PUMPING TEST EFFECTS ON GROUNDWATER AND SETTLEMENT FOR WATERVIEW TUNNEL

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ABSTRACT

The New Zealand Transport Agency has applied to construct 5 km of new state highway in Auckland as part of the Waterview Connection project including a 2.5 km tunnel section excavated primarily within the East Coast Bays Formation (ECBF) of the Waitemata Group. Depending on the approach to tunnel construction, any inflows to the tunnel and the subsequent drawdown of groundwater levels may cause settlement of compressible soils, which may result in settlement of overlying structures. Other effects include the potential to reduce base flows in nearby Oakley Creek and the potential to spread contaminants from former landfill areas.

This paper describes two contrasting long duration pumping tests with an unusually comprehensive monitoring regime. The approach was designed to help assess the potential effects of constructing the tunnel in "open mode". Although the pumping bores are close together, the response to pumping was very different with the first test located in an area of significantly higher permeability.

The data from the pumping tests on the behaviour and variability of the Waitemata Group and overlying formations will inform selection of the construction method for the tunnel and improve understanding of the potential effects, and will also be of benefit to future projects within the same hydrogeological setting.

KEYWORDS

Groundwater, drawdown, pumping test, monitoring, Waitemata Formation, Tauranga Group, ground settlement, tunnel.

1 INTRODUCTION

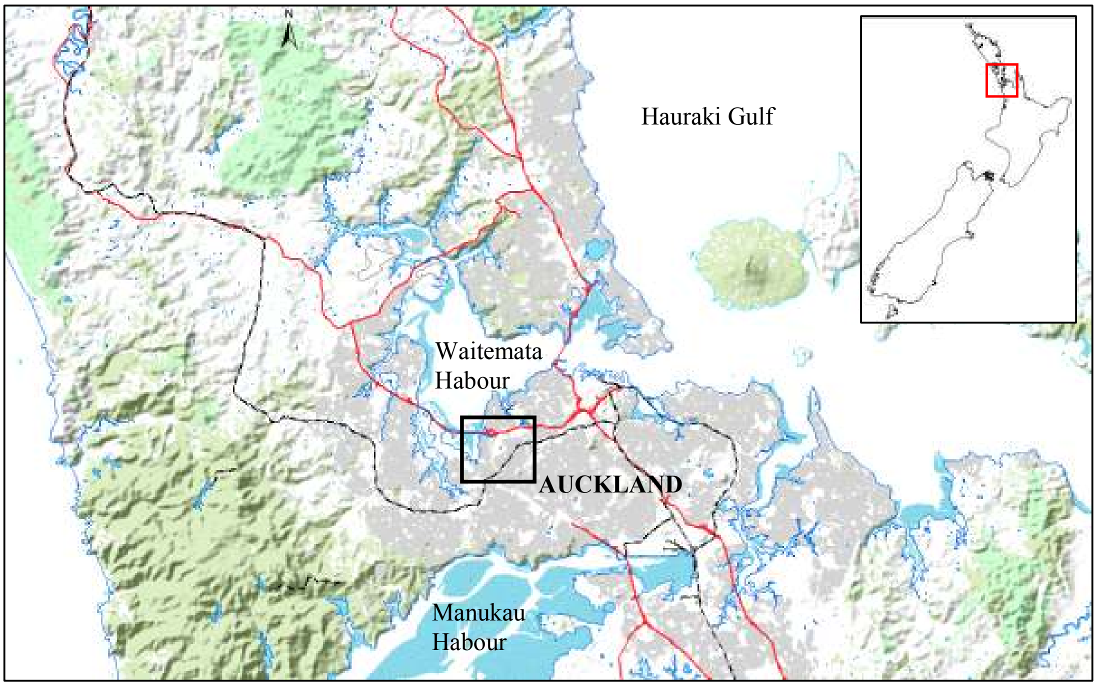
The New Zealand Transport Agency (NZTA) has applied to construct 5 km of new state highway in Auckland as part of the Waterview Connection project including a 2.5 km tunnel section with three lanes in both directions. The new highway would link State Highway 16 and State Highway 20 between their current Great North Road and Maioro Street exits. The NZTA has applied for designation and resource consents under the new national consenting process through the Environmental Protection Authority (EPA). Waterview is the first roading project to use this process for projects of national significance. Figure 1 shows the location within Auckland.

The Waterview tunnel section comprises two separate tunnels which will be bored with a Tunnel Boring Machine (TBM) rather than through the cut and cover approach. The tunnel would primarily be excavated within the East Coast Bays Formation of the Waitemata Group. Different approaches to tunnelling can be used depending on the expected groundwater regime and water pressures. TBMs can be operated either as a sealed system in "closed mode" where ground and groundwater pressures are balanced at the tunnel face and water is prevented from entering the tunnel; or in "open mode" where groundwater inflows occur at the face prior to installation of a lining.

If the tunnel is constructed in "open mode", any groundwater inflows to the tunnel will lead to drawdown in groundwater levels. Drawdown of groundwater levels may cause settlement of compressible soils due to a reduction in pore water pressure, which may result in settlement of overlying structures. Other effects include the potential to reduce base flows in nearby Oakley Creek and the potential to spread contaminants from former landfill areas.

This paper describes two long duration pumping tests that have been undertaken on bores in Mount Albert, Auckland, one situated in Phyllis Reserve, and the other in the car park of the local Pak 'n Save supermarket. The two bores were selected because potential groundwater inflows to the tunnel (assuming "open mode" construction) were expected to be high compared to the remainder of the tunnel alignment due to the presence of zones of higher permeability Parnell Grit. The primary objectives of the tests were to provide new data on the drawdown response in the Waitemata Group, to identify the extent of any high permeability zones, to investigate the hydraulic linkage with the former landfills and to identify any effects on Oakley Creek stream flows. Additionally, the tests aimed to provide new information on the drawdown response in upper formations to inform the settlement assessment, including the development of perched zones and their mitigative effect on drawdown in compressible sediments.

Figure 1: Location Map



2 APPROACH

2.1 GEOLOGY AND HYDROGEOLOGY

The Waterview Connection route alignment follows an incised stream valley (Oakley Creek) between the western edge of Mount Albert volcano lava and the Great North Road / Blockhouse Bay Road ridge. The tunnel will primarily be excavated within the East Coast Bays Formation (ECBF) of the Waitemata Group which was deposited in a generally low energy marine environment between 24 and 18 million years ago. Periodic dense gravity flows give rise to the characteristic alternating siltstones and sandstones. Over the past 18 million years, the Waitemata Group sediments were uplifted and weathered with alluvial deposits of the Tauranga Group (TG) deposited along the ancient alignment of Oakley Creek. The Mount Albert volcanic eruption 30,000 years ago caused the creek to establish its present course along the western edge of the lava flow. Figure 2 shows the geology of the area and location of the two pumping bores.

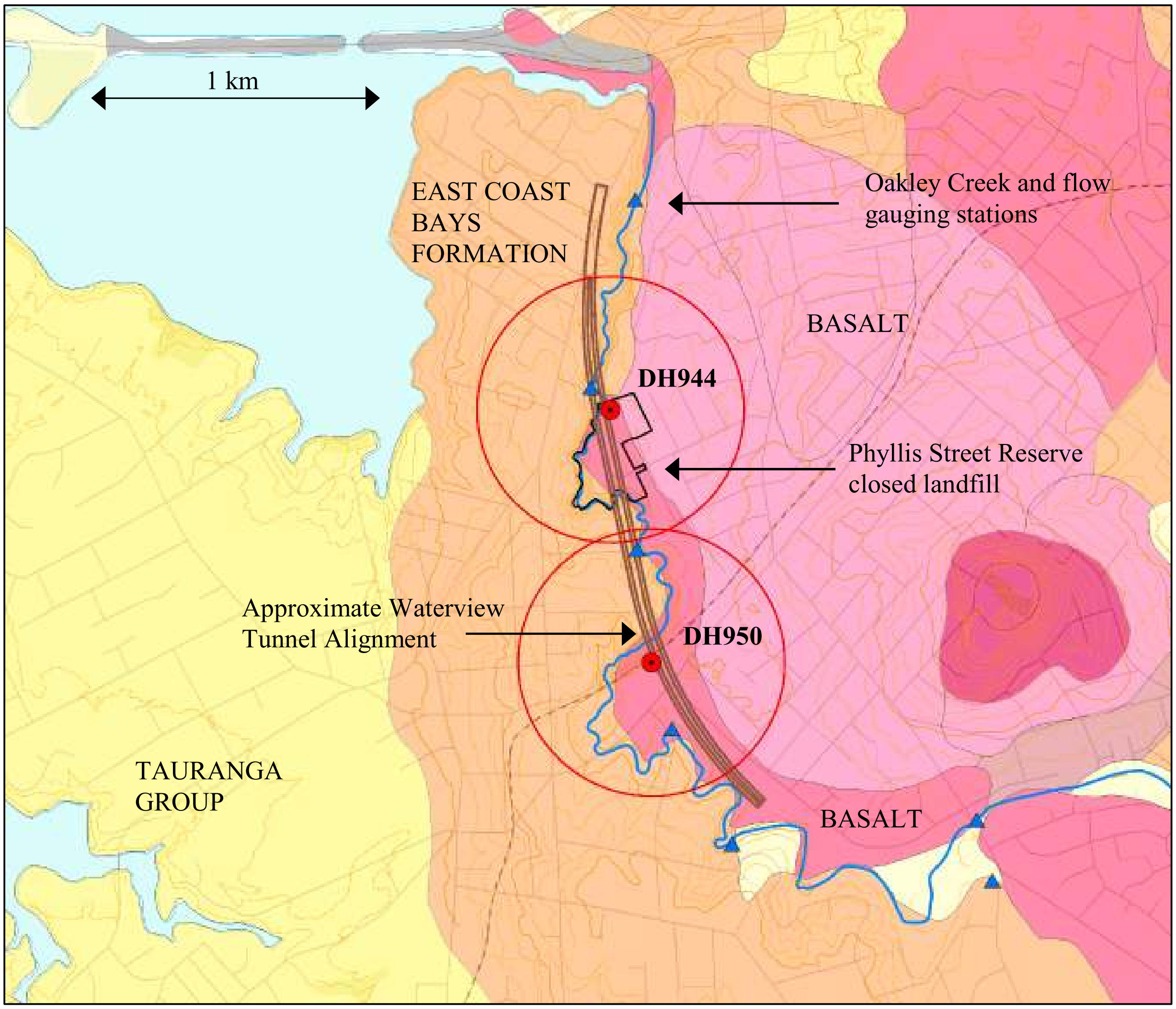
The weathered ECBF, unweathered ECBF and TG all have similar generally low permeabilities. However, there is vertical anisotropy in the sequence due to layering and bedding. Additionally, there is variability in the ECBF, in particular the presence of Parnell Grit, deposited by dense gravity flows, which has a higher permeability.

Groundwater flow through the ECBF in the Phyllis Reserve area is locally towards Oakley Creek where groundwater discharge occurs. This local pattern of flow towards the creek is superimposed on a general regional north-westerly flow direction towards the coast. Monitoring data collected for the Waterview

Connection project indicates that seasonal variations in the water levels are generally less than 0.5 m in the ECBF.

The basalt is considered to be a separate unconfined aquifer system, and basalt groundwater levels respond directly to rainfall. The relatively high hydraulic conductivity basalt is underlain by the lower hydraulic conductivity TG silts and clays. The dominant flow in the basalt is in a north westerly direction to discharge zones along Oakley Creek. Additionally, groundwater is expected to flow from the basalt aquifer into the closed landfill underlying Phyllis Reserve.

Figure 2: Geology and location of pumping bores



Prior to the two long term pumping tests, data on aquifer properties in the Waterview area was available from in-situ packer tests undertaken during drilling, slug tests, and six previously conducted pumping tests on wells screened in the basalt, ECBF and Parnell Grit. The previous pumping tests were all less than seven days in duration and showed that when dewatered the ECBF locally under-drains the TG, resulting in drawdown in water levels within the TG.

2.2 TEST SET UP

2.2.1 PUMPING BORES

Prior to starting the main pumping test, a step test on the Phyllis Reserve pumping bore (DH944) (shown in Photograph 1) was used to measure well performance. The well was pumped up to a maximum pumping rate of

1400 m^3/d. Following the step test, the bore water level was allowed to recover to its natural condition. The main pumping test commenced on 7 February 2011 at 2:56 pm.

The Pak 'n Save pumping bore (DH950) (shown in Photograph 2) was tested on 14 and 15 April 2011 to determine the pumping rate that could be sustained during the constant rate pumping test. The constant rate pumping test commenced on 16 April at 9:51 am.

The two bores were pumped continuously for 30 days (DH944) and 17 days (DH950) respectively to allow drawdown effects to spread widely. The water levels recovered back to natural conditions before the start of the test on DH950.

Photograph 1: Phyllis Street pumping test: pumped bore DH944

Photograph 2: Pak 'n Save pumping test: pumped bore DH950

Table 1 summarises the construction details and geology of the two pumping bores

Table 1: Pumping bore details

	DH944: Phyllis Reserve	**DH950: Pak 'n Save**
Ground level	31.1 mRL	40.1 mRL
Geology	0 – 12.6 mBGL: landfill debris 12.6 – 15.2 mBGL: TG 15.2 – 21.1 mBGL residually weathered ECBF 21.1 – 21.7 mBGL: highly weathered EBF 21.7 – 100 mBGL: moderately, slightly and unweathered ECBF	0 – 5.3 mBGL: basalt 5.3 – 14.9 mBGL: TG 14.9 – 99.6 mBGL slightly and unweathered ECBF
Bore construction details	0 - 38 mBGL: Plain casing 38 - 50 mBGL: Slotted casing 50 - 56 mBGL: Blank casing to house the pump 56 - 100 mBGL: Open hole	0 - 54.3 mBGL: Plain casing 54.3 - 99.6 mBGL: Open hole
Pump details	Pump intake: 54 mBGL (-22.89 mRL) Grundfos SP-45-9 (three phase) pump	The pump intake: 72.5 mBGL (-32.41 mRL) Grundfos SP-8A-25 (three phase) pump

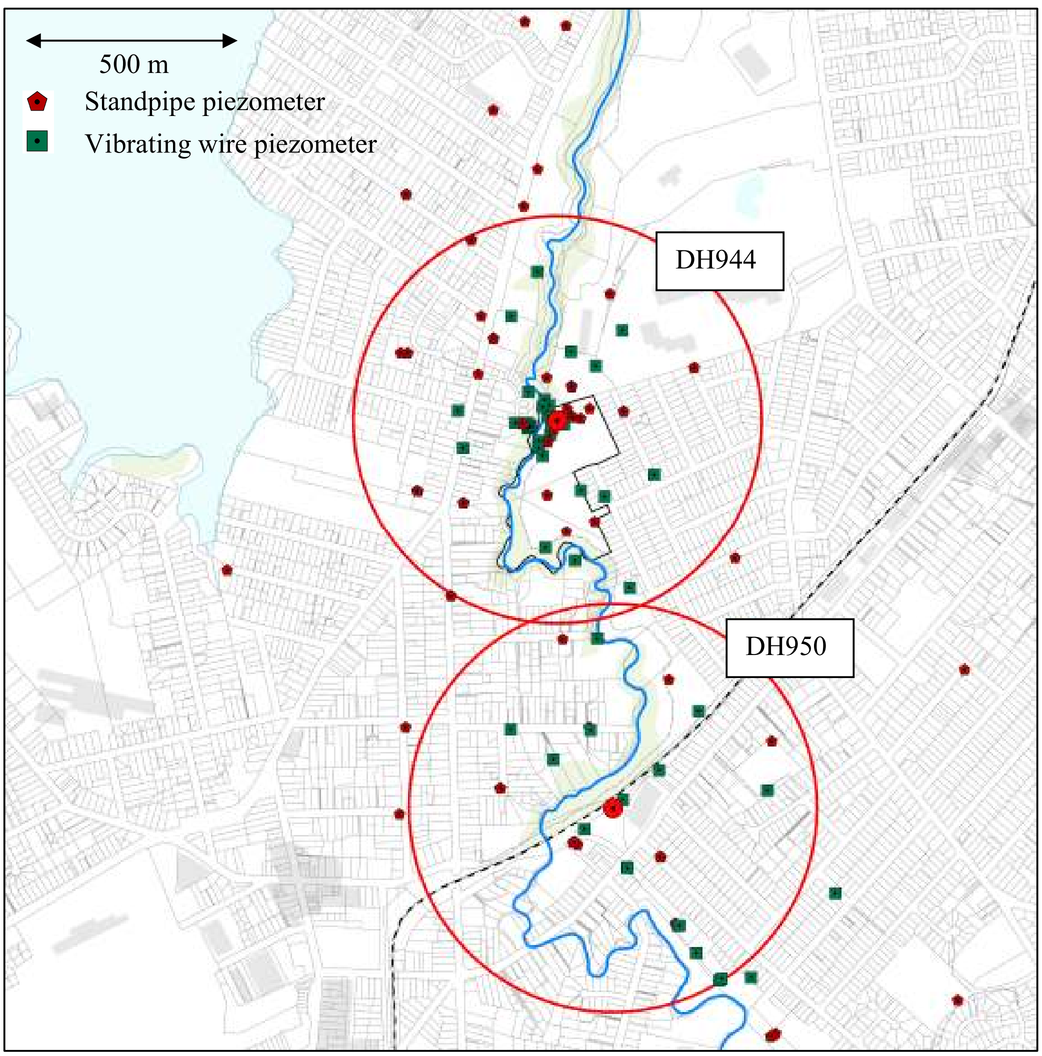
2.2.2 MONITORING REGIME

A comprehensive regime of groundwater monitoring was implemented, with piezometers located up to approximately 1 km from the pumping bores at varying depths to cover all geological formations. The piezometer locations are shown in Figure 3. During the Phyllis Reserve pumping test on DH944, groundwater levels were recorded at 81 bores, many of which recorded groundwater levels at multiple depths, giving a total of 136 individual piezometers. A total of 90 individual piezometers were monitored in the test on DH950. Two types of piezometer were monitored: standpipes and vibrating wire pressure transducers. Barometric pressure transducers were positioned in the area to allow data to be corrected for atmospheric pressure changes during the tests.

During the tests manual measurements of the electrical conductivity, pH and temperature of the water pumped from the bores were taken. Additionally, three samples of the water from the pumping bores were taken for laboratory analysis to record any changes in water chemistry during the pumping test. The discharge from the pumping bores was recorded throughout the two tests using volumetric measurements. Rainfall data and data on the flow in Oakley Creek were obtained from NIWA after the end of the two tests.

A baseline settlement monitoring network for the Waterview Tunnel was installed during 2011. Monitoring locations surrounding the two pumping bores were surveyed before, during and at the end of the test to record any vertical deformation of the land surface.

Figure 3: Groundwater monitoring regime: both tests



2.3 RESULTS

2.3.1 RESPONSE IN PUMPING BORES

Although the two pumping bores are less than 1 km apart, the results showed that the response to pumping was very different in each test. The first test on DH944 in Phyllis Reserve was undertaken in an area of higher permeability with a pumping rate of between 1400 m^3/d and 630 m^3/d. In contrast, in the second test on DH950 flow rates above 40 m^3/d could not be sustained due to the lower permeability in this area. DH950 was pumped for 17 days at approximately 25 m^3/d. In both tests, the maximum drawdown in the pumping bores had been reached by the end of the test.

Figure 4 shows the drawdown in DH944 and discharge during the main 30 day pumping test. The semi-log plot of drawdown shown in Figure 5 indicates a dual porosity effect, with the influence of delayed yield causing the rate of drawdown to decrease after approximately 20,000 seconds (0.2 days). Prior to this, flow towards the well is likely to be predominantly through fractures, with increasing flow from the matrix after 0.2 days (and potentially also from overlying less permeable formations) causing the reduction in the rate of drawdown. Between approximately 2.6 days (225,000 seconds) and 3 days after pumping, the gradient of the drawdown curve steepened beyond the theoretical prediction. This suggests that the cone of depression may have intercepted a boundary or a zone with reduced permeability. The maximum drawdown in the pumping bore stabilised at approximately 35 m after three days of pumping until the end of the test. The pumping bore discharge gradually reduced after the maximum drawdown was reached, generally in accordance with the typical decay of groundwater inflows during a constant head test.

Figure 4: Drawdown in DH944 and pumping rate versus time

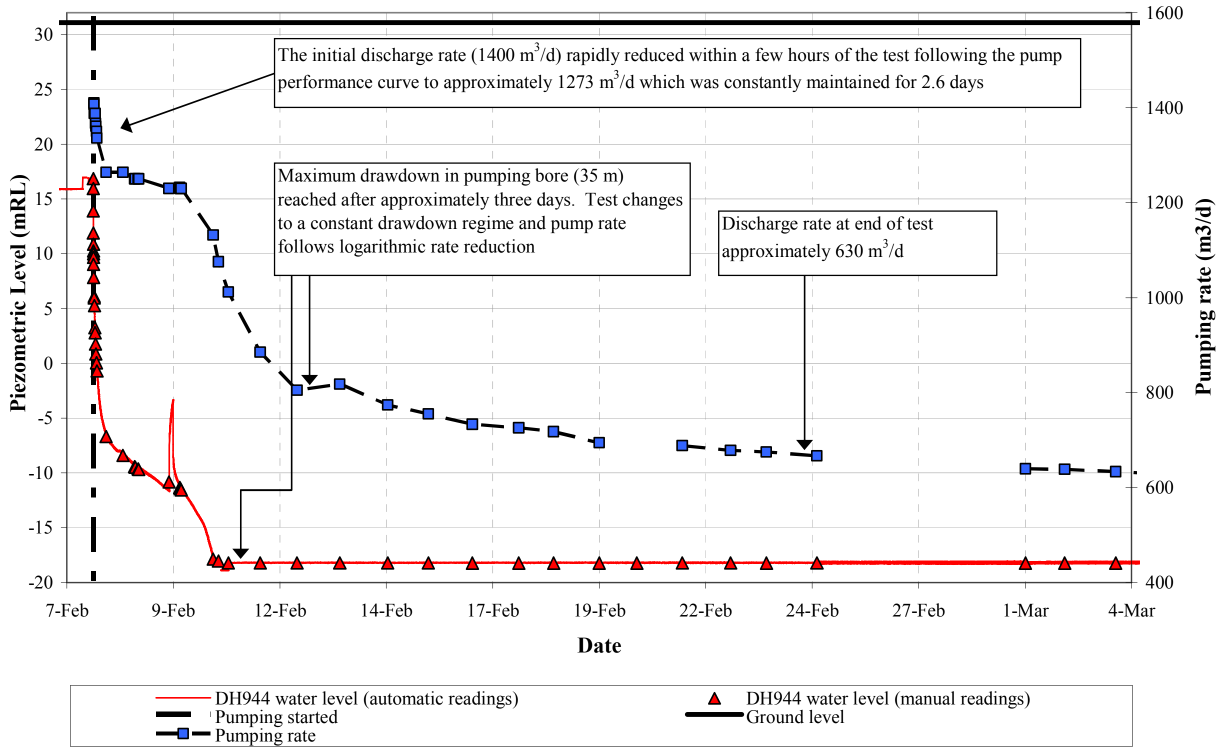


Figure 5: Drawdown in DH944 versus time: semi logarithmic plot

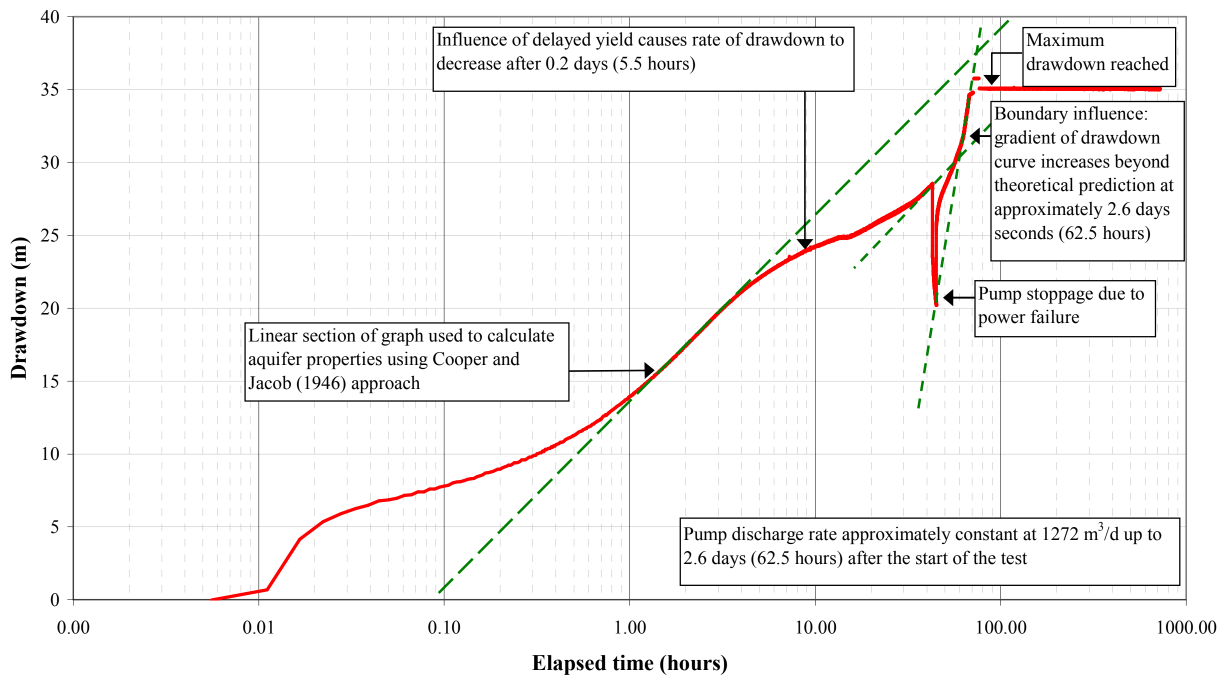
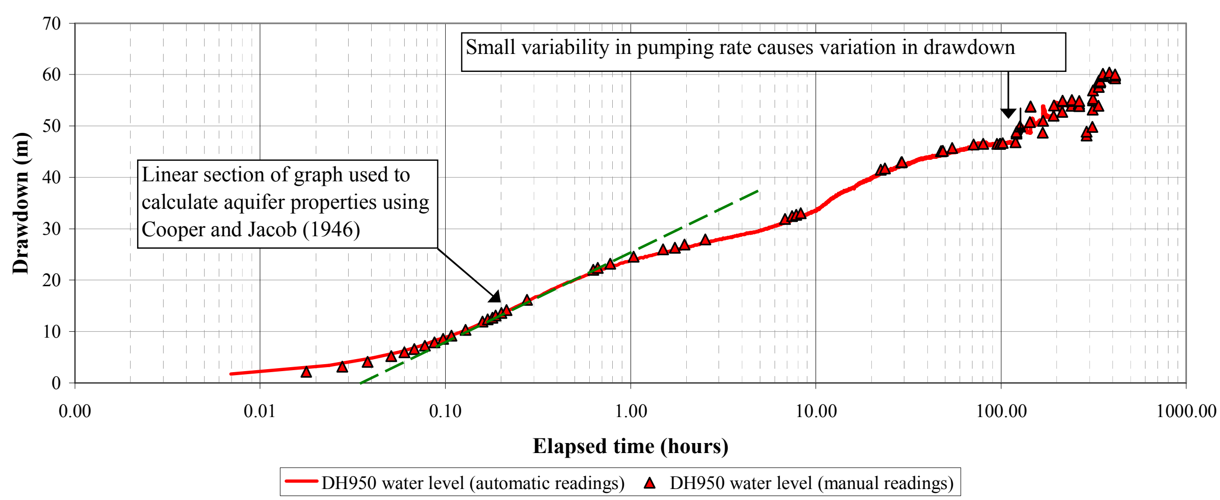


Figure 6 shows the drawdown versus elapsed time for the DH950 pumping test. The water level rapidly reduced within a few hours of the test start on the 16 April, and then declined more gradually to the 1 May beyond which the water level remained approximately constant to the end of the test on the 3 May. A minimum water level of -28.4 mRL was observed, corresponding to a maximum drawdown of 60.4 m. The pumping rate was approximately maintained at 25 m^3/d (within 3 m^3/d) to the end of the test. The semi-log plot of drawdown shown in Figure 6 also indicates a dual porosity effect.

Figure 6: Drawdown in DH950 versus time: semi logarithmic plot

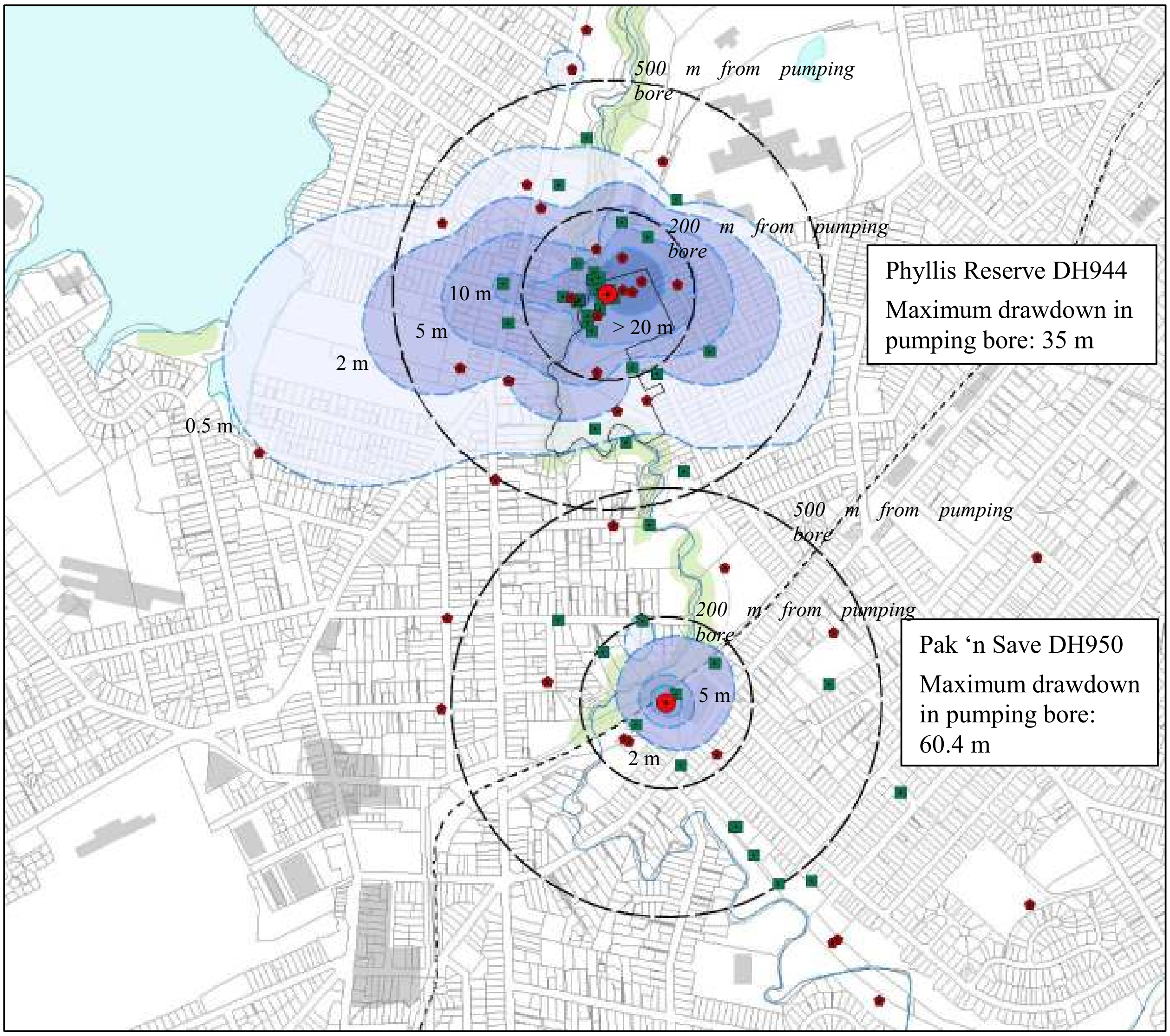


2.3.2 EFFECTS ON GROUNDWATER LEVELS

The drawdown effects observed during the pumping test are considered to provide a good indication of what could be expected during tunnel construction, assuming “open mode” operation. Although the pumping bores have a radial effect on groundwater levels around a single point, rather than a linear feature such as the tunnel, the inflow zone to the pumping bores was set at approximately the same elevation as the tunnel. The extent and magnitude of drawdown will also influence the extent and magnitude of potential settlement, discussed in Section 2.3.6.

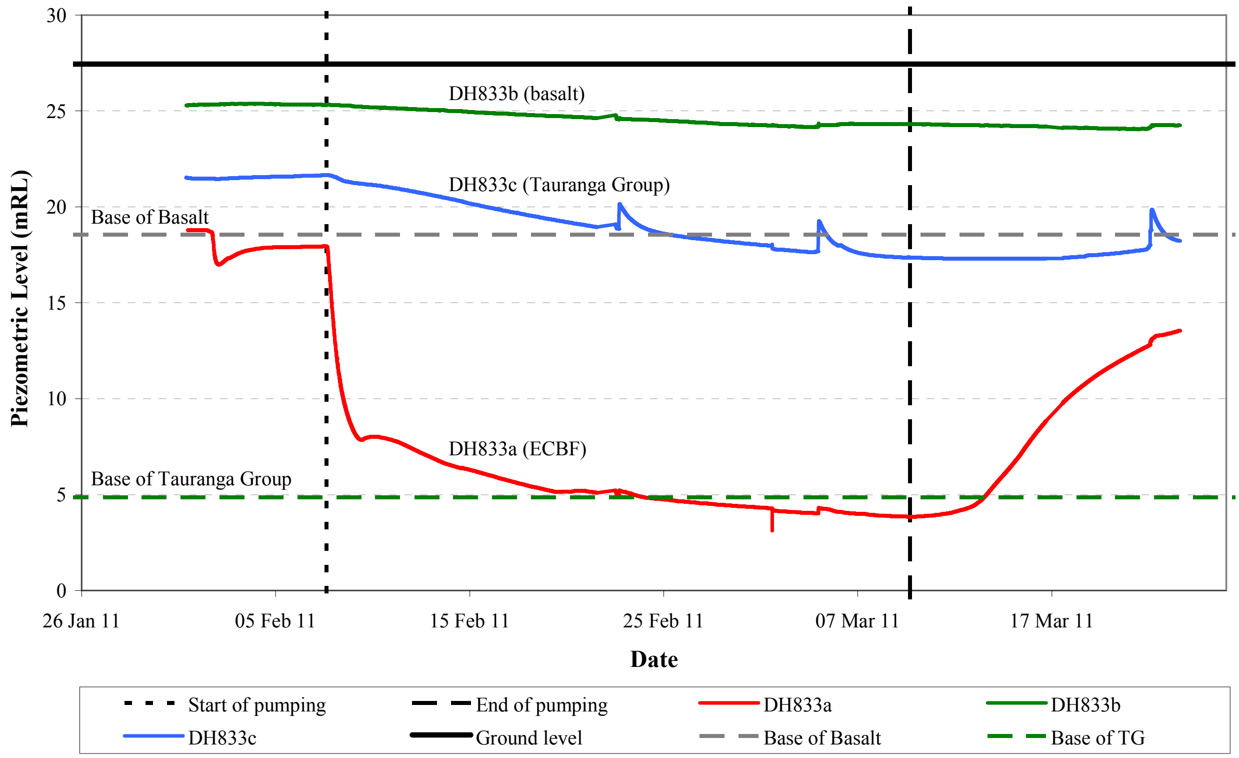
Figure 7 shows the estimated contours of maximum drawdown in the unweathered ECBF piezometers for the two tests on the same plot. In the Phyllis Reserve pumping test on DH944, drawdown was observed in piezometers up to 550 m away, with variations depending on depth and formation. The Hantush Jacob method for a leaky aquifer (Kruseman and de Ridder, 1994) was used to extrapolate the maximum estimated extent of drawdown as 900 m. In contrast, during the Pak ‘n Save test, no bores more than 200 m from the pumping bore showed a response to pumping.

Figure 7: Maximum drawdown in unweathered ECBF piezometers from both tests



The results show that when dewatered, the ECBF locally under-drains the TG, resulting in drawdown in water levels within the TG, and also in the overlying basalt where these units are present. The magnitude of drawdown in the TG and basalt is less than in the underlying ECBF. This response is illustrated in Figure 8 showing the water levels in monitoring bore DH833 situated 164 m to the east of DH944; here a maximum drawdown of 13.9 m was observed in the ECBF, with 4.3 m drawdown in the overlying TG, and approximately 2.7 m drawdown in the basalt.

Figure 8: Drawdown in monitoring bore DH833a versus time during pumping test on DH950



Comparison of Figures 8 and 4 also shows that while the pumping bore reached a maximum drawdown after approximately three days, groundwater levels in many of the monitoring bores continued to decline for much of the 30 day pumping period, only levelling off and reaching equilibrium at the end of the test. This highlights the benefit of pumping for a long duration to fully establish the effects on each formation.

The drawdown response in the compressible formations of residually weathered ECBF (defined as being weathered to soils) and TG was reviewed in detail to identify where these layers may have become perched or depressurised as a result of pumping. These conditions are relevant to the assessment of ground settlement caused by groundwater drawdowns. Perched conditions are defined here as where the compressible layer remained saturated or partly saturated, while the top of the underlying layer became unsaturated. This is illustrated in Figure 8 above where the water level in the ECBF fell below the base of the Tauranga Group after approximately the 25th February. Perched and depressurised conditions indicate that these layers would no longer be influenced by additional drawdown in the unweathered ECBF. If recharge is less than the vertical leakage from the TG, the TG would be expected to drain over time.

During the Phyllis Reserve test on DH944, review of the groundwater level data in different piezometers showed that, where present, perched conditions had developed in the residually weathered ECBF in most piezometers within 200 m and about 40% of locations within 500 m of the pumping bore by the end of the test. Perched conditions developed in the TG (where present) in most bores within approximately 200 m of the pumping bore. The TG does not appear to have become fully depressurised in any locations whereas the ER became depressurised in six piezometers all located within 300 m of the pumping bore.

2.3.3 AQUIFER PROPERTIES DERIVED FROM TEST RESULTS

The properties of the unweathered ECBF aquifer have been derived using the drawdown response in the monitoring piezometers using the Cooper and Jacob (1946) approach assuming a constant discharge from the pumping bores. The Cooper and Jacob approach assumes that flow occurs horizontally through the aquifer. 57 piezometers were analysed following the test on DH944 and 11 were analysed following the test on DH950. The results are presented in Table 2.

Table 2: Aquifer properties from pumping test results

	DH944: Phyllis Reserve	**DH950: Pak 'n Save**
Transmissivity of pumping bore	18 m^2/d	0.3 m^2/d
Unweathered ECBF transmissivity	11 m^2/d - 206 m^2/d Geometric mean of 38 m^2/d	0.3 m^2/d - 4.1 m^2/d Geometric mean of 1.5 m^2/d

2.3.4 EFFECTS ON WATER QUALITY

Two closed landfills owned by Auckland Council (Phyllis Reserve and Habitat Reserve) are situated close to the Waterview tunnel alignment. The Phyllis Reserve landfill was filled between the middle of the 1940s and late 1980s with a range of refuse types including household waste, construction / demolition waste, green waste and cleanfill.

The samples taken of water pumped from both bores showed that the key landfill-derived contaminants were found to be present in low concentrations below ANZECC guideline values with the exception of zinc in DH950. The water quality results indicate that there was no significant effect of any landfill leachate on groundwater quality as a result of groundwater drawdown during the pumping test.

Elevated concentrations of dissolved and total zinc were detected in water samples collected during the test on DH950. The source of the elevated zinc in these water samples was found to be the galvanised iron pipe used as a riser from the submerged pump which the water sample had to pass though before the sample was collected. The reported zinc concentrations in these samples are not representative of the groundwater quality found within the ECBF in this area.

Iron flakes were observed in the water pumped from the DH950 bore due to precipitation of iron minerals as shown in Photograph 3. This was also noticed for the test on DH944 but to a lesser extent. The iron precipitation may be due to the pump "snoring" when the water level has been drawn down close to the pump and oxygen is being entrained.

Photograph 3: Iron flocculation encountered when disconnecting Pak 'n Save bore pump

2.3.5 EFFECTS ON FLOW IN OAKLEY CREEK

Any drawdown of groundwater due to tunnel construction has the potential to temporarily reverse the contribution of groundwater that naturally flows towards Oakley Creek, and draw it into the tunnels. Leakage of water in the Creek through the bed into the underlying groundwater system may also be initiated.

Seven flow gauges have been established by NIWA on Oakley Creek along the route of the proposed Waterview Tunnel alignment shown in Figure 2. Calibration gauging was completed for a range of low and mid flow conditions at all of the flow monitoring sites by April 2011 to confirm the relationship between stage (river level) and flow.

The Waterview Downs gauging station is located approximately 100 m from the DH944 pumping bore, and is downstream of the test discharge point. At Waterview Downs the flow increased immediately after pumping commenced by approximately 1260 m^3/d, consistent with the volume abstracted from the pumping bore. The discharge from BH944 was subtracted from the flows at Waterview Downs to remove the influence of the discharge.

The flows at Waterview Downs (with the influence of the discharge removed) were compared to the Bollard Avenue gauging station which is situated upstream of the Pak 'n Save supermarket, and well outside the area where groundwater drawdown occurred. A significant reduction in flows at Waterview Downs during the pumping test is not apparent and the difference in flows at the two locations does not appear to increase significantly (any difference is estimated to be less than 100 m^3/d). Any effects on baseflow to Oakley Creek during the pumping test were expected to be limited.

The Waterview Downs gauging station is located downstream of Bollard Avenue gauging station; however, the flows in the creek are lower at Waterview Downs. There are no take consents from the creek between the two gauging stations. Flows are likely to be lower at Waterview Downs because water is bypassing the creek by flowing through the adjacent basalt. A detailed analysis of the contribution of baseflow to the creek along its length has not been undertaken.

2.3.6 GROUND SETTLEMENT

The vertical deformation of the ground recorded on the 15 March 2011 was compared to the baseline condition before the Phyllis Reserve pumping test, defined as the 20 September 2011. The maximum settlement observed was 8.1 mm. Settlement was observed in pins surrounding the bore including those located on the basalt.

Prior to the start of the Pak 'n Save pumping test, the vertical deformation in the area varied by up to 2 mm between the 10 September 2010 and 4 April 2011. This may be due to limitations in the accuracy of monitoring results, or to natural variations. After the test start, the vertical deformation results show a slight downward trend, suggesting that settlement may have occurred; however, any impacts are generally less than 2 mm which may be within the range of accuracy of the monitoring.

3 DISCUSSION

3.1 GROUNDWATER DRAWDOWN

Groundwater flow, and correspondingly the drawdown effect in the ECBF are influenced by a number of geological factors including:

- Local structural variations. Disrupted beds, folds and slumps have been inferred in the Phyllis Reserve area, interpreted as disturbance of soft sediment. These features may have increased the hydraulic conductivity of the ECBF in the Phyllis Reserve area, compared to less disturbed areas such as around the Pak ‘n Save pumping bore DH950.

- Lithological features. The Phyllis Reserve area has a greater proportion of Parnell Grit (PG) material, with a distinctive coarser grained lithology and higher permeability compared to the Pak ‘n Save site. The depositional environment of the PG means that the PG intervals are variable and not necessarily laterally traceable between bores.

- Weathering. Where weathering of the ECBF to soils has occurred, the permeability is expected to be lower than the parent rock due to the loss of secondary permeability. The weathering profile is affected by paleo-topography and along the tunnel alignment is generally thickest (up to 10 m) on the spur crests (where erosion is least) and generally thin or non-existent (i.e. Tauranga Group sitting directly on unweathered ECBF) in the valleys between spurs which are interpreted as erosional features. However, some parts of the tunnel alignment, including the area around Phyllis Reserve, have anomalously deep weathering (Aurecon, January 2011).

The pumping tests provide a good insight into the behaviour and variability of the Waitemata Group and overlying formations. The results showed that in a higher permeability area of the ECBF formation drawdowns were observed at distances up to 550 m from the pumping bore, with the estimated maximum extent of drawdown estimated to be 900 m, whereas in the lower permeability area drawdowns were only observed at distances up to 200 m. The TG responded to underdrainage from the ECBF and perched conditions developed.

3.2 GROUND SETTLEMENT DUE TO GROUNDWATER DRAWDOWN

Settlement of compressible formations can occur as a result of a reduction in pore pressure due to groundwater drawdowns. One dimensional consolidation theory has been used to predict ground settlement due to the groundwater drawdown observed during the Phyllis Reserve pumping test using the coefficient of volume compressibility method. The coefficients of compressibility (m_v values) required for these calculations were available from laboratory oedometer testing carried out for NZTA in 2010 across a range of effective stresses.

The predicted total settlement is generally higher (up to five times higher) than that observed during the pumping test, for various reasons including development of perched conditions and geological conditions that did not match the one dimensional theory of consolidation. The magnitude of groundwater related settlement is influenced by the drawdown magnitude and development of perched and depressurised zones, and the compressibility of the residually weathered ECBF and TG formations.

Perched conditions in the TG and ER indicate that these layers would no be longer influenced by additional drawdown in the unweathered ECBF, and, therefore, limited additional settlement would be expected over time.

Settlement was observed in numerous monitoring pins located on basalt however, the basalt itself is considered to be incompressible. The pumping test results and comparison with settlement predictions suggest that the overlying basalt may be attenuating the settlement through a rafting effect.

The TG thickness increases to the east of Phyllis Reserve, with increasing distance from the pumping bore due to to the depositional environment of the alluvial deposits in the Oakley Creek palaeo-valley. Therefore, a location further from the pumping bore with less drawdown but a greater thickness of TG would potentially have more settlement than if the TG thickness was constant. The thickness of the residually weathered ECBF layer is also variable and relates to the palaeo-topography of the ECBF erosion surface. There may also be some variability in the interpretation and logging of weathering between different bores.

In addition to settlement due to the Phyllis Reserve pumping test, groundwater drawdown related settlement may have occurred due to the pumping test undertaken in February 2010 on BH709a where drawdown of 16.85 m in the pumped bore was achieved; however, no settlement monitoring was undertaken during this test.

Given that the drawdown effects during the pumping tests are considered to provide a good indication of what could be expected during tunnel construction (assuming "open mode" operation), the observed settlement would also be indicative of tunnel effects.

4 CONCLUSIONS / RECOMMENDATIONS

The pumping tests provide a good insight into the behaviour of the Waitemata Group and overlying formations. The contrasting results from the two tests show that the response to pumping can be variable over a short distance. During the Phyllis Reserve test undertaken in an area of higher permeability, the drawdown effects spread over a wide area and pumping from the ECBF induced vertical flow from the overlying formations where perched conditions developed. In contrast, the Pak 'n Save test was undertaken in an area of lower permeability and a much smaller area was influenced by pumping.

The actual ground settlements that occurred during the pumping tests were less than predicted using the observed drawdowns, for various reasons including development of perched conditions and geological conditions that did not match the one dimensional theory of consolidation.

The results provide additional insight into the potential groundwater and settlement effects of constructing the Waterview Tunnel in "open mode". The actual amount of groundwater inflow that will occur to the tunnels during construction will depend on the tunnelling method used and the type of strata encountered. Larger tunnel inflows, and larger associated drawdowns within the surrounding strata, may result in settlement of the compressible soils, which could affect overlying structures.

The comprehensive nature of the monitoring undertaken during the two tests and the long duration of pumping enabled a full understanding of the vertical and lateral effects of pumping to be generated which is of particular importance for a project such as the Waterview Tunnel.

ACKNOWLEDGEMENTS

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