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Drained tunnel impacts on groundwater: Observations and implications from recent experience of tunnelling in Sydney, Australia

Effets de tunnels drainés sur eaux souterraines : observations et conséquences de récents travaux de percement de tunnels à Sydney, en Australie

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ABSTRACT: Sydney Australia is currently experiencing unprecedented rates of development of tunneled transportation infrastructure. Whereas metro rail tunnels are being developed using circular profile TBM construction methods with undrained linings, motor vehicle tunnels are being constructed using conventional hard rock road header mining methods and generally minimalist tunnel lining systems that allow drainage of groundwater into the tunnels. These drained linings bring significant cost savings compared to linings designed to withstand groundwater pressures, particularly as record tunnels spans, currently up to 35m, are created to facilitate high volume underground interchanges. Within the inner city area, underground congestion and geological features have resulted in alignments that push new boundaries in terms of depth. Alignments with tunnel invert levels as low as 75m below sea level are designed in attempts to avoid high water bearing ground conditions associated with 40m deep infilled paleochannels. Despite attempts to reduce groundwater inflow rates using pre and post grouting, significant drawdown impacts have been observed. These impacts are greater than predicted using current hydrogeological modelling approaches. This paper discusses some key consequences of these impacts, namely risk of property damage resulting from settlement, long term durability, safety to tunnel users and mobilisation of contaminants. The groundwater observations reveal an interconnectivity of hydraulic fractures and their connection with the overlying alluvial sediments. This connectivity points to the need to reconsider the zone of influence related to groundwater drawdown. This zone is likely to be significantly more extensive than previously assessed. The observations also raise implications for long term maintenance of free draining tunnel lining systems that are only designed to withstand nominal groundwater pressures.

RÉSUMÉ : La ville de Sydney (Australie) connaît actuellement un développement sans précédent de tunnels pour ses infrastructures de transport. Alors que les tunnels de métro sont développés par des méthodes de construction employant des tunneliers à profil circulaire avec des revêtements imperméables, les tunnels pour véhicules à moteur sont eux, construits selon des méthodes conventionnelles de forage en roche dure par machines à attaque ponctuelle avec des revêtement de tunnel généralement minimalistes qui permettent le drainage des eaux souterraines. Ces revêtements drainés procurent des économies de coût significatives par rapport aux revêtements conçus pour résister aux pressions des eaux souterraines, d'autant plus qu'on note des largeurs record de tunnels, actuellement jusqu'à 35 m, créées pour des échangeurs à haut trafic. En centre-ville, la congestion souterraine et les caractéristiques géologiques ont entraîné l'implémentation de tracés qui repoussent de nouvelles limites en termes de profondeur. Des tracés aboutissant à des niveaux de radier aussi bas que 75 m sous le niveau de la mer sont conçus pour tenter d'éviter les conditions de sols à forte teneur en eau associés à des paléo-canaux remblayés de 40 m de profondeur. Malgré les tentatives visant à réduire les débits d'entrée des eaux souterraines à l'aide de pré et post injection de ciment dans la roche pour augmenter son étanchéité, on a observé d'importantes conséquences de la baisse du niveau des eaux souterraines. Ces effets sont plus importants que prévu par les méthodes actuelles de modélisation hydrogéologique. Cet article traite de certaines conséquences clés, à savoir le risque de dommages matériels résultant du tassement, la durabilité à long terme, la sécurité des utilisateurs du tunnel et la dispersion de polluants. L'observation des eaux souterraines révèle une interconnectivité des fractures hydrauliques et leur connexion avec les sédiments alluviaux sus-jacents. Cette connexion indique qu'il faut reconsidérer la zone d'influence liée à la baisse du niveau des eaux souterraines, zone susceptible d'être beaucoup plus étendue que précédemment évalué. Ces observations ont également des implications pour la maintenance à long terme des revêtement drainés qui ne sont conçus que pour résister aux pressions nominales des eaux souterraines.

KEYWORDS: Drained tunnel, hydrogeology, groundwater drawdown, specific storage, poroelasticity.

1 INTRODUCTION

Unprecedented construction of underground infrastructure (tunnels) is being carried out in Sydney Australia. The dominant geology of Hawkesbury Sandstone has historically provided an advantageous construction medium for tunnelling due to its ability to be relatively simply reinforced to create significant spans, but also due to the relatively tight nature of the bedding planes and other discontinuities that limit groundwater inflow to previously perceived tolerable levels. Published ground truthing of the hydrogeological predictions of the impacts of this drainage into tunnels have been few – yet significant parameters used in the hydrogeological models are frequently "assumed from the literature", limited sensitivity analyses are carried out, and monitoring on completion of projects seldom back analysed to improve modelling accuracy.

However, with tunnels getting bigger, deeper, and longer, less favorable locations are being tunneled through, and there is the possibility that impacts on the city's groundwater is being unappreciated, and under predicted.

This paper provides groundwater drawdown data collected from one of Sydney's recently constructed motorway tunnels. The data are compared with predictions lodged and agreed with Department of Primary Industry and Environment (DPIE) which regulates groundwater in NSW. The comparisons show significant underprediction of groundwater drawdown. While the value of in-situ hydraulic conductivity is typically known to an order of magnitude (Pells and Pells, 2016), the specific storage occurs in a much narrower range (Rau et al, 2018). Use of unrealistic values of both hydraulic conductivity and specific storage can result in significant incorrect predictions of depressurisation resulting from drained tunnels. This paper hypothesizes that the value of specific storage (Ss) parameter is one of the reasons for this underprediction in this Sydney tunnel project. Ss is rarely assessed from monitoring data and a number of groundwater models prepared for major projects are using a literature value for this parameter with potentially serious environmental implications.

2 HYDROGEOLOGICAL CONTEXT

The Sydney region is underlain by three geological units that need consideration in infrastructure projects: the Triassic Hawkesbury Sandstone overlain by Ashfield Shale, and Quaternary soils, including the Botany Sands. The region also contains numerous major north-northeast striking strike-slip faults (Och *et al*, 2009). The Wooloomooloo fault zone, has been intersected by a number of underground developments in Sydney and is known to be a zone of varying thickness (up to at least 200m thick in places) with numerous associated features such as en-echelon structures, splays and fold-accommodation faults of varying dimensions. Numerous dykes also occur in the Sydney Region, many approximately orthogonal to the major fault zones. Dykes frequently intersect with faults. They vary in thickness and are often deeply weathered to clay. The major faults contain numerous gouge zones up to 3m in thickness. Geomorphological features such as valleys, and paleochannels have formed along these orthogonal trends. Paleochannels have subsequently been infilled with Holocene and Pleistocene deposits (Albani and Rickwood, 1998).

Hydraulic conductivity of the Hawkesbury Sandstone is not only influenced by these faults and dykes, but by interconnected vertical / sub vertical joints and horizontal / sub horizontal bedding planes and dilated fractures. The rock matrix of Hawkesbury Sandstone has very low permeability.

Hawkesbury Sandstone in Sydney is up to 500 m thick. It consists of fine to medium quartz sand with a fairly uniform texture; it is typically moderately to well cemented. Some strata within the Hawkesbury are massive; others are cross bedded or have prominent horizontal bedding and may include some lenses of silty and clayey laminite.

The unscaled geometric mean hydraulic conductivity interpreted from packer tests varies from about 0.1 m/day (10 Lu or 1×10^{-6} m/s) near the surface to about 0.002 m/day (0.2 Lu or 2×10^{-8} m/s) at 50 m depth (Hewitt, 2012). In most places, Hawkesbury Sandstone is massive to sparsely jointed. In some places, however, the large-scale rock mass permeability is much higher, even reaching 10^{-4} m/s. These areas of higher permeability tend to occur in three general settings:

- around major fault zones, where swarms of high-angle joints and dilated bedding planes are common.
- where dolerite dykes have intruded and produced zones of alteration and fracturing in the Hawkesbury sandstone.
- deep paleochannels have cut down into the rock, resulting in valley floor bulging with large, dilated bedding-plane joints.

The areas of highest permeability tend to occur where more than one of these three settings co-exist, but to further complicate the hydrogeological setting, deeply weathered dykes and fault gouge zones can act either as barriers to flow perpendicular to their strike or as conduits of flow parallel to their strike.

Construction of drained tunnels beneath the water table typically causes ongoing groundwater inflow to the tunnels, inducing groundwater drawdown along the tunnel alignment, essentially reducing the ground water level to tunnel invert level in a cone shaped groundwater depression where the steepness depends on recharge.

Groundwater level drawdown is dependent on a number of factors, including piezometric level, proximity to the tunnel alignment and the specific geological and hydrogeological conditions present.

Tunnel inflows are controlled by three principal factors of co-equal importance:

1. the permeability of the rock mass;
2. the depth of the tunnel below the static water table; and
3. the source of the water that provides the ongoing, long-term inflows.

If the permeability is low, the inflows are likely to be low. If the depth of the tunnel is shallow (minor hydraulic gradient between the water table and the tunnel elevation), the inflows are likely to be low. If the source of water is limited (storage, flow across distant boundary and limited recharge), the inflows will likely decline over time and become low. However, if these parameters are large (or unlimited), then the inflows are likely to become large.

Groundwater models are used to predict potential groundwater drawdown (vertical and spatial) due to tunnel construction. The cone of depression created due to the tunnel alignment under watercourses will be influenced by the higher hydraulic conductivity of the strata above the tunnel (typically associated with the watercourses).

Where the tunnel alignment crosses infilled paleochannels, tunnels are typically designed so there will be no direct inflow from the alluvium into the tunnels. This would be achieved by designing the tunnels to dive beneath the alluvium, combined with grouting to reduce the permeability of the Hawkesbury Sandstone in the tunnel zone (Pells 1994, Yim *et al* 2017, Raymer *et al* 2019).

During the site investigation phases of a project, groundwater pump tests would usually be carried out in zones with particular geological complexity. In Sydney, this has been found to be particularly essential beneath paleochannels infilled with alluvial materials that respond to groundwater drawdown by significant settlements.

Pump tests help to develop an understanding on whether the alluvial materials within the paleochannels are hydraulically linked to the underlying Hawkesbury sandstone aquifer. The interpretation of these pump tests has (in the authors experience) focused on establishing permeability primarily to assist with the design of groundwater inflow control to address contractual requirements or commercial imperatives to maximise tunnel advance rates. However, while permeability is assessed by numerous Packer tests, rare pumping tests, and an extensive database exists for the Sydney Basin, Ss is not adequately considered (it is estimated based on the pumping tests). There is a perception that drawdown of the water table is not usually a problem where it occurs in the sandstone because of the low compressibility of these rocks.

Hence the poroelasticity of the sandstone aquifers does not appear to have been explored in the interpretations, and reliance has been placed on published hydrogeological parameter values in the literature – that cannot have been informed by observations since records of wider, deeper, longer tunnels are being broken on each new project.

In Hawkesbury Sandstone predicted depressurisation and drawdowns would coincide with tunnel inverts but would diminish rapidly with distance from the tunnel envelope. The lateral extent of drawdown might range many hundreds of metres either side of the alignment.

Hydrogeological modelling mainly focuses on calibration of hydraulic permeability, particularly in these more complex geological zones, yet the depth and width of the depressurisation and drawdown predictions are heavily influenced by the Ss parameter used in the hydrogeological modelling, as is discussed in the following section.

3 GROUNDWATER SPECIFIC STORAGE PARAMETER SELECTION

Appropriate selection of parameters for a reliable groundwater model has crucial influence on the prediction of inflows to tunnels and the extent of drawdown. Groundwater models for tunnel projects in Sydney have typically used hydraulic conductivity as the principal calibration parameter due to the contractual requirements to limit groundwater inflow, as it is relatively easy to measure using a range of field and data analysis methods. However, specific storage (Ss) is a parameter that is rarely assessed from monitoring data and several groundwater models prepared for major projects are using a literature or uncalibrated value for this parameter.

Specific storage defines the amount of water that is released from a storage of a confined aquifer for unit decline in piezometric head. In a ground water model, this parameter influences the interconnectivity between aquifers and vertical leakage. It also influences how quickly and to what extent drawdown effects travel from a source of aquifer interference, such as a drained tunnel.

The incorrect selection of the value for specific storage can result in either overestimating or underestimating the impact of drawdown in confined aquifers.

A good example (Anderson *et al* 2018) shows the impact of only half an order of magnitude decrease in Ss results in 50-100% increase in predicted drawdown. Anderson *et al* further comment that model predictions are very sensitive to the value of Ss.

Similar observations were made by Acworth *et al* (2017) and Evans *et al* (2015). The review of the groundwater model (Anderson *et al*, 2019) prepared for the coal project (AGE, 2013) found a number of incorrectly assigned Ss values for different units resulting in incorrect predictions of the extent of cone of depression.

A study by Rau *et al* (2018) recommends review of groundwater models where the Ss value is not consistent with the poroelasticity theory.

Given that Ss can only physically range within two orders of magnitude (Rau *et al* 2018) it is very important that this parameter is constrained during calibration and sensitivity analysis undertaken if the aim of the model prediction is accurate impact assessment and spatial extent of drawdown.

4 HYDROGEOLOGICAL MODELLING FOR A RECENT TUNNEL

The project runs from an area with a portal at about 20m above sea level, descends for 7.5km to a tunnel invert level of about 75m below sea level where it crosses below a deep alluvium infilled paleochannel, and then rises continuously for about 3km to a ground level portal at about 15m above sea level.

Groundwater impacts due to tunnel drainage were predicted using 3D steady-state and transient numerical hydrogeological models. The models were developed in accordance with protocols outlined in the Australian Groundwater Modelling Guidelines (Barnett et al., 2012). A regional scale model was developed to predict overall tunnel inflows and groundwater drawdowns along the entire project alignment.

The groundwater system was assumed to behave with homogeneous equivalent porous media parameters despite, as discussed above, flow of groundwater in the bedrock mainly flowing along open bedding partings and to a lesser extent along sub-vertical joints. This anisotropy in the flow was accounted for by adopting separate hydraulic conductivity values for horizontal and vertical flow within each homogeneous hydrogeological unit.

The model was calibrated to groundwater level observations from over 130 monitoring and observation bores located mostly along the alignment. Calibration was performed by adjusting recharge rates, maximum evapotranspiration rates, evapotranspiration extinction depth, hydraulic conductivity and river, creek, and neighbouring tunnels drainage conductance until an acceptable fit between model predicted and observation data was achieved.

A telescoped local scale model of the paleochannel area was developed to allow for finer grid resolution around the proposed tunnels. The finer grid resolution enabled more detailed modelling of the geological structures including sub-horizontal shear zones and sub-vertical faults, and utilised calibration with two pump tests that had been carried out in the area.

Groundwater heads at the boundary of the local scale model were adopted from the regional groundwater model and the conductance parameter of the General Head boundary was altered until groundwater gradients at the boundary of the local scale model matched gradients of the regional model.

Maximum drawdowns of up to 49 m were calculated in the paleochannel area and predicted inflows of this “base case” and predicted surface settlement impacts exceeded project requirements. Consequently, grouting to reduce inflows was adopted in the design.

A range of grouting scenarios were simulated in the hydrogeological models to determine what grouting measures would be required to control groundwater inflows to the tunnel through permeable structures. These grouting scenarios were simulated by reducing the hydraulic conductivity of high permeability geological features where they crossed the tunnels and reducing permeability within a 10m radius of the tunnel perimeters.

The simulations showed that inflow could almost be reduced to acceptable levels with grouting targeting permeability of 10^{-7}m/s. Drawdowns were similarly predicted to be reduced in the paleochannel area compared to the “no grouting” base case modeling. The predicted drawdowns away from the paleochannel did not change. Predictions at all monitoring piezometers in the paleochannel area for the grouting to 10^{-7}m/s permeability case were provided to centimetre accuracy on project drawings and triggers assigned and response plans developed. Predictions away from the paleochannel area were interpolated to from “base case” contour plots to a resolution of approximately 1m.

The groundwater numerical modelling was independently reviewed, deemed fit for purpose, and deemed to satisfy Class 2 Level model requirements.

5 DRAWDOWN DATA FROM A RECENT TUNNEL

Field monitoring of groundwater levels was carried out to establish defensible base line data prior to construction and continued during and after construction. Data in the form of hydrographs cover the period up to opening for operation approximately one years after the completion of tunnel excavation. These have been interpreted to determine essentially stabilised groundwater drawdowns for each instrument. The monitoring instruments comprise both grouted Vibrating Wire Piezometers (VWP), and Standpipe Piezometers (SP) with both data logger and manual dipping records to assist with interpretation. There is confidence in all data presented here to better than 1m accuracy, and to better than 0.5m for most data.

Figures 1 and 2 show the monitored drawdowns at tunnel opening compared against the results of the groundwater model predicted drawdown in the alluvium and Hawkesbury sandstone in the paleochannel area – i.e., with the grouting to 10^{-7}m/s modelled. Note data points recorded in VWPs unless marked as SP.

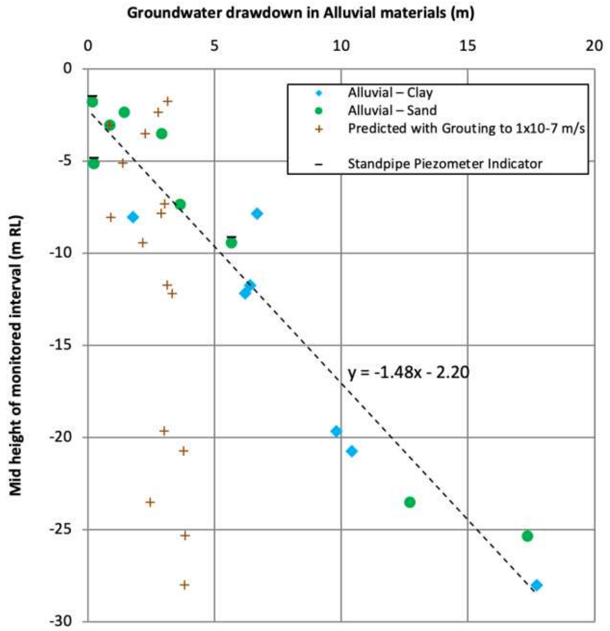

Figure 1. Groundwater drawdown observed in Paleochannel alluvial materials compared with hydrogeological model for grouted scenario.

Figure 1 presents the drawdown data within alluvium. In the top 5m, there are inconsistent relationships between predicted and measured drawdowns, likely due to short term variable recharge or interference from unrelated surface construction projects. However, from RL -7 to -30mAHD observed drawdown exceeds predictions by a factor of two to four times.

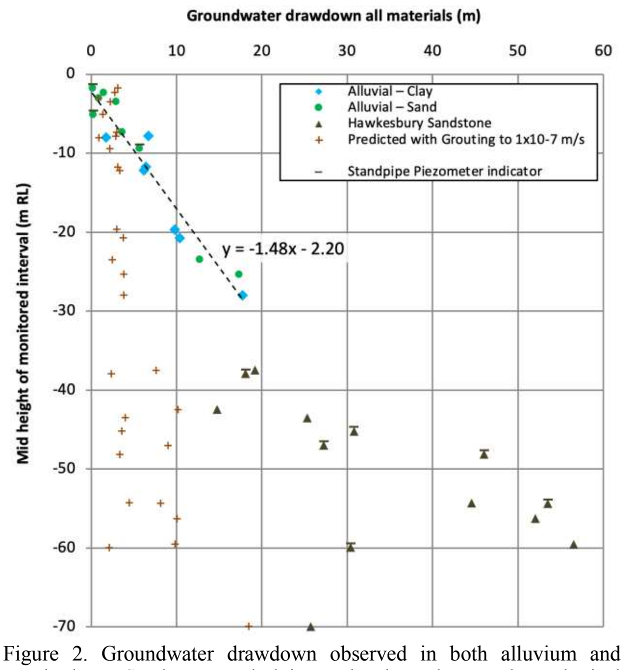

Figure 2. Groundwater drawdown observed in both alluvium and Hawkesbury Sandstone underlying paleochannel. Hydrogeological model predictions for grouting case included.

Figure 2 presents the data for the Hawkesbury sandstone along with the overlying alluvium. The observed piezometric levels in Hawkesbury Sandstone are similarly higher than the observed as monitored for depths from -40 to -70mRL. However, the exceedance in Hawkesbury Sandstone is up to an order of magnitude greater than the predicted values.

Figure 3 presents the predicted stabilised drawdown in Hawkesbury Sandstone relative to the horizontal distance from the tunnel. Groundwater monitoring data is plotted separately for piezometers in the Hawkesbury sandstone below the paleochannel area and away from the paleochannel. The predicted drawdown diminishes with the distance from the tunnel, with a maximum being just over 20m at the tunnel and reducing to less than 5 m at a distance 500m away from the alignment. However, the observed drawdowns range up to 57 m near the tunnel but are do not reduce as quickly as the predictions with a 30m drawdown being recorded 400m away from the tunnels.

Surprisingly, there do not appear to be any relationships between the observed drawdowns with respect to proximity to the paleo channel, despite the observation that groundwater inflows to tunnels are significantly greater below the paleochannel. This appears to indicate that bulk hydrogeological characteristics of the Hawkesbury sandstone are similar in both areas, regardless of the perceived presence of valley floor bulging being associated with large, dilated bedding-plane joints beneath paleochannels and local scale model considering geological structures.

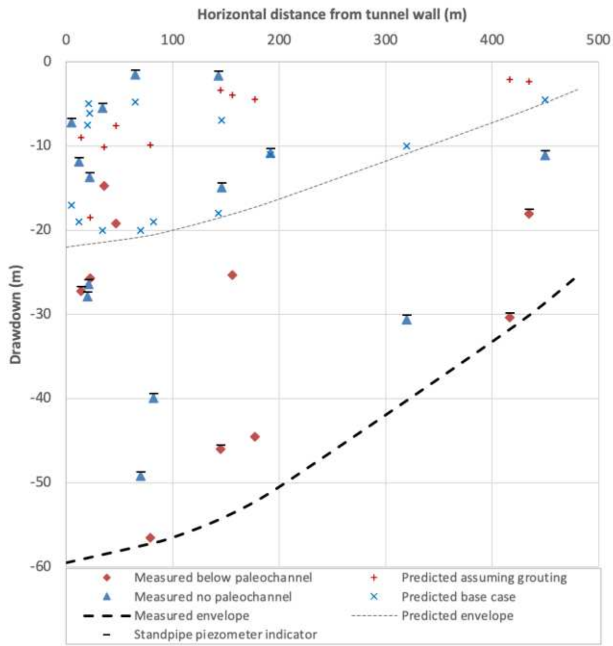

Figure 3. Measured and predicted groundwater drawdown in Hawkesbury Sandstone both below paleochannel and for tunnels away from the paleochannel.

To avoid bias, Figure 4 shows the same data set as presented in Figure 3 but normalised by tunnel invert depth below baseline piezometric groundwater level at each borehole location.

Envelopes for both the predicted and monitored normalised drawdowns are proposed in Figure 4. These envelopes have similar gradients in this normalised space. The envelopes emphasise the mismatch between the magnitude of predicted drawdown and observations, further reinforcing the implication that there is some fundamental discrepancy between both the base case and the grouted scenario. As alluded to previously, the authors believe that sensitivity consideration of Ss (specific storage) as a non-linear stress dependent parameter is missing from the modelling.

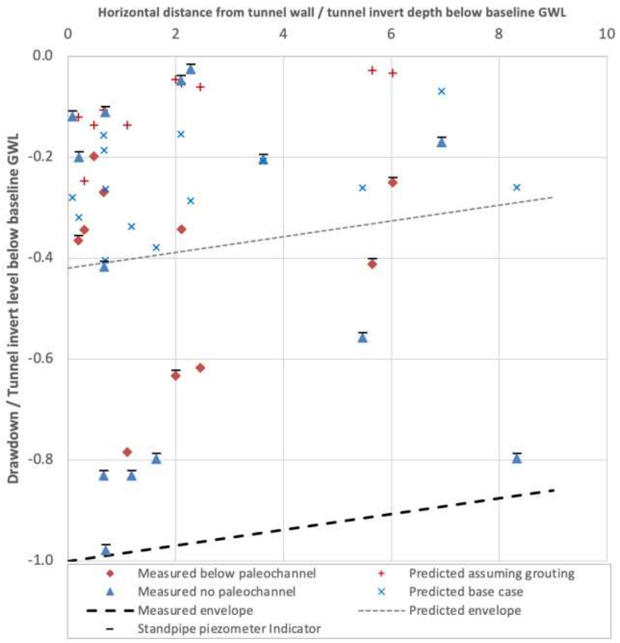

Figure 4. Normalised measured and predicted groundwater drawdown in Hawkesbury Sandstone both below paleochannel and away from the paleochannel.

6 GROUNDWATER DRAWDOWN IMPLICATIONS

The presented data shows groundwater drawdowns exceeding model predictions (as agreed with regulators) by up to an order of magnitude. This is clear evidence of significant groundwater drawdown that would not likely be considered acceptable within the concepts of "minimal harm" and "long term viability" within the NSW Water Management Act 2000.

Surface settlements resulting from these greater than predicted drawdowns have been observed of up to 200mm, where maximum predictions were of the order of 50mm. The full impacts of these settlements on the environment – both natural and anthropogenic – will perhaps take many years to become apparent.

The impacts on changes to baseflow, saltwater intrusion, ecosystems and potential for contamination migration could similarly be expected to exceed predictions, but due to being less visible, might go unnoticed for a longer time. If the observed drawdown is significantly greater, then this will limit baseflow contribution to surface water. This needs to be considered in the context of ecosystems which may rely on this water both in terms of quantity and quality.

New adjacent tunnel projects are in various stages of delivery, and their combined impact begs the question of whether the hydrogeological modelling will learn from what is reported in this paper.

There is a requirement within the NSW regulatory system for "24 Month Groundwater model Review". This is intended to provide an opportunity for calibration checks after 24 months of construction and associated ground water monitoring. But for this project, the process did not result in any significant revision of the model.

If the designer doesn't know the hydraulic conductivity or storativity of the rock mass, they can't assess sealing effect of grouting exactly, or design works without substantial allowances for post-excavation grouting. Geotechnical engineers normally run sensitivity checks on engineering parameters used in design. Conversely, similar hydrogeological sensitivity checks on model calibrations are rare in civil engineering. Much the same as engineers design for worst likely case and adverse loads (using terminology in Eurocode 7), there seems to be a case for this to be an essential part of hydrogeological modelling such that uncertainty is approached consistently, and industry assumes adverse case scenarios in their models and designs.

7 IMPLICATIONS FOR TUNNEL STRUCTURES

Since the dawn of the geotechnical engineering discipline, hydrogeological effects have been known to impact geomechanical properties of the ground. Terzaghi's effective stress principle (Terzaghi 1922) is fundamental to the understanding of soil behaviour. More recently Rutqvist and Stephansson (2002) provided an in-depth discussion on hydromechanical coupled effects in fractured rock and Sullivan (2007) has applied these effects to open pit mine slope behaviour. To the authors knowledge, direct discussions on coupled hydromechanical effects resulting from tunnel construction are absent from the literature. This is despite frequent acknowledgement that depressurisation predictions are frequently erroneous e.g., Pells and Pells (2016), which notes that many hydrogeological and geotechnical analytical methods result in inaccurate depressurisation assessments, and Raymer *et al* (2019) note simple relationships between hydraulic conductivity and depth because of higher *in situ* stresses at depth leading to tighter joints.

Rutqvist and Stephansson (2002) identified both direct and indirect coupled effects, both of which apply to tunnels. For example, the ground generally relaxes towards to the tunnel opening, relaxing the rock mass, typically accompanied by dilation of sub horizontal bedding partings, with associated increases in horizontal hydraulic conductivity. Likewise, redistribution of *in situ* stress around tunnel openings both reduces hydraulic conductivity where stress is concentrated and increases hydraulic conductivity where stresses reduce.

Despite the accessibility of computational methods, tunnel designers in Sydney do not undertake staged, coupled hydromechanical assessments. Design assessments typically assume simplified models, resulting in erroneous hydrogeological predictions.

Consistent with the groundwater drawdown implications, long term impacts on the tunnel structure may occur as a consequence of not appreciating the combined geomechanical and hydrogeological processes due to drained or undrained creep effects on rock discontinuities. This creep may contribute to accelerated deterioration mechanisms on ground support (both grouted rock bolts and concrete and shotcrete linings). The impacts may be further exacerbated where tunnel concrete and shotcrete linings rely on adhesion to a rock mass and where the interface between the tunnel lining and rock mass can readily deteriorate given the often-acidic nature of groundwater in Hawkesbury Sandstone (often as low as pH = 4).

8 CONCLUSIONS

This paper has discussed groundwater model predicted drawdown and depressurisation within the alluvium and Hawkesbury Sandstone caused by tunnel excavation on a recently constructed motorway tunnel in the Sydney Region. The paper compares the predicted values to those observed after the construction of the tunnel.

The principal findings include

1) the underestimation of drawdown and depressurisation even though the hydraulic conductivity data selected in the groundwater models are collected from the field data or calibrated from literature values for the same lithology unit elsewhere.

2) the lack of a defined mechanism to model the combined geomechanical with hydrogeological processes in high stress environments resulting in erroneous depressurisation and dewatering outcomes.
3) the lack of consideration of limitations and uncertainties in assumptions and a lack of appreciation of the consequences if unfavourable outcomes eventuate.

In the absence of thorough uncertainty analysis to test the whole range of possible values, the resulting drawdown and depressurisation can be underestimated. This has consequences not only for issues such as impact on yield in private bores, settlement of infrastructure, impact to ecosystems, reduction in baseflow and impact on rivers and creeks, but also the durability of the tunnels themselves.

The evidence of significantly greater groundwater drawdown and depressurisation from this recent tunnel project in Sydney compared to predicted demonstrates that more certainty is required in groundwater modelling. This can be ideally achieved through development of modelling techniques to combine geomechanical and hydrogeological processes with more realistic uncertainty analysis in groundwater modeling. There is room for significant improvement in the management of groundwater impacts in Sydney due to the construction of drained tunnels.

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