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Exploring innovative groundwater control methods and waterproofing techniques in Sydney tunnels (ATC2025)

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ABSTRACT: Groundwater control is a critical aspect of all tunnelling projects, safeguarding structural integrity and providing warranty for meeting the proposed design life. Typically, in the context of Sydney mined tunnels, stringent inflow criteria are set by the Client and administered under D&C contracts through Contractor managed groundwater selection processes. This paper explores the integral role of a formal groundwater control systems process through a collaborative approach to groundwater ingress management, with a particular focus on significant changes in Client waterproofing requirements enabling innovative design and construction methods.

The intention of this paper is to highlight challenges and opportunities of an innovative tunnel groundwater management approach in the Sydney context and assess its feasibility for future projects. The viability of a collaborative groundwater control systems processes are evaluated against a challenging commercial environment along with the practicality of Client involvement in a D&C contract.

1 TUNNEL GROUNDWATER INFLOW REQUIREMENTS

1.1 Typical Sydney road tunnelling requirements

With the already stringent groundwater inflow criteria for Sydney tunnelling projects, more innovative design and construction methods have been established to minimise water ingress and maintain drier tunnel conditions. Continuous advancements in tunnel groundwater control systems have been driven by lessons learned from previous projects, as well as the increasing commercial pressure to minimise operational expenditure through improving long-term durability, operational efficiency, and safety within the underground space.

Sydney road tunnels are almost exclusively mined tunnels, excavated with a fleet of roadheaders due to the favourable geotechnical conditions of Sydney sandstone. In a challenging commercial climate with increasing cost pressures, Sydney's significant road tunnel investment is scrutinised heavily to ensure reduced whole of life costs to the taxpayer. This often leads to a reduction in tunnel scope during tender, with successful tenders typically designing thin shotcrete and rock bolt linings, with groundwater control systems typically installed within layers of shotcrete, draining into the stormwater system under the road pavement.

The Scope of Works and Technical Criteria (SWTC) within the Design and Construct contracts for Sydney road tunnelling projects typically mandate that the Contractor must ensure groundwater passes through a designated Groundwater Control System (GWCS). Water infiltration is not permitted to drip or flow onto road pavements or walkways within tunnels, nor is it allowed to run down or accumulate on the external surfaces of tunnel walls.

Despite variations in project-specific requirements, the inflow criteria for Sydney tunnelling projects have remained relatively consistent. Undrained tunnels are typically mandated in soft ground tunnels with high existing groundwater levels and are specifically designed to prevent external groundwater from infiltrating the tunnel space. This approach results in the accumulation of hydrostatic pressure against the structural lining, effectively "tanking" the tunnel. The significantly higher expenses associated with constructing a fully tanked tunnel often render it a less viable option for most Sydney road projects. For these undrained tunnels, the allowable inflow is limited to: 0.2 litres per square metre of tunnel surface area per day for any 100 m length of tunnel.

Conversely, drained tunnels permit controlled groundwater ingress through the GWCS. This reduces hydrostatic pressure buildup which allows for an optimised structural lining. Most mined tunnels in Sydney are designed in this manner due to their favourable balance between quality and cost-effectiveness. Typically, Sydney drained tunnels adhere to an inflow limit of 1 litre per second per kilometre and 0.3 litres per second in any given 120 m of tunnel.

1.2 M6 requirements

The SWTC for the M6 project introduced a significant shift in Client waterproofing requirements, further improving on the standards implemented in previous Sydney tunnelling projects. Specifically, the SWTC for the M6 Project mandates that the Groundwater Control Systems (GWCS) must be installed behind the primary structural lining. This represents a departure from conventional practices, where the GWCS is typically positioned within the structural lining.

By placing the GWCS behind the structural lining the intent of this change was to:

1. Minimise operational expenditure through improving long-term durability, operational maintenance, and safety within the underground space
2. Reduce the risk of damage due to drilling of M&E anchors within the lining
3. Improved water resistance behind the structure to better direct water into the GWCS
4. Adopt a consistent amount of shotcrete applied aiming to improve the performance of the tunnel to withstand permeation, excessive cracking and drainage within the tunnel environment

Another key change within the SWTC for the M6 Project is a mandated structural connection of this structural lining to each rock reinforcement element. This was introduced to ensure a more durable structural lining, ensuring that the beneficial effects of adhesion weren't relied upon in the design space, minimising any rework to the lining in the future. This occurs by ensuring that the shotcrete structural lining is essentially hanging off the rock bolts embedded within the crown of the tunnel. The tunnel lining then acts as a single composite layer with additional redundancy to minimise the risk of shotcrete fallout. When combined, these modifications have unintendedly necessitated the adoption of an alternative construction methodology to enable installation of the revised placement of the GWCS.

2 GROUND WATER CONTROL SYSTEM (GWCS)

2.1 Components and process

Groundwater control systems in Sydney tunnels comprise of drainage elements such as strip drains, drainage mats, geotextile, sprayed / sheet membrane and are encased in shotcrete to control the impact of water on the tunnel structure and direct it into the tunnel drainage system.

There are 3 systems typically used in Sydney tunnels to direct groundwater into drainage channels:

- Groundwater Control System A (GWCS-A): Systematic use of strip drains
- Groundwater Control System B (GWCS-B): Sprayed waterproofing membrane
- Groundwater Control System C (GWCS-C): Sheet waterproofing membrane

Figure 1. Groundwater control systems GWCS-A, GWCS-B, GWCS-C

These systems can be used across both drained and tanked tunnels, but all three are more commonly applied in drained tunnel designs. Drained tunnels employ either / a combination of the GWCS types to manage and direct groundwater inflow, whereas tanked tunnels most commonly adopt sheet membrane as the primary solution due to its ability to provide a continuous and more robust barrier against water ingress.

Typically, GWCS's must be installed by the contractor at locations with significant geological structures, including faults, dykes bedding planes and joints that are, or have the potential to be water bearing during the design life of the tunnel. This includes geological structures that have or currently show evidence of water inflow/seepage, structures that are affected by seasonal change and or any ground that required grouting to restrict the water inflow. Typically GWCS-B or GWCS-C would be mandated in these areas to reduce risk of seepage through the shotcrete.

The SWTC and design drawings also stipulate specific zones which are designated as mandatory spray or sheet membrane areas to ensure the structural integrity, durability and long-term functionality of the tunnel. These mandatory membrane areas include tunnel equipment spaces such as EER's or substations, any locations that intersect major geological structures / features and areas that have been grouted for the purpose of groundwater control.

Megaflo drains have also been adopted on the M6 for all the tunnel waterproofing works instead of the typical top hat drainage system. Megaflo is a wide flat shaped HDPE system designed for effective sub-surface drainage used to capture groundwater inflow in a tunnel environment with a larger capacity compared to the top hat strip drains. Typically, on previous projects Megaflo was only used in high inflow areas and around brows or ledges of the tunnel as a collection point from multiple other drains but the M6 had adopted this solution throughout their tunnel. This system is more flexible and quicker to install system with a higher water capacity leading to it being used more and more in tunnelling projects.

2.2 GWCS selection approach

The M6 adopted a collaborative approach to the GWCS process, actively engaging all key stakeholders—including the client, independent certifier (IC) and designer—throughout every phase, from initial planning to installation and verification which is unique in the Sydney tunnelling market which is dominated by D&C Contracts.

Selection of each groundwater control system will vary between projects depending on the individual projects SWTC and design requirements / specifications. This approach was a valuable process which helped the timely alignment, approval and construction of the GWCS and was essential in achieving compliance with the stringent groundwater management requirements outlined in the M6 SWTC. A formal sign-off process was developed involving the geotechnical team, designers, contractor, IC and client in the planning, installation and verification/sign-off stages. During planning, the geotechnical team identify high-risk water-bearing zones from geological data compiling them on longitudinal maps of the tunnel. Witness points and general inspections were organized with all parties having the opportunity to assess existing site conditions and determine appropriate GWCS treatment measures based on mapping and site conditions. Following install completion, a final verification and sign off inspection was conducted allowing all parties to assess compliance and resolve issues prior to the spraying final lining over the GWCS. The involvement of the client and IC in the GWCS process enabled the early alignment of expectations, thereby enhancing the overall project quality, ensuring more effective implementation with minimal areas of rework post.

3 CONSTRUCTION METHODOLOGY

3.1 Methodology changes

Managing groundwater ingress is a significant challenge in tunnel construction, particularly when excavating through high-risk geological zones. Uncontrolled water inflow can lead to construction delays, increased costs, and safety hazards, hence, implementing proactive measures to manage groundwater is crucial for reducing these project risks. Traditionally these risks are mitigated through an effective excavation methodology. In Sydney a sequential excavation methodology is standard with production decisions has been production driven, with groundwater control an afterthought. The process has previously consisted of:

1. Excavation
2. Rock bolting; and
3. Shotcrete

With groundwater control systems installation and final shotcrete applied months after excavation clears an area. In this method the GWCS is typically incorporated within the primary structural lining, often resulting in minimal shotcrete coverage of the GWCS which may allow greater water penetration through the lining system.

The M6 project's SWTC marks a departure from previous Sydney tunnelling standards by mandating the Groundwater Control System (GWCS) be installed behind the structural lining. This requirement necessitated the adoption of an alternative construction methodology, highlighting the need for adaptive engineering to meet evolving waterproofing requirements. Forward probing and pre-excavation grouting was heavily relied upon to mitigate water inflow ahead of the tunnel face. This also enabled the gathering of vital groundwater condition information ahead of the excavation face helping to identify high-water inflow zones and potential water-bearing structures.

To accommodate the SWTC changes, the M6 project implemented a revised construction sequence:

1. Forward probing
2. Excavation
3. Shotcrete
4. Rock bolting
5. Groundwater control
6. Final shotcrete

This methodology requires shotcreting prior to bolting which enables the bolt plates to be used as a structural connection for the additional layers of shotcrete. This allows for better integration of the bolting system with the sprayed shotcrete, enhancing overall structural performance.

3.2 Performance of the revised methodology

A notable distinction was observed in the performance of the final lining, with the revised approach yielding a perceptibly drier tunnel environment. This improved outcome could be a result from the increased thickness of shotcrete layers applied over the strip drains in the new methodology. An example of this would be the revised approach which mandates a minimum of 110 mm of shotcrete cover above GWCS-A, thickening the barrier against water ingress and promoting more effective diversion of groundwater to the nearest drain as shown in Figure 2.2 on the RHS compared to the previous typical detail in Figure 2.1 which has GWCS-A strip drains embedded within the 110mm of shotcrete.

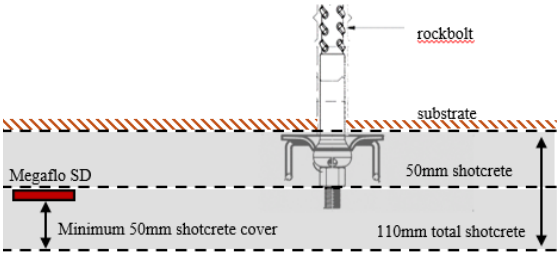

Figure 2.1. Previous GWCS-A detail.

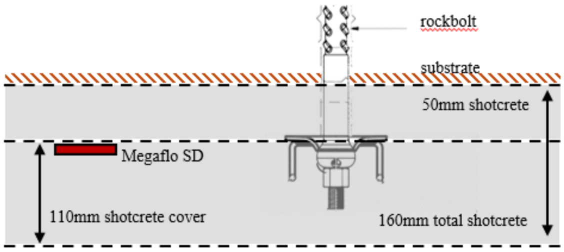

Figure 2.2. M6 adopted GWCS-A detail

Other key benefits of the revised methodology include significantly reduced damage to the Groundwater Collection System (GWCS) from mechanical and electrical penetrations, primarily due to the increased thickness of the shotcrete lining. This added layer of protection enhances the durability and resilience of the drainage infrastructure, helping to maintain its functionality throughout the tunnel's operational life. In addition, the implementation of more stringent client waterproofing requirements led to a broader application of spray-applied waterproofing membrane, which has proven effective in minimising water ingress and achieving a consistently drier tunnel environment. The methodology also introduced the use of Megaflo drainage in place of traditional top hat strip drains, offering advantages such as simplified and faster installation as well as improved flow capacity, which collectively enhance the overall efficiency of groundwater management. Additionally, the inclusion of a separate groundwater drainage line allows for more targeted and manageable system maintenance, reducing the risk of blockages or service interruptions and will ultimately contribute to lowering operational expenditure over the life of the project.

4 CHALLENGES IN WATERPROOFING & GROUND SUPPORT INTEGRATION ON M6

The revised SWTC requirements for the Groundwater Control System introduced several construction-phase challenges, resulting in the need for rework across multiple areas. In regards to spray membrane, which was used for over 30% of total lining a significant increase in duration was seen when adopting the new methodology due to the more stringent SWTC requirements. A summary of the additional works / challenges encountered with the revised sequence include:

- Shotcrete adhesion from change in construction method
- Further waterproofing detail required around rock bolt heads/handlebar plates
- Increased rework and time spent lining
- Additional works stopping leaking bolts
- Lack of sight for rock bolt operators to install spot bolts due to shotcrete being sprayed prior to bolting

Figure 3. Spray membrane install around rockbolts

4.1 Shotcrete adhesion issues

A key issue arising from the adoption of the new construction methodology was encountered during excavation, particularly in water-bearing zones where shotcrete adhesion to the crown proved problematic. Under conventional practice, rock bolts are installed immediately after excavation, providing additional anchorage points to facilitate shotcrete adherence, even in wet conditions. The modified sequence adopted for the M6 project—where shotcrete was applied prior to bolting—led to reduced adhesion and instances of shotcrete fallout in saturated ground conditions. To address this, the construction team had to revert back to the traditional "cut, bolt, then spray" sequence in affected areas. These sections were later re-bolted as initial bolts were sprayed over in SC and did not have sufficient exposure for a proper structural connection for the final lining installation.

4.2 Protrusions through membrane

The number of bolt and handlebar plate protrusions have increased significantly when compared to the traditional approach. Typically, there are two methods for the traditional approach when it comes to spray membrane areas.

1. In configurations where abutments are integrated into the excavation profile, there is no requirement for bolt tails or handlebar plate protrusions. In such cases, the shotcrete applied over the spray membrane is structurally designed to function as an arch, effectively spanning across the abutments. This eliminates the need for embedded bolts to support the final lining.
2. Alternatively, where abutments are not present, a pattern of long-tail bolts may be installed with only the threaded rod extending beyond the surface. This configuration necessitates the application of spray membrane around the protruding bolt tails prior to installing a mesh layer and applying the final shotcrete lining.

The newly adopted methodology closely aligns with the second traditional method but introduces a considerably greater number of protrusions and potential paths for water to flow through, specifically the addition of handlebar plates with all CT bolts. As a result, each of these protrusions require more focus on spray membrane application around all handlebar plates and additional coats in order to fully encapsulate and seal this system. The M6 design utilises CT bolts as a structural connection for the secondary lining to hang off hence emphasis on installing this connection correctly and sealing this system is critical.

Gaps between the handlebar plates and shotcrete are typically present as the CT bolts are not always sitting on a smooth, flush surface. The crack bridging properties of spray membrane had a minimum requirement of 2.5mm which typically was not able to bridge this gap between plates and shotcrete due to their size. This required the contractor to have crews come back before spray membrane works commenced and seal the edges of the bolts with grout. This additional works as a result of the methodology changes significantly increasing both the time, cost and amount of resources required to treat these areas.

Figure 4. Membrane gap at bolt / shotcrete interface

4.3 *Construction duration and rework*

Another time and resource consuming task as a result of the methodology change was the requirement to protect all CT bolts prior to smoothing and cleaning bolts in preparation for spray membrane. All handlebar plates and bolt tails needed to be free from debris/ excessive shotcrete prior to applying spray membrane hence site developed a metal cover that was screwed onto the end of the CT bolts protecting them from being covered in smoothing. This methodology worked in minimising the amount of bolt cleaning that would have been required if covers weren't used but still resulted in significant additional work in the area. After each smoothing spray site would have to remove all protective covers and in areas where smoothing was sprayed too thick would have to manually chamfer back the edges with demolition hammer which was a lengthy and costly exercise.

4.4 *Leaking bolts*

Leaking rock bolts were another persistent issue encountered throughout wet areas in the tunnel requiring remedial works including rebolting and resin injection prior to the application of spray membrane. The presence of wet or actively leaking bolts poses both structural and durability issues within the tunnel hence required rectification prior to subsequent works. From a construction standpoint, these conditions required substantial additional sealing efforts to establish the dry substrate conditions essential for successful spray membrane adhesion. Injection grouting—predominantly using polyurethane (PU)-based products—was frequently employed to mitigate the leakage. However, this process introduced further complications: PU injection material often migrated to nearby strip drains, resulting in unintended blockage of drainage pathways. These obstructions diminished the effectiveness of the drainage system and necessitated additional rework to restore strip drain functionality, thereby increasing labour, material costs, and construction time.

Given the critical role of rock bolts in maintaining both structural integrity and waterproofing, it is recommended that future dedicated testing regimes and durability tests for PU-injected bolts, such as prolonged water pressure testing, chemical resistance assessment or ageing simulation would be beneficial to validate the long-term effectiveness of injection materials under representative tunnel conditions. This would ensure that remedial interventions not only restore immediate function but also maintain durability throughout the assets intended design life.

5 FINDINGS / CONCLUSION: FEASIBILITY FOR FUTURE PROJECTS

The M6 was the first tunnelling project within Sydney which mandated that the Groundwater Control System (GWCS) must be installed behind the structural lining as shown in Figure 5.2, differing from the conventional practices on previous projects. The rationale behind the client implementing this change in waterproofing requirements was to achieve a drier tunnel environment and deliver a higher-quality end product.

The cut, spray, bolt approach was not the sole solution to addressing the revised tunnelling requirements; however, it was the preferred methodology selected at the time by site construction teams due to its practicality and efficiency. A potential alternative solution for drained tunnels to be investigated for future projects involves utilising longer handlebar plates for GWCS-B which protrude out further through the initial lining as shown in Figure 5.3. This approach may minimise amount of additional works around bolt tails/handlebar plates whilst potentially retaining the traditional excavation sequence where required particularly in water bearing areas. Given the significant amount of labour required for protecting the initial bolts with covers and chamfering of edges around rockbolts this proposed solution could be a viable option with less additional labour-intensive work required to achieve a similar outcome. Additionally, this would also save the need to install additional bolts in order to support the secondary lining as was done on previous projects like Rozelle and WHT enabling works as shown in Figure 5.1. Although some additional labour would still be necessary to install protection compared to the traditional method, the elimination of chamfering shotcrete, as seen on the M6 project, this system could result in a net reduction of cost and time.

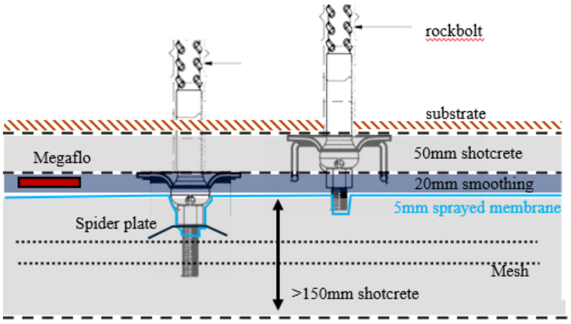

Figure 5.1. Previous GWCS-B.

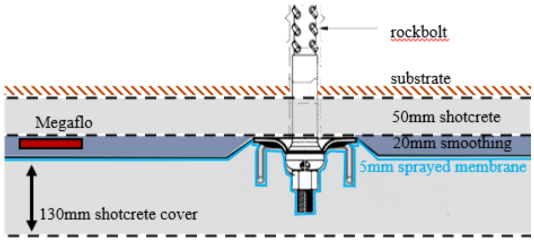

Figure 5.2. Adopted M6 GWCS-B solution.

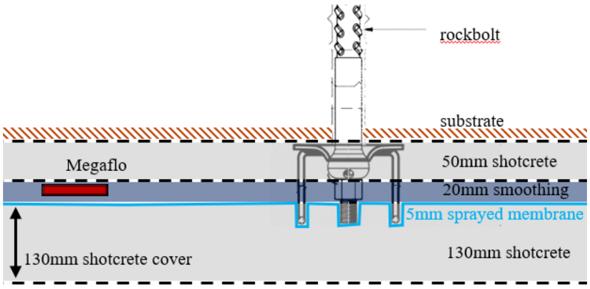

Figure 5.3. Potential solution for future projects

A key implication of this procedural change is the initial layer of shotcrete, applied immediately after excavation, serves only to provide temporary ground support for manned entry and is not considered part of the structural lining. Utilising this new methodology means that the whole tunnel is sprayed with an additional 50mm of shotcrete compared to the traditional tunnelling approach which is a costly exercise.

The below summarises the key findings arising from the implementation of the more stringent groundwater control criteria on the M6 project.

- Forward probing, combined with pre-excavation grouting is the preferred method for managing water ingress ahead of excavation.
- The involvement of the client and IC in the GWCS process was successful, enabling the early alignment of expectations, thereby enhancing the overall quality of the product. There were many areas with rework during the beginning of the process while expectations were being aligned, but following this initial phase, the contractor demonstrated improved consistency and execution.
- Innovations such as Cut-Spray-Bolt sequencing can provide benefits for groundwater control systems but do incur additional challenges and work required for spray membrane solutions. A notable distinction was observed in the performance of the final lining, with the revised approach yielding a perceptibly drier tunnel environment due to a thicker lining promoting more effective diversion of groundwater to the nearest strip drain.
- While the Cut-Spray-Bolt approach was successfully implemented for the M6, future projects may explore hybrid solutions to retain the traditional Cut-Bolt-Spray sequence with the same dry tunnel outcomes.

Though the revised waterproofing methodology introduced construction complexities, it has delivered demonstrable improvements in tunnel dryness and performance. By refining these methodologies, future Sydney tunnelling projects can achieve greater construction efficiency, cost-effectiveness, and long-term durability in groundwater management.