydraulic conductivity and hydraulic boundaries.

5 DISCUSSION AND CONCLUSION

From the analysis of the dataset, several salient features emerge for the hydraulic properties of Hawkesbury Sandstone in the study area. These are summarised below.

5.1 STRUCTURE

- The main orientation of sub-horizontal defects is a dip direction of about 45 degrees with respect to grid north. The main orientation of sub-vertical defects is a strike direction of 15 degrees with respect to grid north, sub-parallel to the major horizontal stress direction. Based on pump test results, anisotropy imparted to the lateral hydraulic conductivity field results in the average hydraulic conductivity being about 1.5 to 2 times higher in the direction of major horizontal stress than other directions.
- Spacing for sub-horizontal defects varies enormously, but is an arithmetic average of around 1m over most of the investigated depth profile. Spacing for sub-vertical defects is similar.
- Horizontal continuity of sub-horizontal defects is difficult to quantify. Depending on the type of cross-bed set, defects related to cross bedding may have upper bounds for their continuities ranging between 4 m and 40 m. For these types of defects, a continuity of at least 5 m, but probably around 10 m to 20 m, seems reasonable. Horizontal continuity of sub-vertical defects has no particular relationship with lateral spacing and can vary between 0.2 m and 20 m. Vertical continuity of sub-vertical defects generally ranges between 1 m and 3 m over a large range of lateral spacing (0.1 m to 10 m), indicating the propensity for these defects to terminate against sub-horizontal defects.
- Moving vertically or laterally, defects appear to occur in a cyclic pattern. For sub-horizontal defects, the cycle in the vertical direction with the highest probability of being observed is about 5 m, however this probability is small in absolute terms. Most cycles will range between 2 m and 10 m. For sub-vertical defects, the typical lateral cycle (based on limited data) is probably about 7 m but may increase with depth (possibly to around 10 m or more at 30 m depth).

5.2 HYDRAULIC CONDUCTIVITY AND GROUNDWATER INFLOW

- The hydraulic conductivity of the Hawkesbury Sandstone is related to defect characteristics, which in turn are heavily influenced by depth and *in situ* stress conditions. The hydraulic conductivity decreases with depth, due mainly to decreasing sub-horizontal defect aperture (from overburden pressure) with increasing depth. The influence of horizontal stress on the aperture of sub-vertical defects may be variable, depending on the orientation of the defect.

- The unscaled geometric mean hydraulic conductivity interpreted from packer tests varies from about 0.1 m/day (10 Lu or 1 x 10^{-6} m/s) near the surface to about 0.002 m/day (0.2 Lu or 2 x 10^{-8} m/s) at 50 m depth. The log standard deviation for hydraulic conductivity over 5 m depth intervals is typically about 1 log cycle, and comparable to the log standard deviation of sub-horizontal defect spacing. The hydraulic conductivity probability distribution within a small depth interval is likely to be a simple function of the probability distributions for sub-horizontal and sub-vertical defect density.
- Geometric mean hydraulic conductivity results from packer tests in the Hawkesbury Sandstone generally need to be upscaled by a factor of at least 5 to be comparable with expected hydraulic conductivities over a regional flow field applicable to assessment of inflows to tunnels and underground excavations.
- For the ECRL, measured inflows to date are between 63% and 83% of predictive estimates using numerical simulation, with the difference probably being accounted for by losses of groundwater to ventilation. The numerical simulation provided more reliable estimates than would be obtained using analytical or semi-empirical equations. There does not appear to be a strict correlation of hydraulic conductivity with the widely used Sydney rock class classification system (Pells et al., 1998), however the classification was developed primarily for foundation design and is based on rock strength, defect spacing, and allowable seams.
- At the Lane Cove River crossing, pre-excavation grouting using Portland cement and specialised additives including microfine cements reduced the average rock mass hydraulic conductivity from over 100 Lu to between 1 Lu and 5 Lu. Greater use of microfine or ultrafine cements would likely be required to achieve lower permeabilities in the sandstone.

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