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A Preliminary Study on the Thermal Properties of the Ground under Sydney Harbour and the Sensitivity of Tunnel Air Temperatures

D. Saunsbury[1], D. Fernandes[1] and D. Och[1]
[1]WSP Australia Pty Limited
Level 27, Ernst & Young Centre, 680 George Street
Sydney NSW 2000
AUSTRALIA
E-mail: Duncan.Saunbury@wsp.com

Abstract: *The thermal properties of the ground around tunnels is an important parameter in the design of tunnel ventilation systems, particularly for metro systems. The heat generated in metro tunnels is transferred through the tunnel lining and into the ground. The magnitude of this heat transfer is influenced by the composition of the ground surrounding the tunnel. Geological investigations into thermal properties of the ground in Sydney were conducted for the Sydney Metro City & Southwest Project. As part of the Reference Design process for the City Section of Sydney Metro, testing of borehole samples along the alignment was undertaken to determine the thermal conductivity and diffusivity of the ground around the tunnels. This paper presents the results and analysis of that testing. The sensitivity of tunnel air temperatures to the thermal properties of the ground is also presented from the Reference Design analysis using WSP's Subway Ventilation Simulation (SVS) software.*

Keywords: *Tunnel Ventilation, Ground thermal properties, Hawkesbury Sandstone, Ashfield Shale, Mittagong Formation, Harbour sediment, geology, Sydney Metro*

1. INTRODUCTION

Tunnel ventilation systems are incorporated into all underground rapid transit systems, such as the Sydney Metro, to not only control smoke in the event of a fire, but also control tunnel air temperatures during normal and degraded train operations. The control of tunnel air temperatures can be the defining criteria in the size and design of a tunnel ventilation system.

An important consideration in the design of tunnel ventilation systems, particularly for underground rapid transit networks, is the transfer of heat between the tunnel air and the surrounding ground through the tunnel lining. There can be significant sources of heat generation within the tunnels of a high frequency metro system, such as; train braking and acceleration, car air conditioning systems, friction and tunnel equipment. Depending on the ambient environment and the particular nature of the metro infrastructure, the tunnel air temperature can exceed the temperature of the tunnel wall surface. The tunnel lining and the surrounding ground will then act as a heat sink effectively helping reduce the tunnel air temperature.

Although the tunnel wall surface temperature will vary along its length, at any one location it will remain relatively stable over time. However, there is a long term thermal inertia caused by daily and annual variations of outside air temperature and variations in system utilisation. To accurately model the tunnel air temperature, the long-term heat transfer effect created by the temperature gradient between the tunnel air and the ground must be considered. The rate of heat transfer will be dependent on several factors including the temperature gradient and thermal transfer properties of the tunnel lining but will also depend on the thermal transfer properties of the ground. [1]

A detailed study of the thermal properties of the ground is often not practicable when designing a new metro system, particularly as these properties may vary along the alignment due to the non-homogeneity and anisotropy of the local ground composition. However, typical reference values for similar ground types may differ significantly from the actual local properties. During development of the Reference Design for the City Section of the Sydney Metro, testing of ground thermal properties was conducted on a selection of geotechnical borehole samples. This allowed for thermal properties to be determined at two locations of the 15.5 km twin tunnels from Chatswood to Sydenham. These inputs were used in the tunnel ventilation modelling and analysis to more appropriately design the tunnel ventilation system.

This paper describes the general ground composition along the alignment of the City Section of the Sydney Metro and the testing results of the ground thermal properties in each of the borehole samples collected. The sensitivity of these ground thermal properties on the tunnel air temperatures is subsequently presented. The tunnel ventilation modelling was conducted using the Subway Ventilation Simulation (SVS) software, which is a WSP developed proprietary version of the Subway Environmental Simulation (SES) software.

2. GEOLOGY OF SYDNEY METRO

The Sydney Metro alignment is located within the geological region known as the Sydney Basin. This basin developed during the Permian and Triassic Periods (298 to 200 million years ago) due to an infill of a thick sequence of sediments deposited in both marine and fluvial 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. [2]

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.

Tunnelling along the Sydney Metro alignment will dominantly be in rock of the Ashfield Shale, Mittagong Formation and Hawkesbury Sandstone. The alignment will also tunnel approximately 160m through a NW-SE trending deeply incised palaeovalley with a maximum depth of around - 56 m Australian Height Datum (AHD) consisting of a Holocene and Pleistocene (Quaternary) sediment infill up to 38 m thick. [3]

2.1. Hawkesbury Sandstone

The Hawkesbury Sandstone is typically a medium to coarse-grained sandstone. Published petrographic analysis of the sandstones indicates that 50% to 80% of the rock is made of fine to coarse quartz grains, with the cement/matrix comprising clay (5% to 40%), quartz cement (secondary silica, up to 20%), carbonate (Fe) cement (0% to 15%, up to 35%) and up to 5% pore space. Moisture content in the sandstones are on average 6.8%.

The stratigraphic units of the Hawkesbury Sandstone generally comprise three distinct facies types, each representing a differing depositional process, namely:

- Massive Sandstone facies
- Cross bedded or sheet facies (well developed or indistinct/poorly developed)
- Shale/siltstone interbed facies.

2.2. Mittagong Formation

The Mittagong Formation lies conformably below Ashfield Shale and consists of alternating dark shale and sandstone beds and laminae of varying thickness and often disturbed by soft sediment deformation and bioturbation with an average thickness of about 6 m. The interbedded siltstone and fine sandstone are termed laminites and are comparable with those of the overlying Ashfield Shale, but are distinguished by the presence of dominantly siltstone of the Rouse Hill Siltstone Member above a laminite layer that grades into thicker interbeds of siltstone and sandstone with similar properties to the Ashfield Shale below.

2.3. Ashfield Shale

This rock unit is up to 50 m thick and comprises four members as defined by Herbert (1983) [4] and which are all present along the underground Sydney Metro alignment:

- Mulgoa Laminite Member – comprises dark grey siltstone and fine light grey sandstone laminations.
- Regentville Siltstone Member – comprises dark grey sideritic-banded siltstone that gradationally underlies the Mulgoa Laminite with a sharp boundary at its base.
- Kellyville Laminite Member –comprises a light-grey siltstone and fine to medium-grained sandstone laminations.
- Rouse Hill Siltstone Member –comprises a dark grey to black sideritic claystone - siltstone, which can be slightly carbonaceous at its base and has an increase in faint siltstone laminations towards the top.

These laminated rocks are dominantly highly anisotropic with a lower strength parallel to bedding. These rocks are not visibly porous (<1% pores) but do absorb water slightly with an average moisture content of 3%. The laminite layers comprise between 3% to 30% fine-grained quartz. The remaining rock component comprises carbonated clasts and cement (up to 20%) and sericitic/illitic clay cement variably stained by secondary iron oxides (up to 80%).

2.4. Quaternary Sediments

The Sydney Harbour crossing is defined by five distinctive sediment units as shown in Figure 1. The tunnel will transition out of Hawkesbury Sandstone into a firm to very stiff clay and silty clay (80%) with some interbeds of sandy fines and shells (Unit 3) and silty sand (70%) with interbeds of silty clay (20%) and includes sub-rounded gravels, charcoal layers and wood fragments (Unit 4) then transitioning through a buried colluvial deposit (Unit 5) into the Hawkesbury Sandstone.

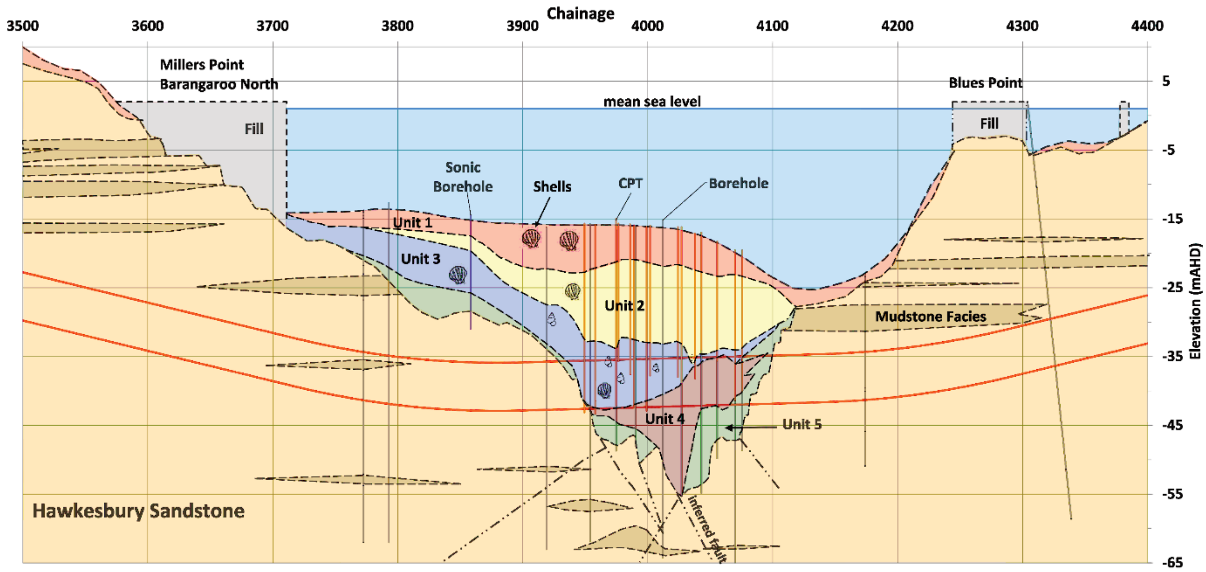

Figure 1 Sydney Harbour crossing profile with characterised sediments [3]

3. GROUND THERMAL PROPERTIES

The parameters used to describe the thermal properties of the ground for tunnel ventilation modelling and design are typically the Thermal Conductivity and Diffusivity. Indeed, these parameters are a direct input into the SVS software. Legacy values for conductivity and diffusivity of sandstone of 1.80 W/m·K and 1.15 E^{-6} m^2/s respectively, have been used for the design of tunnel ventilation systems on several previous major infrastructure projects in Sydney.

For the Sydney Metro City & Southwest Reference Design, Thermal Resistivity testing was conducted on a selection of geotechnical borehole samples to either verify the legacy values or provide more appropriate design information. Thermal resistivity is simply the inverse of conductivity.

3.1. Thermal Resistivity testing

Laboratory testing of Thermal Resistivity was performed on nine geotechnical borehole samples taken along the alignment of the City Section of Sydney Metro. Samples were selected from both the Marrickville area and the Sydney Harbour crossing. Samples were chosen to provide information on both the sandstone and sedimentary material which the tunnels will pass through. The details of these borehole samples are presented in Table 1.

Table 1 Borehole samples tested for Thermal Resistivity

Test ID	Borehole	Borehole sample depth	Location	Material type
01	SRT BH004	40.7-40.9 m	Marrickville	Siltstone (Ashfield Shale)
02	SRT BH004	41.75-42.00 m	Marrickville	Medium-grained sandstone (Mittagong Fm)
03	SRT BH004	59.08-59.31 m	Marrickville	Medium to coarse-grained sandstone (Hawkesbury Sandstone)
04	SRT BH203	27.0-27.2 m	Sydney Harbour	Medium-grained sandstone (Hawkesbury Sandstone)
05	SRT BH210	41.75-42.00 m	Sydney Harbour	Medium to coarse-grained sandstone (Hawkesbury Sandstone)
06	SRT BH206	23.4-23.6m	Sydney Harbour	Silty clay (sediment)
07	SRT BH206	23.6-23.8m	Sydney Harbour	Silty clay (sediment)
08	SRT BH206	24.3-24.5m	Sydney Harbour	Silty clay (sediment)
09	SRT BH206	24.5-24.7m	Sydney Harbour	Fine to medium -grained sand (sediment)

The Thermal Resistivity testing conducted was done in accordance with IEEE Standard 442 [5], ASTM Standard D5334 [6] and Ausgrid NS130 Appendix K [7]. The results of the Thermal Resistivity testing are provided in Table 2.

Table 2 Thermal Resistivity (TR) - Borehole core sample test results

Test ID	Moisture Content (% dry weight)	Pre Dry-Out TR (K·m/W)	Approximate Dry Density (kg/m^3)	Fully Dry TR (K·m/W)
01	1.9	0.70	2480	0.88
02	1.0	0.73	2560	0.77
03	6.2	0.72	2200	0.97
04	5.9	0.78	2250	1.02
05	6.6	0.81	2200	1.01
06	51.3	0.85	N/A	1.95
07	49.3	0.95	N/A	2.54
08	35.4	0.72	N/A	1.99
09	23.1	0.52	N/A	1.58

Tunnel alignment remains below the water table for the majority of the alignment. The sandstone has a porosity of around 4-10% of its mass which act as conduits for ground water to flow through. Sydney sandstone also has zones of faulting or fractures which also act as conduits for groundwater flow.

Based on these factors it is assumed that the sandstone surrounding the tunnels will be fully saturated for the majority of the alignment.

The condition of the borehole test samples at time of testing would have been of a moisture content less or equal to the in-situ moisture content of the samples. This is due to uncertainty in the condition and process that the samples were subjected to prior to testing. If un-protected the samples naturally dry out relatively quickly. A conservative assumption could therefore be made that the pre-dry out moisture content of the samples is equal to the in-situ moisture content of the ground conditions.

The pre dry-out thermal conductivity of the sandstone (Test ID 01-05) ranges from 1.23 to 1.43 W/m·K. The pre dry-out thermal conductivity of the sedimentary material (Test ID 06-09) ranges from 1.05 to 1.92 W/m·K.

3.2. Thermal Diffusivity

Thermal Diffusivity can be calculated from the conductivity, density and specific heat capacity with the following equation:

$$a = \frac{k}{\rho c_p} \tag{1}$$

Where
a = Thermal Diffusivity (m^2/s)
k = Thermal Conductivity (W/m·K)
ρ = density (kg/m^3)
c_p = Specific heat capacity (J/kg·K)

The specific heat capacity of the borehole samples was not tested and therefore it has not been possible to directly derive a diffusivity value. Although the thermal diffusivity is an important parameter, the tunnel ventilation modelling, shown in Section 4, indicates that tunnel air temperature is less sensitive to the ground thermal diffusivity than conductivity. Further investigation is required to develop an accurate estimation of the thermal diffusivity of the borehole sample.

Work done by Konakova et al [8] on the thermal properties of selected sandstones quarried in the Czech Republic, provided a range of specific heat capacities from 646 to 801 J/kg·K. By applying this specific heat capacity range to the corresponding minimum and maximum values of the tested sandstone conductivity, a maximum range of sandstone diffusivity values can be derived, as shown in Table 3.

Table 3 Derived thermal diffusivity range

Thermal Conductivity (W/m·K)	Wet Density (kg/m^3)	Specific Heat Capacity (J/kg·K)	Thermal Diffusivity (m^2/s)
1.43	2527	645.62	8.76E^{-07}
1.23	2345	801.23	6.57E^{-07}

4. SENSITIVITY OF TUNNEL AIR TEMPERATURES

The sensitivity of the tunnel air temperature to the ranges of thermal conductivity and diffusivity from the tested sandstone and sediment borehole samples is shown in the figures below. The results shown are from an indicative normal operations scenario from the SVS modelling that was conducted for the Reference Design of the City section of the Sydney Metro. The modelling results shown are for the purposes of demonstrating sensitivity only and are not necessarily indicative of the final Reference Design. Only a portion of the City section is shown to aid legibility.

The results provided show the tunnel air temperatures for a summer afternoon peak period after 30 years of operations. The ambient air temperature is set at 31.9°C dry bulb and the deep sink ground temperature at 17.8°C. The tunnel ventilation system is operating in draught relief mode combined with an active station trackway exhaust system.

For comparison, the legacy values of conductivity and diffusivity used on previous Sydney tunnel infrastructure projects is also shown.

4.1. Thermal Conductivity

To demonstrate the sensitivity of tunnel air temperature to the ground thermal conductivity, the maximum and minimum values from the tested sandstone borehole samples have been applied. Only the sandstone values have been used as the majority of the tunnel alignment will be in sandstone. Each thermal conductivity value has been applied as a constant value along the entire length of the alignment. In addition to the range measured from the borehole sample, the legacy thermal conductivity value of 1.8 W/m·K has also been applied. The resultant tunnel air temperatures for these conductivity values are shown in Figure 2. The results show an approximately 1°C temperature difference between the conductivity values measured from the borehole sample. There is a further 2-3°C between these results and the legacy thermal conductivity value.

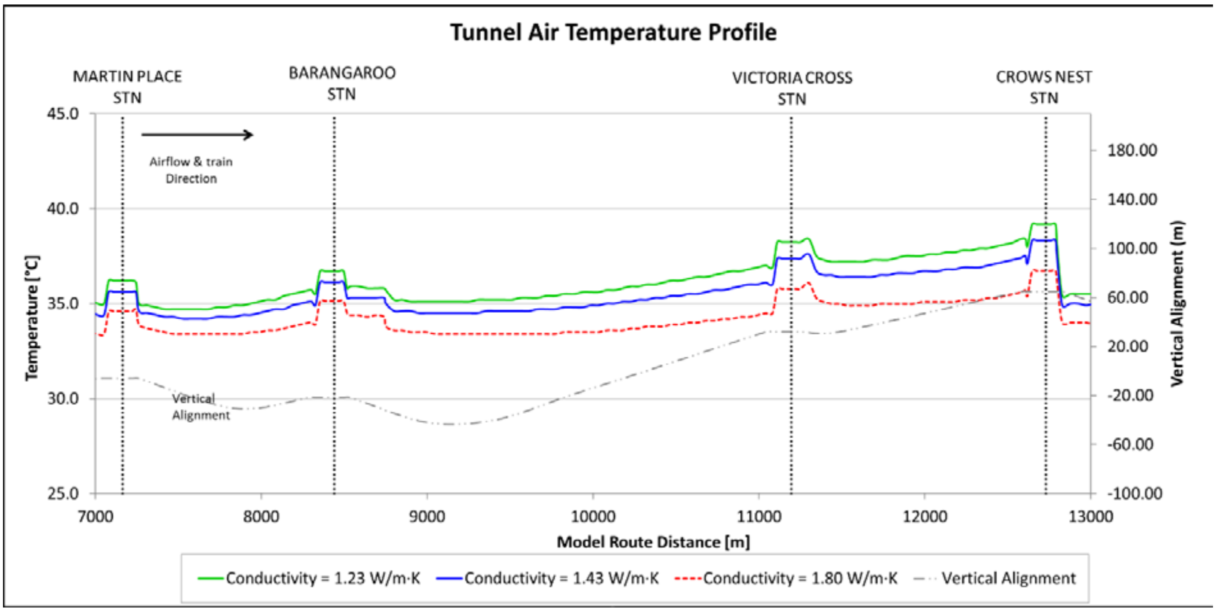

Figure 2 Sensitivity of tunnel air temperature to ground thermal conductivity

4.2. Thermal Diffusivity

The maximum and minimum from the derived thermal diffusivities of sandstone has been applied as a constant value along the entire length of the alignment. The sensitivity of the tunnel air temperature is shown in Figure 3. The tunnel air temperature, in this particular scenario, is relatively insensitive to the range of thermal diffusivity values derived for the sandstone borehole samples. Even with the legacy diffusivity value of $1.15E^{-06}$ m^2/s applied, which is outside of the range derived from the borehole samples, the tunnel air temperature is still within approximately 1°C.

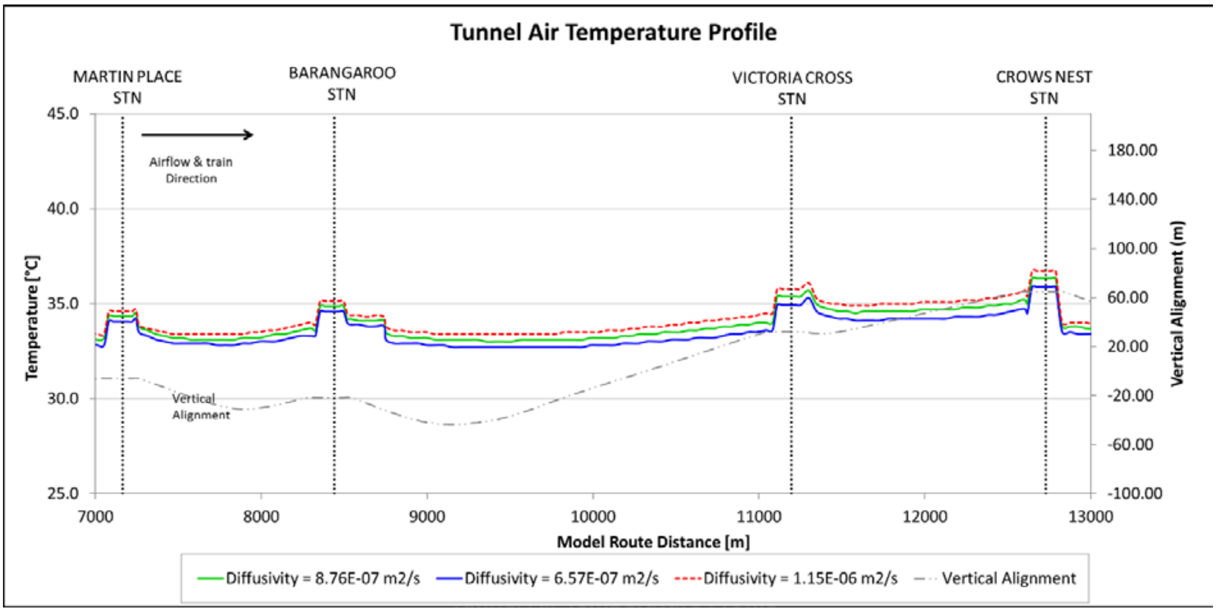

Figure 3 Sensitivity of tunnel air temperature to ground thermal diffusivity

5. CONCLUSIONS

Thermal resistivity testing was conducted on a selection of geotechnical borehole samples taken on the alignment of the City Section of the Sydney Metro during Reference Design.

The results of this testing produced thermal conductivity values ranging from 1.23-1.43 W/m·K for the sandstone samples and 1.05-1.92 W/m·K for the sedimentary material samples. Although only a limited number of samples were tested, the range of results for sandstone are significantly below a legacy value of 1.80 W/m·K which has been used for sandstone on several Sydney tunnel infrastructure projects in the past.

The sensitivity of the tunnel air temperature to these ranges of thermal conductivity was tested through SVS modelling for an indicative normal operations scenario conducted for the Reference Design of the City Section of the Sydney Metro. The difference in tunnel air temperature between the legacy conductivity value and the tested sandstone values peaked at 2-3°C.

A range of thermal diffusivity values was also derived from the borehole sample testing. The specific heat capacity of the borehole samples was not known and therefore a range of specific heat capacities was applied to derive diffusivity values. The diffusivity values derived for the sandstone samples ranged from 8.76E^{-07}-6.57E^{-07} m^2/s. It is noted that further investigation is required to derive more accurate values for the borehole samples tested. The diffusivity values derived are lower than the legacy value of 1.15 E-6 m^2/s which has been used for sandstone on several Sydney tunnel infrastructure projects in the past. The sensitivity analysis has shown that the tunnel air temperature, for the scenario tested, is relatively insensitive to the range of diffusivity values derived and the legacy value.

6. ACKNOWLEDGMENTS

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