TUNNEL DESIGN GUIDANCE REVIEW

In this article, Benoit Jones reviews the information available for people wishing to learn about tunnel design in soft ground.

IN RECENT YEARS, quite a few new books have been written about tunnelling, and as a growing industry we might well expect this number to increase. Many of these books, however, focus mainly on construction planning and construction methods. So what guidance is there for people who want to learn how to design a tunnel? What is someone new to the industry meant to do? This article will focus on textbooks and design guides to give an overview of what is available.

Introduction

There appears to be a distinct lack of contemporary information on tunnel design in soft ground. There are several books that outline the process of rock tunnel design, and there are several books that cover tunnel construction methods in both hard rock and soft ground, but there are very few that explain how to design a tunnel in soft ground beyond the generalities or preliminaries such as determining the required space envelope.

There may be several reasons for this, so we can have a bit of fun speculating:

1. It is especially difficult and no-one actually knows how to do it. Everyone who claims to know how to do it suspects that they are missing something, so they don't want to stick their head above the parapet and get shot down.
2. It is really easy but specialist designers don't want anyone to find out how easy it is and enter their lucrative market.
3. No-one wants their competitors to know their secret highly sophisticated design methods that are better than everyone else's and thus lose their competitive edge.
4. No-one has the time to write a book.

No.3 may be true but it isn't rational because if you do a very sophisticated design that is very efficient but the independent checker is using less sophisticated design methods, all efficiency savings will be lost when they insist on a more robust design. Also, I don't believe no.2 is correct – I think tunnel design may be simpler than many people make it seem, but it is still a complex problem. So by a process of elimination, it must be either no.1 or no.4, or both.

Textbooks and guidance

The following books will be reviewed, all of which have at least a small section on tunnel design in soft ground:

1. Maidl, B., Thewes, M. & Maidl, U. (2014). Handbook of Tunnel Engineering Volume II – Basics and Additional Services for Design and Construction, English edition (translation by D. Sturge). Berlin, Germany: Ernst & Sohn. ISBN 978-3-433-03049-3.
2. Kolymbas, D. (2008). Tunnelling and Tunnel Mechanics – A Rational Approach to Tunnelling, 2nd corrected printing. Berlin Heidelberg, Germany: Springer Verlag. ISBN 978-3-540-25196-5.
3. Guglielmetti, V., Grasso, P., Mahtab, A. & Xu, S. (2008). Mechanized Tunnelling in Urban Areas. London, UK: Taylor & Francis Group. ISBN 978-0-415-42010-5.
4. Chapman, D., Metje, N. & Stärk, A. (2010). Introduction to tunnel construction. Abingdon, UK: Spon Press/Taylor & Francis Group. ISBN10: 0-415-46842-6.
5. Ng, C. W. W., Simons, N. & Menzies, B. (2004). A Short Course in Soil-Structure Engineering (reprinted with corrections 2008). London, UK: Thomas Telford. ISBN 978-0-7277-3263-3.
6. Mair, R. J. & Taylor, R. N. (1997). Bored tunnelling in the urban environment. Theme Lecture, Plenary Session 4. Proc. 14th Int. Conf. Soil Mechanics and Foundation Engineering, Hamburg, Vol.4.

As you can judge by the titles, some of the books focus mainly on construction methods and have only a single chapter on design. Mair & Taylor (1997) is not a textbook but a state-of-the-art review paper 33 pages long. It is now nearly 20 years old and so slightly out of date in some areas but still mostly valid. It is included as a comparison.

Subject matter

The following are the main topics one would expect to be covered in order to understand tunnel design in soft ground. I have to say here that I believe it to be extremely important that tunnel designers also understand the construction methods, but as I noted earlier, there is plenty of information available for that so here I am focussing on the actual design of the tunnel lining.

1. Determining the characteristic values of geotechnical parameters
2. Heading stability:
   a. Drained
   b. Undrained
3. Design of ground improvement or dewatering methods
4. Ground movements induced by tunnelling
5. Building damage assessments
6. Global structural design:
   a. Structural design of circular tunnels or shafts of constant lining thickness
   b. Structural design of circular tunnels or shafts with a segmental lining of rectangular section
   c. Structural design of circular tunnels or shafts with a 'standard' (panelled) segmental lining
   d. Structural design of tunnels or shafts of non-circular cross-section
7. Detailed design of segmental linings:

a. Calculations for handling loads and jacking forces on segments
b. Calculations for designing joints and packers
c. Calculations for gasket compression
d. Watertightness
e. Fire design

8. Detailed design of sprayed concrete linings:
a. Material properties for plain, steel fibre and bar-reinforced concrete with age
b. Stress-strain curves and plastic hinge rotation capacity
c. Design by testing
d. Design of pre-support measures
e. Watertightness
f. Fire design

9. Design of junctions
10. Seismic tunnel design
11. Design for durability
12. Other tunnel lining types and materials, e.g. timber, steel, masonry, cast iron
13. Structural assessment of existing tunnels

I should make it clear at this point that what I am looking for are instructions or examples for how to do calculations. Table 1 summarises the content of the publications that have been reviewed. An empty circle means a superficial coverage of the topic. A grey circle means there is some detail but coverage is not comprehensive, e.g. only one method is described when several are available, or a method is described but not in sufficient detail for someone to be able to do the calculation without referring to other publications. A black circle means the topic is covered reasonably comprehensively such that someone could follow the instructions and do the calculation.

It should also be clear by now that I am focussing on detailed calculations – not just awareness of issues or qualitative descriptions.

Discussion of Table 1

Maidl et al.'s (2014) strength is in the comprehensive sections on construction methods in both Volume I and II. The section on design is perhaps over-reliant on German references and is not comprehensive, such that the reader obtains only a partial awareness of the issues and is not able to go away and design a tunnel independently. Almost half the pages are devoted to testing of rotation capacity of steel fibre reinforced concrete, which was the subject of a research project at Ruhr Universität Bochum where the authors are based.

Kolymbas (2008) is the only book that is mainly about tunnel design, rather than being a book about tunnel construction methods with a design section in it. It includes quite a large chapter on soil and rock material behaviour, which is really interesting, but does not discuss the selection of characteristic values for use in design. Nor does it cover the structural design of a segmental or sprayed concrete lining. It is the only book that mentions seismic tunnel design or design for fire at all. It also includes in-depth

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Table Table 1: Soft ground tunnel design topics and their coverage in textbooks and guidance documents
(○ = superficial, ● = some detail but not comprehensive, ● = comprehensive)

		Maidl et al. (2014)	Kolymbas (2008)	Guglielmetti et al. (2008)	Chapman et al. (2010)	Ng et al. (2004)	Mair & Taylor (1997)
Determining the characteristic values of geotechnical parameters					○		
Heading stability	Drained		●	●	●	●	●
	Undrained		○	●	●	●	●
Design of ground improvement or dewatering measures		○	●				○
Ground movements		○	●	●	●	●	●
Building damage assessment		●	●	●	●	●	●
Global structural design	Circular, constant thickness	●	●		●		
	Circular, segmental lining			●			
	Circular, standard segmental lining						
	Non-circular cross-section	○				●	
Detailed design of segmental linings	Handling loads and jacking forces			●			
	Joints and packers			●			
	Gaskets			●			
	Watertightness	●					
	Design for fire						
Detailed design of sprayed concrete linings	Material properties with age for plain, steel fibre and bar reinforced concrete				○		
	Stress-strain curves and plastic hinge rotation capacity	●					
	Design by testing	●					
	Design of pre-support measures					●	○
	Watertightness	●					
	Design for fire		●				
Design of junctions							
Seismic tunnel design			●				
Design for durability							
Other tunnel lining types – timber, steel, masonry, cast iron							
Structural assessment of existing tunnels							

sections on ventilation and groundwater flow.

Guglielmetti et al. (2008) focusses, as the title suggests, on mechanised shield tunnelling. Therefore, sprayed concrete, or the use of other materials or methods other than precast concrete segments, are not covered. That being said, the coverage of design aspects for precast concrete segmental linings is quite detailed. Seismic design and design for durability, fire and watertightness are not covered.

Chapman et al. (2010) covers the basics and is particularly good on ground movements, but does not really even begin to give the reader the tools to design a tunnel lining. This is clearly not the aim of the book, which like Maidl et al. (2014), is focussed on construction methods.

Ng et al. (2004) is a book about more than just tunnels, also covering piling and multi-propped deep excavations. What it does well is show the reader, using step-by-step examples, how to actually do calculations. It draws heavily from a small selection of review papers, notably Mair & Taylor (1997), which explains the correlation of topics in the table.

Conclusions

The analysis in Table 1 is to some extent subjective, and I am sure some may disagree with the choice of categories or the assessments made. There are also perhaps books out there that I haven't included. However, I think what is clear is that there is a dearth of good textbooks or guidance that teach tunnel design in soft ground in a comprehensive manner.

There are topics, such as heading stability, which are well-covered by many sources, but there are also topics, such as choice of characteristic geotechnical parameters, durability, watertightness, design for fire, tunnel junction design, as well as assessment of existing tunnels and linings made from materials other than concrete, which have very little presence in textbooks, and this should be addressed.

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