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Tunnels and the geologist – are we using geologists effectively? Thoughts and case studies from a 20 year career.

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ABSTRACT: Geologists are a fundamental part of the tunnelling workforce through all stages – site investigation, design and construction. How their skills have been used since the turn of the century has changed, fundamentally as a consequence of mandated changes in tunnel support requirements to improve tunnel safety. This paper discusses case studies demonstrating effective contributions by geologists beyond the requirements of Standards and classification systems. It presents observations as to how the geologists role has changed and the impacts that has on tunnelling in Australia, with particular commentary on whether or not we are using geologists effectively on projects at present. The paper discusses whether these changes have been for the better or to the detriment of the industry and whether the push for the use of technology and reduced facetime, guised as improvements to safety, are truly making for a safe workplace.

1 INTRODUCTION

Specialist trained geologists are fundamental when it comes to investigation and design of tunnels, but even more so at the construction stage. While their role encompasses a multitude of tasks, the key roles of the geologist at each stage are:

- Investigation Stage:
  - Collect soil and rock geotechnical data to the relevant standard of the time (presently to AS1726-2017).
  - Advise / supervise / delegate the necessary testing (field and laboratory) that will allow for characterisation of the soil or rock mass and the geological structure/s.
  - Collate and report the factual information that is reliable and consistently catalogued into the Geotechnical Factual Report (GFR).
- Design Stage:
  - Classify borehole data using stratigraphy specific engineering classification schemes.
  - Develop the engineering geological model (EGM) and complete associated reporting.
  - Advise geotechnical strength parameters for geological structures, defects and rock mass.
  - Advise possible geohazards.
  - Advise tunnel optimisation that could improve the ratio of tunnelling in good ground conditions to poor conditions, optimal tunnelling directions to avoid crown spalling or delamination, optimal orientation of caverns to minimise influence of stress etc.
  - Develop the Geotechnical Interpretive Report (GIR) (potentially as key input to the Geotechnical Baseline Report (GBR)).
- Construction Stage:
  - Collect geological data at prescribed cycles such that the entirety of the excavation is documented.
  - Collate the as-built geological data and compare to the predicted.

- Advise where conditions are deviating from predicted.
- Update the model and predictions based on the newly acquired construction data to allow for an update the design or support recommendations.
- Document the completed as-built record, preferably with the development of a geological digital twin 3D model.

There is consistency in the approach and associated tasks required to be completed by the geologist across all tunnelling projects, but, as with anything in nature, there is significant variability in the complexity and level of data collection required to document a site. As such, it is reasonable to assume the size and abilities of the geological workforce used should only be influenced by the geological complexity of a site and physical scale of a project. However, we have seen a different pattern emerge since the early 2000s, particularly influenced by the contractual deadlines enforced on construction programs.

This is not a smite on the engineer - they most definitely have their role to play. The commentary on this paper is a reflection on how geologists are used and are being gradually replaced from project roles despite the apparent increase in numbers being used on projects.

This paper compares the single-heading scale, road-header excavation components of two projects completed within the Sydney Basin's Hawkesbury Sandstone, and discusses how the use of the geologist has changed over the last twenty years, despite the stratigraphy, lithology and basics of design remaining the same. The paper provides commentary on the impacts changes in safety regulations have had on the required workforce (and project costs) in response to tunnel instability incidents, and how the changes implemented may result in a hidden danger. It foreshadows potential issues related to increased use of technology at the expense of the observational method of tunnel data collection and design validation and the implications this may have if underground face-time of the geologist is further reduced.

Further, the paper discusses how a requirement of geotechnical site investigation standards is to inform the stratigraphy (Standards Australia, 2017), yet tunnel design is reliant on inputs more related to lithology-based classification schemes than stratigraphy and where refinements to the unit demarcation are made, significant improvements to a design can be obtained through understanding lithological variations as opposed to stratigraphy.

2 CHANGES OBSERVED IN INDUSTRY PRACTICE FOR THE GEOLOGISTS CONSTRUCTION PHASE ROLES

The Hawkesbury Sandstone stratigraphic unit provides a sound basis for assessing how industry practice has changed since the turn of the century. The unit has long been recognised for its engineering properties, reusability and limited need for excavation support, dating back to the convict excavation of the Argyle Cut in the Rocks area of Sydney – an excavation that commenced in 1842 by hand, progressing to explosive use in 1859, with minimal to no support (Rocks Discovery Museum, 2025), Figure 1.

The authors first underground experience came with the Epping to Chatswood Rail Line – a combination of road header excavation station caverns and tunnel boring machine (TBM) rail lines. The project included five stations, each with a single geologist completing mapping during daily road header maintenance shutdowns, with one dedicated TBM geologist. Support consisted of pattern bolting of various spacing/lengths for each of the ground types and support classes. The entirety of the crown remained visible until project fit outs and mapping could be revisited and double checked at any time.

Fast-forward 15 years to the WestConnex megaprojects and excavation was 24/7, with a team of geologists covering multiple excavation faces under simultaneous development. Geologist coverage was also 24/7, on call to map faces upon exposure, immediately prior to the application of shotcrete as a support (on top of whatever bolting pattern is assessed as appropriate in the design and approved for installation at excavation). That drastic increase in staffing also notably saw geotechnical engineers positioned as mappers due to a shortage in engineering geologists. While these geotechnical engineers were trained for their daily duties, there is an inherent limitation to their understanding of geology and ability to recognise the implications of changing geological situations that is a project risk. We, as an industry have to recognise that we function best when using the most appropriately trained persons for each task.

A comparison between the road-header single-heading excavation progress between the projects is presented in Table 1. The single-heading excavations were of approximately the same size dimensions, completed by similar machinery. This shows two key differences between the heading excavation rates for the projects – the overall daily meterage has reduced per road header heading excavation while the number of staff has dramatically increased. A less obvious difference is the excavation exposures are covered by shotcrete in the more recent projects preventing any rechecks or validation of the mapping data collected.

What has caused this change in support requirements in the same stratigraphy, same excavation scale and tunnelling conditions? A notable fatality in the Cross-City Tunnel in August 2004 in which, as documented by Burman, Kotze and Chan (2018) resulted in a change to industry policy that "mandated one round of pattern bolting must be installed as part of every single excavation sequence irrespective of span and ground conditions", together with use of structural shotcrete. It is noted that the Cross-City Tunnel incident occurred in excavation within the Ashfield Shale stratigraphic unit, but the changes to industry practise have been implemented across all stratigraphic units, in civil tunnels Australia-wide, such that no work is conducted under "unsupported ground", which in all subsequent projects now includes the use of structural shotcrete to satisfy project specifications. Pells (2008) states: "The basic principle behind the design of shotcrete, in the loosening pressure environment, is to support and contain the rock between the rockbolts", however, a result of this is the time required to spray and cure the shotcrete impacts excavation schedule and further reduces the geologists face-time to complete the observational method of mapping, while also excluding the possibility of reviewing or checking the data collection. This further highlights the criticality of using an experienced engineering geologist for the task such that if anything untoward is apparent, it is more likely that it will be captured, documented and advised and actioned appropriately.

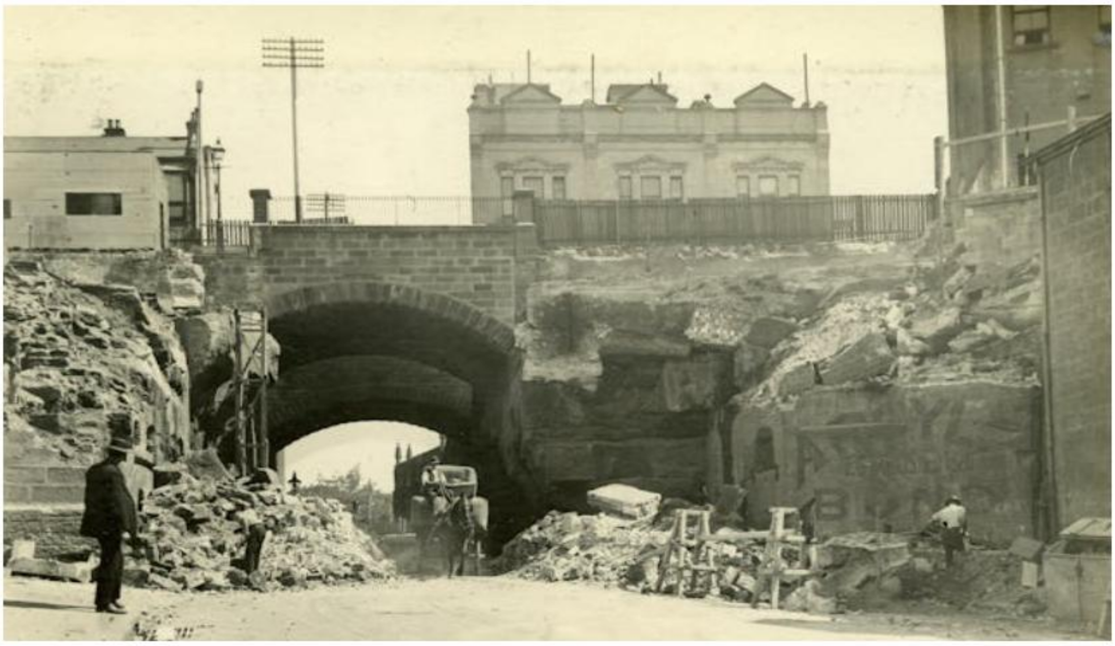

Figure 1. Historic photograph of the Argyle Cut, the Rocks, Sydney, showing the excavated spoil and unsupported slopes. (Rocks Discovery Museum, 2025)

Some projects are adopting the use of LiDAR scanning technology to capture the face conditions. This is fantastic for record keeping, providing a 3D output of the excavation profile and defect orientation assessments, but is pushing further tasks onto an already stretched work-force, resulting in further use of lesser experienced or appropriate personnel. Additionally, the skills required to "map" from LiDAR are deeply rooted in the skills obtained by mapping in person. It's the observations you learn to make through mapping in real life that allows you to recognise the key features observable from a point cloud. Just being able to load the point cloud into a 3D modelling program does not upskill you enough to process the data.

Table 1. Comparison between road-header heading excavation progress of projects in Hawkesbury Sandstone pre and post the Cross-City Tunnel fatality in 2004

Project	Epping to Chatswood Rail Line	WestConnex New M5 (M8)
Era	2002-2008[1]	2017-2020
Excavation area	Single heading road-header cutting within station cavern	Single heading road-header cutting within mainline
Typical road header progress rates for each heading/machine	10-15m per day (15 to 20m per day for benching)	5-8m per day (15 to 20m per day for benching)
Geologist schedule	1 geologist per station (each covering 2 active headings)	2 to 8 geologists per base site (each covering up to 4 active headings)
	Mapping during daily 4 hr maintenance	24/7 on call coverage
	5 days per week, no weekends	7 days per week
	10hr shifts, days only	8 to 12 hr shifts, including overnight
Peak geologists count	4	24
Support used	Pattern bolts, spot bolts, localised mesh	Pattern bolts with mandatory shotcrete

[1] Roadheader component completed by end of 2003.

Key issues for the geological workforce that have arisen with the mandated changes are:

- Doubling of personnel (as a minimum) to provide 24-hour coverage. In reality, fatigue management usually means this needs to be three persons on eight hour shifts or teams of four with rotating day and night shift combinations. Result: cost increase three to four times.
- Further, replacement or gap filling of geological personnel with geotechnical engineers as part of the pool of face mapping staff to ensure adequate bodies are provided, but who have limited geological background.
- Lesser time to complete their maps, increasing the risk that something is missed.
- Safety push preventing any actual mapping of the face. Geological compasses can no longer be used to measure the in situ orientation of defects in a face exposure as this is considered “unsupported ground” despite being at a distance of less than one bolt pattern array from “supported ground”. This means defect orientations are estimated via line of sight and may be erroneous.
- Safety and “innovation” push to use LiDAR scanning of faces rather than field personnel. This work is being delegated to survey workforce but any delay in data delivery results in delay of information to a “desk geologist” and limits real observations.
- The risk in itself of the shotcrete – both hiding geological features and as a spalling hazard. The author has observed significantly more spalling of shotcrete from the crown than rock spalling as a hazard when working underground.

3 STRATIGRAPHY – IS THIS NEEDED AS A REQUIRED PART OF LOGGING?

A required component of any geotechnical borehole log to comply with AS1726-2017 is to assign the stratigraphy. However, the state-run Geological Surveys have struggled to keep up to date with mapping to accurately reflect the stratigraphic distribution of units, particularly at the 1:100,000 scale. The Sydney 1:100,000 geological map dates back to 1983 (Geological Survey of New South Wales, 1983) - its older than many of the staff presently working in the engineering geology sector in NSW. The adjacent Penrith (1991) and Wollongong-Port Hacking (1985) sheets are of comparable vintage. These have been digitised on the Seamless Geology platform, however, there appears to be little, if any updating of the data. Known variations in the stratigraphy of the Sydney Basin from the significant infrastructure works completed (and much of it published) by the wider government or private sectors has not been incorporated into the maps.

Taking a further example from Sydney, the main stratigraphic unit present (and which comprises much of the tunnelling completed) is the Hawkesbury Sandstone, a unit that is some 300 m thick. The Hawkesbury Sandstone is a fluvial sequence that comprises sheet (cross-bedded) facies, massive facies and siltstone or shale facies, Figure 2, each of variable thickness and continuity, formed through variations in the dynamics of fluvial action at the time of deposition. The continuity and persistence of each facies band is then further complicated by post-lithification faulting and folding.

Presently, the majority of excavations in the Hawkesbury Sandstone have centred around Sydney in the upper portion of the unit, underlying the contact with the Mittagong Formation. We are fortuitous that there has been enough data collected and laboratory testing completed that the material property parameters in this upper portion are well understood. However, a negative impact of that advanced knowledge base is that project specific laboratory testing programs have been observed to be reduced as a means of cost cutting. As tunnels extend further from Sydney, with the fast rail services presently being considered, the risk becomes that a change in the relative position within the 300 m sequence is not appropriately recognised and future project workers adopt limited laboratory testing as that has been their personal "recent experience". The full 300 m sequence took over 5 million years to deposit which would suggest there must be an inherent variation to its composition and testing of the Hawkesbury Sandstones geochemical make-up varies across the Sydney Basin would support this, with laboratory assessments of quartz to feldspar ratio varying from 7:1 to 400:1 (Swanson, Ward, & Franklin, 2002), a characteristic attributable to the variation in performance of the material as a building façade stone. It is not unreasonable to assume there could be an inherent difference in the geotechnical properties of the unit over its 300 m thickness either.

Engineers have modified the original Pells Classification Scheme developed for foundation design in Sydney of Pells, Mostyn and Walker (1998) for sandstone to be used in tunnel design which simplifies the rock mass into five classes defined by strength, defect spacing and allowable seams (Pells P. , 2002). This allows for design of tunnel support systems commensurate to each class and simplifies the design and support process. Geologists can contribute further to design improvements by understanding the intricacies of the Hawkesbury Sandstone lithology and assessing the facies distribution. The ground behaviour and response to tunnel excavations is different depending on the facies encountered and the required support also varies accordingly. A tunnel crown in massive sandstone is desirable, as it is more favourable to self-supporting arch action and therefore require less installed artificial support, while cross-bedded sandstone may delaminate in the crown, and require local increased support. Shale/siltstone horizons may act as focus for shoulder convergence, spalling of the crown, or heave of the invert. As such, the geologist can contribute significantly to a tunnel design by undertaking facies analysis. Which begs the question, why then, do the standards focus on stratigraphy?

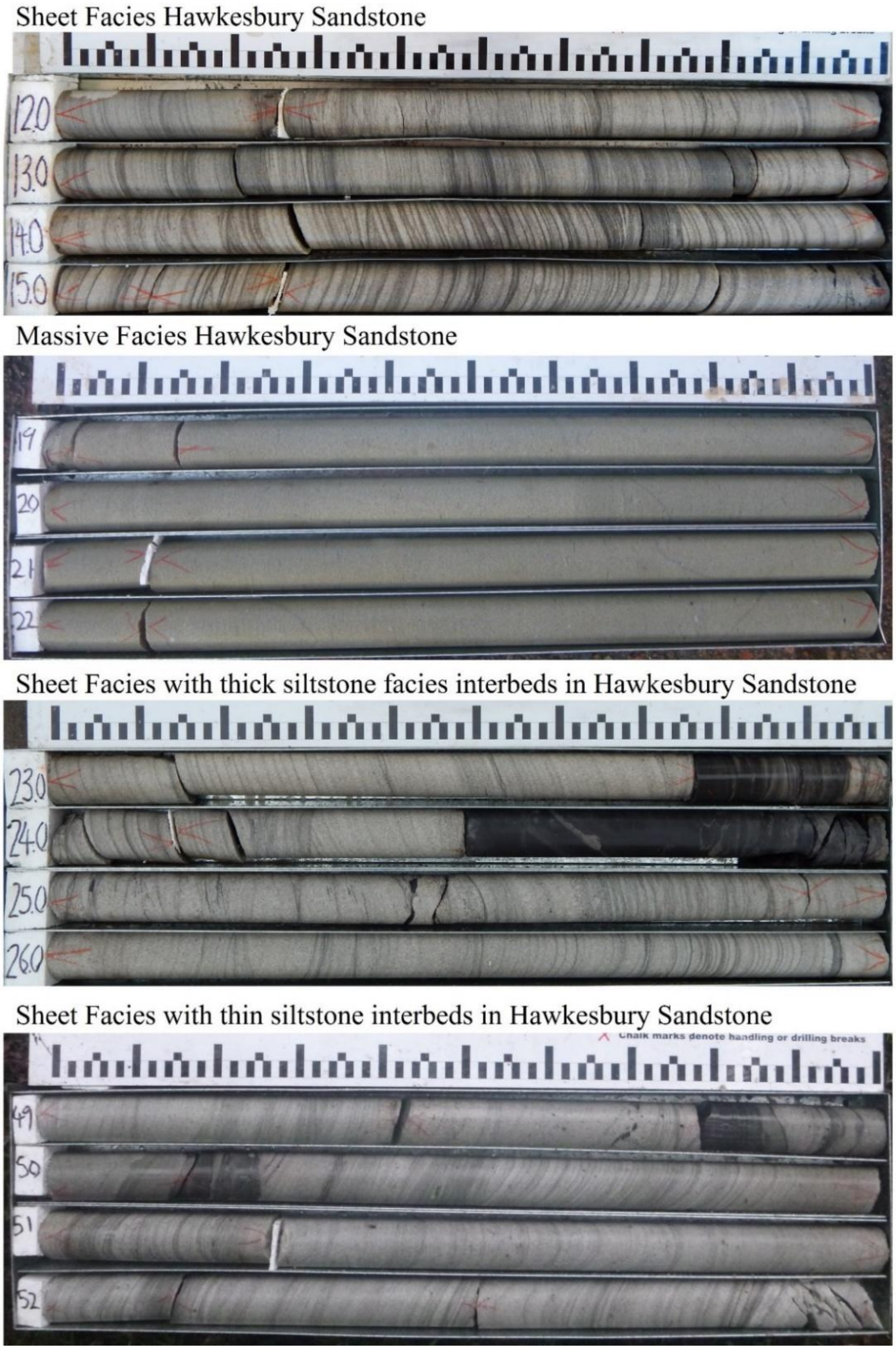

Figure 2. Examples of sheet, massive and siltstone/shale facies in the Hawkesbury Sandstone

Similarly, if stratigraphy is such a key field, it must be included in all factual borehole logs, why is the geotechnical characterisation of the Mittagong Formation so contentious? The Mittagong Formation is typically less than 10 m thick and comprises interbedded to interlaminated siltstone and sandstone. Various adjacent projects have considered it a shale class (adopting the Pells scheme for shale), others a sandstone class, based on relative (local) variation as to which lithology dominated.

As we move even further afield, to greenfield locations being targeted for pumped hydro schemes, not only are we not confident the geological survey mapping accurately reflects the stratigraphy, we know even less about the lithology and we don't have the vast testing databases to help with design. The inclusion of stratigraphy on logs in these situations, becomes more interpretive than factual and defeats the intent of the standard.

4.1 *Facies Differentiation Completed Case Study*

Design for the dual tunnel M8 alignment from Kingsgrove to St Peter's involved assessment of lithological conditions in Hawkesbury Sandstone for much of the 8km alignment with both tunnel exits in Ashfield Shale. Drilling at close spacing along the alignment was not economic or warranted. As such, along the mainline tunnels, the drill spacing was 300 to 1000m with a higher density of drilling around the Bexley and Arncliffe tunnel access areas where there were junctions of adits and shafts into the mainline tunnels. A facies model, attempting to align the distribution of cross-bedded sandstone layers and massive sandstone layers and identify any areas of persistent siltstone was developed by the design geological team. This model helped in two key ways:

1. By cross-checking lineaments observed in the surface topography against the facies distribution either side of the lineament, the geologists could advise whether there was any indication of displacement of material either side of the lineament (suggestive of faulting) and advise if further site investigation was warranted and
2. The tunnel profile could be assessed to identify areas of tunnel that may have less than ideal rock material in the crown (cross-bedded sandstone or siltstone lenses), and allow the geologists to advise options for changes to tunnel crown elevation that could be assessed by engineers to optimise the design.

Within the Arncliffe area of the tunnels, such an optimisation was possible. Geologists recognised a persistent, 5m thick massive sandstone bed occurred a few metres above the original proposed tunnel crown. With this information in hand, engineers were able to redesign the tunnels to align the crown with the more favourable rock. This shifted this section of tunnel from a class III support to a class I/II support, reducing support costs and improving excavation rates.

4.2 *Facies Differentiation Not Completed Case Study*

For the Macquarie University Station of the Epping to Chatswood Rail Line, there was no facies differentiation completed. The crown of the station was expected to be in the projects rock classification type II, a robust material type with 1.5m bolt spacing and spot bolts as required. However, one portion of the crown intersected distinctly cross-bedded sandstone and at an angle of intersection and excavation direction for a most undesirable result – daylighting cross-beds that delaminated in the crown. The support was locally increased to a type IV mesh and bolt combination – no requirement for shotcrete. While this project predates use of televiewer for defect orientation, oriented core was available to provide understanding of the unfavourable excavation direction for this portion of crown and excavation from the opposite direction was in fact possible.

5 DISCUSSION AND CONCLUSIONS

The paper is not suggesting there is a need for an increase in overall geology-specific inputs to a tunnel design/construction – the geologists provision of GFR, GIR and inputs to GBR are appropriate for design and the use of geologists for mapping is appropriate for construction. However, the inherent knowledge base of the geologist is needed to flag atypical ground conditions bespoke to a geology type and when unusual or deteriorating geological conditions are occurring during construction. To quote Fookes, Lee and Gilligan (2005) "Problems have to be identified before they can be solved" and that is where the geologist provides the most to a project.

So how do we keep the right personnel doing the tasks they are specifically trained for in a stretched workforce to maintain quality in our projects? Is it possible for the industry to take a collective breath and revert back to 20 hour excavation and maintenance shifts? Are there ground types that do not gain from the addition of shotcrete that we can leave visible? Can we think outside the box and develop skills for newer graduates via training centres to have them at the faces mapping so the mid-levels are available to action rigorous review both data and alternate data collection methods? These are all things we can think about.

In a lot of ways, the safety culture has changed for the better, particularly in regard to respiratory protection. But the mandate for shotcrete as a means of temporary support on all exposed stratigraphies has resulted in a balancing act between allowing the geologists the necessary time to map the exposures, while maintaining excavation performance rates. This balance is often tipped to be unfavourable to the geologist. This should be cause for alarm – if the time to map appropriately is not given, we run the risk that something critical will be missed. The mandated application of shotcrete on all rock classes, prevents later checks or capture of this information.

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