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Design of deep undrained tunnels for groundwater pressure using Australian Standards

H. Alaedini, H, Asche & T. Peglas
Aurecon, Brisbane, Australia

ABSTRACT: As urban areas expand, tunnels are increasingly constructed at greater depths to avoid existing infrastructure and water bodies. Deep tunnels are sometimes designed as undrained (tanked) to reduce environmental impact, lower operational costs, and minimise settlement risks. In the case of segmental linings installed by Tunnel Boring Machines (TBMs), the PAS 8810/EC2/Fib Model Code combination provides a coherent method of design for such tunnels. No such method exists for non-TBM (mined) tunnels. In Australia, the AS 5100 Bridge Standard set is commonly cited for major public projects. AS5100 has been written to provide bridge and associated infrastructure with a 100-year design life. However, applying AS 5100 to tunnels presents challenges, particularly regarding deep tanked tunnels. These challenges relate to design approaches for tunnels. This paper examines these challenges and proposes recommendations for design approaches and the application of load factors in the design of deep, undrained tunnels using the AS 5100 series, where groundwater is the dominant case and governs the structural response.

1 INTRODUCTION

As urban areas grow, the demand for tunnelled infrastructure increases. In Sydney alone, over 80 km of road and rail tunnels have been constructed in the last two decades. These tunnels often avoid existing or planned infrastructure, and tunnel alignments that were traditionally shallower are now being constructed at greater depths. At the same time, some clients have called for running tunnels to be tanked, citing operational and environmental requirements.

For tunnels constructed using TBMs with precast segmental linings, PAS 8810 is commonly used as the overarching document providing the design approach and the load factors. This is then used with compatible codes for conventionally reinforced or fibre reinforced segments, being Eurocode 2, and the Fib Model Code, respectively. PAS 8810, is specifically written for segmentally lined tunnels and contains a coherent workflow.

For mined tunnels, no such document exists. Australian delivery authorities commonly reference the AS 5100 Bridge Design series as the preferred design standard. Developed for bridges, and intended to deliver infrastructure with a 100 year design life, AS 5100 sets out requirements for the design, assessment, strengthening, and rehabilitation of existing bridges, as well as the design of related structures.

Intended to clarify this matter, the latest revision of AS5100.3 states that the AS5100 series is not intended for the design of driven tunnels. However, it notes that the approach for soil-supported structures may be adopted for driven tunnels, together with the guidance described in the ATS Tunnel Design Guideline (ATS, 2024).

This paper presents the authors' observations on the application of Australian Standards, particularly AS 5100, in tunnel design, based on their experience with major tunnel infrastructure projects across Australia. It provides recommendations for the application of load factoring approaches and effective use of AS 5100, with a focus on deep, undrained tunnels subjected to sustained groundwater pressure, where groundwater is the dominant case and governs the structural response.

2 DRAINED VS UNDRAINED TUNNEL SYSTEMS

Tunnels and other underground structures can be designed with a full-perimeter groundwater control system to prevent groundwater ingress. This approach requires the tunnel structure to withstand the full hydrostatic pressure and its fluctuations over the typical 100-year design life. A full-perimeter groundwater control system is implemented using sealing accessories such as gaskets (for segments) or using a waterproofing membrane for mined tunnels.

In contrast, drained tunnels allow full or partial ingress of groundwater, which is then controlled and redirected through designed drainage elements, typically located around the tunnel perimeter or at the invert. For example, some tunnels feature a waterproofing membrane at the crown to reduce ingress and prevent dripping, while the walls and invert remain unsealed.

Undrained tunnels generally require a more robust structural design than drained tunnels, due to the need to resist groundwater pressure. If this pressure is at all significant the lining will involve a lining all around the tunnel and thick reinforced concrete sections.

3 GROUNDWATER LOAD IN UNDRAINED TUNNELS

3.1 *General*

In undrained tunnel designs, groundwater is often a significant, if not the dominant, load case. As an external load on the tunnel lining, groundwater exhibits several unique characteristics:

- It is a sustained load, continuously present over the tunnel's design life, unlike transient loads which may be intense but short in duration.
- It follows the lining as it deflects without diminishing its intensity, unlike ground loads which tend to diminish with deformation.
- Its pressure increases with depth, typically resulting in the highest load at the invert.
- It can induce flotation, leading to uplift forces and potential gap formation at the invert, subjecting it to bending stresses.
- Groundwater load variability depends on site-specific hydrological conditions, including:
  - In some locations, the groundwater table lies close to the surface. Provided flooding does not occur, the groundwater may rise only to ground level, resulting in limited variability between typical and extreme conditions.
  - In urban environments, groundwater levels are often suppressed by nearby infrastructure such as basements, sewer systems, or stormwater drains, leading to significant variation between typical and extreme levels
  - Where surface flooding can occur and is hydraulically connected to the groundwater; flood levels must be considered in the assessment of load variability.

Figure 1 shows the typical situation. In Figure 1(a), the loading is shown, with a larger magnitude of load on the invert than on the crown (Archimedes principle). In Figure 1(b), the deformation due to this load is shown, with deformation in the crown restrained by the ground, but a gap in the invert allowing deformation. In Figure 1(c), the bending moment is shown. Bending moment is proportional to the second derivative of deflection. In the crown, where deflection is restrained, bending moment is negligible. In the invert, large bending moments can occur.

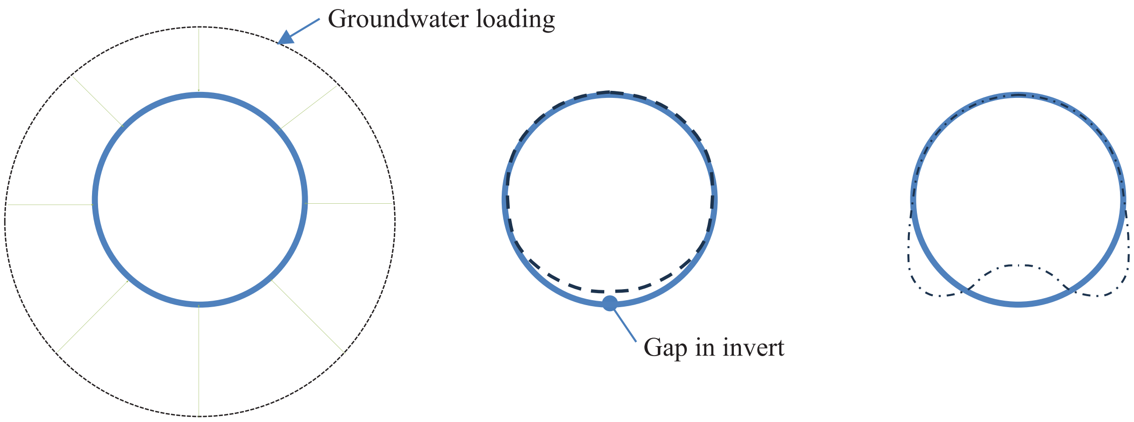

Figure 1 (a) loading due to groundwater, (b) deflection, (c) bending moment

3.2 *TBM tunnels versus mined tanked tunnels*

There is a difference between TBM tunnels with gasketed segmental linings and mined tunnels that are constructed undrained. The following discussion compares a single shield TBM driven with a closed face and some face pressure, with a mined tunnel, however the degree of difference will be less if the TBM is a double shield without face pressure.

In the case of the TBM, the excavation boundary is pressurised to a proportion of the insitu stress, often not to the full extent of the insitu stress, but a significant fraction. The slurry will maintain the pressure around the shield until the backfill grouting; the backfill grouting itself will be injected at a fraction of the insitu stress. The distance behind the face where the lining is installed will depend on the shield geometry, which, in general, tends to be in inverse proportion to the diameter of the tunnel. Thus, due to these three factors, face and shield pressure, backfill grout pressure, and closeness to the face, the segments will be installed without complete release of the insitu ground pressure. In terms of shrinkage of the segments, much of this will have occurred before the segment is installed. As far as the groundwater is concerned, the lining is prestressed by the process, and a gap may not form.

In the case of a mined tanked tunnel, the situation is completely different. The face will be far away from where the lining is installed, and the lining is installed unstressed. The lining will now shrink away from the ground. When the groundwater begins to recover, the lining will tend to float, and the final outcome is that there will be a significant gap between the lining extrados and the ground, in the invert. This gap allows for bending to occur in the invert; this is usually the design case requiring the most reinforcement.

4 LIMIT STATE DESIGN FRAMEWORK FOR TUNNELS

4.1 *Probabilistic Basis and Load Factoring Principles*

The following principles are from the Probabilistic Model Code (JCSS, 2001):

"Structures and structural elements shall be designed, constructed and maintained in such a way that they are suited for their use during the design working life and in an economic way.

In particular they shall, with appropriate levels of reliability, fulfil the following requirements:

- They shall remain fit for the use for which they are required (serviceability limit state requirement)
- They shall withstand extreme and/or frequently repeated actions during their construction and anticipated use (ultimate limit state requirement)
- They shall not be damaged by accidental events like fire, explosions, impact or consequences of human errors, to an extent disproportionate to the triggering event (robustness requirement)."

These statements are carefully worded. The phrase "*with appropriate levels of reliability*" lead in this code, to tables of maximum values of the probability of failure. These values are very low, reflecting societal intolerance for loss of life resulting from structural failure. The use of probabilistic methods in practice is limited, because they require high levels of expertise in a range of mathematical techniques. Nevertheless, interest in and the adoption of these methods are increasing (Low, 2022).

Most current structural design codes have not fully adopted probabilistic methods. Instead, they employ a simplified approach using partial safety factors, known as the Load and Resistance Factor Design (LRFD) method. This method treats loads and resistances as separate and independent probability distributions, and partial factors are chosen to reduce the probability of the load exceeding the resistance to a sufficiently small value.

In reality, load and resistance distributions are not known. At the time of introducing the limit state methods in Australia, Pham and others studied statistical models for loads and resistances, and calculated the probability of failure given by the existing working stress method (Pham 1985). Partial factors for limit state design were chosen for the various dead load, live load, wind load and for materials such as steel and concrete. Pham noted the arbitrary nature of the split between strength and load factors. For example, a load factor of 1.4 combined with a capacity reduction factor of 0.6 has the same result as a load factor of 2.8 with a capacity reduction factor of 1.2. Pham proposed the following criteria for selecting partial factors:

- The strength factor and load factors should reflect, in their relative values, the respective uncertainties associated with the resistance and load effects.
- The strength factor should be kept sufficiently low to allow for potential future increases without exceeding the value of 1.0.
- The combination of factors should provide results consistent with full probabilistic design.

Load factors assigned by code writers can occasionally result in apparent anomalies. An example is given in Day (2001). Day considers a beam supporting an open water tank. Since any excess water simply overflows, the load can be considered to be very certain in its magnitude. However, Day demonstrates that using a partial load factor of 1.0 in this case leads to underdesign. This is because the capacity reduction factors in the normal codes have been chosen to be compatible with load factors for uncertain loads (such as dead and live loads) which the code authors have selected to give "sensible" numerical values. For this reason, AS 1170 assigns a load factor of 1.2 for liquid loads, even though it is physically impossible for the hydrostatic load to reach 1.2 times its nominal value, so as to achieve an acceptable probability of failure for all structures and all load cases.

This example is analogous to a misconception sometimes encountered in the design of undrained tunnels subject to groundwater pressure. Designers argue that when the design groundwater level multiplied by the relevant load factor exceeds the ground surface, the result is physically unrealistic and therefore overly conservative. On this basis, they may justify applying a lower factor of safety. However, this approach overlooks the probabilistic foundations underpinning limit state design. The intent of applying a load factor, even if it leads to seemingly implausible conditions, is to achieve an overall acceptable probability of failure when combined with the relevant capacity reduction factors. Arbitrarily reducing these factors based on perceived physical limitations compromises the limit state approach and may lead to unsafe designs.

In summary:

- The use of partial factors is based on the assumption that load and resistance probability distributions are independent.
- Partial factors are arbitrary and interrelated. Load factors from one standard should not be used with capacity reduction factors from an unrelated standard.
- Partial factors are not independent from each other. Individual load factors relate to corresponding capacity reduction factors and to other load factors.

4.2 *Application of Limit State Design to Tunnel Engineering*

The application of LRFD to geotechnical design has long been controversial.

- In geotechnical engineering, the distinction between "load" and "resistance" is often blurred, as geotechnical materials can function as both, complicating the assignment of partial factors. As a result, geotechnical LRFD codes provide specific design methods for different structures in which individual partial factors are applied differently, depending upon the structure type.
- The strength of geotechnical materials often do not follow a normal distribution; this means that the common definition of the "characteristic value" based on standard deviations from the mean can lead to unreasonable values. In geotechnical design "the characteristic value of a geotechnical value should be a conservatively assessed value" (AS5100.3), noting that AS5100 recommends "engineering judgement" and "geotechnical engineering advice".

Tunnel design presents further complexity, as the ground and groundwater simultaneously serve as both the load and a high proportion of the resistance. Schweiger (2017) considers alternative Design Approaches (DA) within Eurocode 7 to address this issue. There is considerable complexity around this issue, however both PAS 8810 and, as will be described below, AS5100.3 recommend that the approach should be followed such that the analysis is carried out without assigning partial factors either to loads or materials, with checks of capacity occurring after analysis.

5 USE OF AS 5100 FOR TUNNEL DESIGN

5.1 *General*

The AS 5100 Bridge Design codes set comprises nine parts covering the design, assessment, rehabilitation, and strengthening of bridges. Part 1 describes the overall principles for the set. Part 2 describes load cases and load factors. Part 3 describes geotechnical design. Part 5 describes concrete and Part 6 describes steel structures.

The design life for structures under AS 5100 is 100 years. Ultimate and serviceability design actions are defined with a 5% probability of exceedance, either over the design life for ultimate limit states (corresponding to a 2000-year return period), or per year for serviceability limit states (corresponding to a 20-year return period).

For non-geotechnical structures, where loads and resistances are clearly independent, design is based on considering load cases using Part 2 for guidance, and then providing suitable capacity using Part 5 for concrete structures, and Part 6 for steel structures. Specifically for ultimate limit states, load factors are applied to individual loads from Part 2 before deriving actions such as thrust and bending moment, which are checked using the appropriate capacity reduction factors from Parts 5 or 6.

In the case of geotechnical structures; footings, piles, retaining walls, buried structures, Part 3 is to be used. Each of these types of structure are assigned different design methods. For example, for soil-supporting structures, the analysis is carried out with all loads unfactored. At the completion of the analysis, the action effects (thrust, shear, bending moments) are factored by a global factor of 1.5. Structures are then checked using the appropriate capacity reduction factors from Parts 5 or 6.

5.2 *Tunnel design in general*

AS5100.3 Section 1.2 Application, describes how to use this code set in tunnel design.

"The AS5100 series is not intended to be used for the design of driven tunnels. If approved by the relevant authority, temporary and permanent concrete/shotcrete tunnel linings may be designed using the provisions in this Standard for soil-supporting structures, in particular Clause 2.3.3(e), together with the guidance described in the ATS Tunnel Design Guideline."

This is very clear. Clause 2.3.3 specifically describes the procedure of analysing with all loads unfactored. At the completion of the analysis, the action effects (thrust, shear, bending moments) are factored by a global factor.

The words above also mention the ATS Tunnel Design Guideline as a source of guidance. This is because the global load factor approach does not account for the variability or probability of groundwater levels, which can fluctuate significantly over the 100-year design life. Applying a fixed factor of 1.5 does not reflect the probabilistic nature of groundwater loading and may result in either unconservative or overly conservative designs depending on the assumed design level.

6 APPLICATION OF THE ATS TUNNEL DESIGN GUIDELINE TO GROUNDWATER LOADING

The ATS Tunnel Design Guideline (ATS, 2024) provides supplementary design guidance specific to Australian conditions and tunnel practices. Sections 5.4.8 and 5.4.11 provide key insights into groundwater loading, with Section 5.4.11 particularly relevant to deep, undrained tunnels subject to sustained hydrostatic pressure, where groundwater is the dominant case and governs the structural response.

The guideline stresses the importance of appropriately assessing groundwater pressures acting on tunnel linings, particularly in undrained configurations where the permanent lining must withstand constant and unrelenting hydrostatic pressures throughout the design life. Unlike many other loads, groundwater pressure is independent of the tunnel lining behaviour. Groundwater levels should not be considered static. The design should account for a full range of possible scenarios, including climate change impacts, flooding, tidal fluctuations, and post-construction groundwater recovery.

The guideline recommends that groundwater loads for both Ultimate Limit State (ULS) and Serviceability Limit State (SLS) be derived from comprehensive hydrogeological investigations, that consider the most adverse groundwater conditions likely to occur during both construction and operation.

Suggested categorisation of groundwater levels are as follows:

- Initial or Monitored groundwater level: The observed level during investigations.
- Normal or Usual groundwater level: Reflecting seasonal variation, long-term trends, and climate change.
- Unusual groundwater level: Significant deviation from Normal or Usual levels.
- Extreme groundwater level: Associated with rare events such as groundwater levels influenced by the Probable Maximum Flood (PMF), where applicable.

Load factors and load combinations are discussed and direction is provided on reconciling conflicting guidance across different Australian Standards. For ULS design, the guideline recommends applying a different load factor ranging from 1.0 to 1.5, depending on the groundwater level category. The selected load factor should reflect the required factor of safety, the probability of groundwater level occurrence, and the level of confidence in the groundwater level estimates.

In summary, the ATS Tunnel Design Guideline provides guidance for incorporating groundwater loads into undrained tunnel design. It acknowledges the limitations of standard LRFD approaches for geotechnical structures and supports alignment with AS5100.3 methodologies. Importantly, it highlights the importance of considering multiple groundwater scenarios and selecting appropriate load factors, informed by the overall factor of safety requirements, probability of occurrence, and confidence in groundwater level predictions.

7 RISK-BASED METHODOLOGY FOR GROUNDWATER LOAD CLASSIFICATION AND FACTOR SELECTION

Building on the recommendations presented in the ATS Tunnel Design Guideline (ATS, 2024), the following risk-based methodology is proposed for classifying groundwater loading scenarios and assigning appropriate load factors for use with the AS5100.3 approach. This approach is intended to support the design of undrained tunnels subject to sustained groundwater pressures, where groundwater is the dominant case and governs the structural response, allowing engineers to consider load factors based on available data, risk profile, and design objectives.

Table 1. Risk-based approach for assigning groundwater load factor

Step 1	Establish the baseline groundwater level through geotechnical investigations conducted prior to tunnel excavation.
Step 2	Assess groundwater level variability due to seasonal fluctuations, temporary drawdown during construction, permanent drawdown or recharge over the design life of the tunnel, impacts to hydrostatic pressures due to surface flooding (consider return periods from 1:50 to 1:2000, and PMF if applicable), and climate change effects.
Step 3	Classify each groundwater level (load case), in alignment with the ATS Tunnel Design Guideline: - Normal/Usual cases: Observed or seasonally adjusted groundwater levels, including trends and long-term effects such as recharge or climate change. If surface flooding may affect groundwater levels or result in external water pressure on the tunnel lining, consider a 1:100 AEP event. - Unusual cases: Elevated groundwater levels beyond the Normal/Usual range. For cases involving surface flooding that could influence groundwater level or static water pressure acting on the tunnel lining, consider a 1:2000 AEP event. - Extreme cases: Rare events beyond the Unusual category, including PMF or 1:10,000 AEP flooding, where such conditions influence groundwater or induce static pressure on the tunnel lining. These scenarios are unlikely for most urban tunnels, and their applicability should be carefully evaluated based on consequence, infrastructure criticality, and design credibility.
Step 4	Apply groundwater load factors considering the ranges below to achieve the suitable factor of safety, (refer recommended factors of safety in Section 6 of this paper), based on confidence in the groundwater data: - Normal/Usual cases: Load factor 1.25–1.35. Use the lower end if groundwater level reliability is high or variation is <10% of the existing hydraulic head; otherwise, use the higher value. Use a still higher value if the uncertainty surrounding groundwater levels is significant. - Unusual cases: Load factor 1.1–1.25. Apply criteria as above depending on reliability of the data and extent of variation. - Extreme cases: Load factor 1.0–1.1. Use the lower end only if groundwater predictions are well-supported and variation remains low; otherwise, adopt the higher value.
Step 5	- Compare the criticality of groundwater-dominant cases with other load combinations. Remove groundwater to assess whether it governs structural response. - Where groundwater pressure is applied symmetrically, high compressive forces may develop in the lining, increasing apparent moment capacity when assessed using interaction diagrams. These compressive effects may not be uniform throughout the tunnel, particularly in dry sections or areas with low permeability. Therefore, such forces should not be relied upon to unrealistically enhance structural capacity or safety margins.

Engineering judgement is essential in applying this methodology. Designers must consider multiple groundwater scenarios, select appropriate load factors based on the required factor of safety, and account for both the probability of groundwater level occurrence and the confidence in available data. This approach supports a balanced, risk-informed design that reflects the inherent uncertainties in groundwater behaviour over the design life of a tunnel.

The factors proposed above can be compared with the PAS 8810/Eurocode design for segmentally lined tunnels. PAS 8810 considers groundwater load as a Permanent load. In this code, such a load is assigned a partial load factor of 1.35. However, this load factor cannot be considered in the absence of consideration of its relationship to the partial load factors for materials (see discussion in Section 4.1 above). Eurocode 2 assigns, for concrete in bending with limited axial load, a partial factor of 1.5. The equivalent factor in AS5100.5 is a capacity reduction factor of 0.6 (or 1/1.67). A simple comparison between these two cases would suggest a partial load factor of 1.22 in conjunction with AS5100.5. However, as discussed above in Section 3.2, there is a difference between segmental linings and tanked mined tunnels so we recommend a larger number.

8 CONCLUSION

Designing deep, undrained tunnels subjected to sustained groundwater pressure introduces additional challenges not fully addressed by current Australian Standards.

AS 5100.3, although not originally intended for driven tunnels, offers a suitable framework when applied with engineering discretion and in conjunction with the guidance described in the ATS Tunnel Design Guideline.

The ATS Guideline provides a more practical basis for assessing groundwater pressures in tunnel design, recommending a scenario-based approach that categorises groundwater conditions as Usual/Normal, Unusual, or Extreme. Building on this, the paper proposes a risk-based methodology for selecting appropriate groundwater load factors, informed by site-specific conditions, expected variability, and confidence in available data.

Ultimately, the design of deep undrained tunnels should adopt a probabilistic, scenario-based approach that reflects the full range of groundwater conditions likely to be encountered over the tunnel's design life. Load factors, informed by the overall factor of safety requirements, should be selected to suit each scenario, accounting for the probability of occurrence and the reliability of groundwater level predictions.

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