TUNNELS AND UNDERGROUND STRUCTURES
Tunnels and Underground Structures

Edited by

Jian Zhao
School of Civil and Structural Engineering, Nanyang Technological University, Singapore

J. Nicholas Shirlaw & Rajan Krishnan
Land Transport Authority, Singapore
Organiser:

Tunnelling and Underground Construction Society (Singapore)

Supporters:

Land Transport Authority, Singapore

International Tunnelling Association

The texts of the various papers in this volume were set individually by typists under the supervision of each of the authors concerned.

Authorization to photocopy items for internal or personal use, or the internal or personal use of specific clients, is granted by Taylor & Francis provided that the base fee of US$ 1.50 per copy, plus US$ 0.10 per page is paid directly to Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, USA. For those organizations that have been granted a photocopy license by CCC, a separate system of payment has been arranged. The fee code for users of the Transactional Reporting Service is: 90 5809 171 6/00 US$ 1.50 + US$ 0.10.

Published by Taylor & Francis
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN
270 Madison Ave, New York NY 10016

Transferred to Digital Printing 2007

ISBN 90 5809 171 6
© 2000 Taylor & Francis

Publisher’s Note
The publisher has gone to great lengths to ensure the quality of this reprint but points out that some imperfections in the original may be apparent
Table of contents

Foreword XII
Organisation XV

1 Keynote papers

Political and social aspects of present and future tunnelling 3
A. Haack

The challenges of urban tunnelling 15
Z. Eisenstein

Rock mass classification for choosing between TBM and drill-and-blast or a hybrid solution 35
N. Barton

Planning for cost-effective underground space use in urban areas 51
R. L. Sterling

Design of substructures against hydrostatic uplift 61
I. H. Wong

Current issues regarding mechanised and automated tunnelling 75
G. Ishii

2 Tunnelling in Asian regions

Tunnelling and underground projects in Singapore 89
R. Krishnan

Tunnelling and technological progress in tunnelling in China 97
J. Y. Wang

Current and future tunnelling works in Hong Kong for the years 2000-2010 107
I. McFeat-Smith
Tunnelling and underground projects in Korea
H.S.Chung & I.M.Lee

Tunnelling and underground construction in India – Present status and future potential
R.K.Goel

Tunnelling and development of tunnelling technologies in Japan
S.Kuwahara

Commencement of the MRTA Bangkok Subway, part of the M.R.T Chaloem Ratchamongkhon Line
D.F.Stewart, C.F.Schulz & K.I.Harman

Construction of the Khayam Tunnel of the Tehran Main Drainage Scheme
R.C.Frew & N.Khakpour

Australian tunnelling in an urban environment
J.J.Rozek

3 Tunnelling in soft ground

Delhi Metro – Tunnels and stations on the 11km underground metro corridor
M.Singh, A.J.Burchell & K.Nayan

Design criteria for large tunnels in soft ground
K.Zeidler & V.Gall

Determining the parameters of double-layer linings of shallow tunnels
N.N.Fotieva, N.S.Bulychev, S.V.Antziferov & A.S.Sammal

Ground freezing design in tunnelling – Two case studies from Stockholm
B.Stille, J.Brantmark, L.Wilson & U.Håkansson

Construction of North East Line tunnels at Singapore River Crossing
P.Sebastian & P.Nadarajah

Evaluation of face stability with the consideration of seepage forces in shallow tunnels
I.M.Lee & S.W.Nam

NATM tunnelling in Singapore Old Alluvium – Design assumptions and construction experience
O.Sigl & K.Rieker

Lining design and ground response to the construction of the Clarke Quay tunnels
G.V.R.Raju, G.R.Heath & K.Lim

Tunnel linings for Contract C705, Singapore Northeast Line
N.A.Moss
Construction of an advance tunnel for the Deep Tunnel Sewerage System (DTSS) using sprayed concrete linings
R.S. Nair, M.S. Deutscher, K.S. Tham & S.A. McChesney

Design and construction of sewer tunnels under the Deep Tunnel Sewerage System
B.T. Tan & B. Van Weele

Tunnelling under Woodleigh Workers’ Quarters on Contract 705
K.S. Tham & M.S. Deutscher

Special shield tunnelling methods in Japan
Y. Moriya

Application of neural network in estimation of air losses in compressed air tunnelling
A.A. Javadi & S.M. Ng

Construction of the linkway underneath the existing Outram Park Station
B.H. Lim & H.P. Yeo

4 Tunnelling in rocks
Use of rock caverns in urban areas
E. Broch & E. Moe

Underground expansion of the Swedish Museum of Natural History
P.A. Johansson, R. Ekeroth, S.E. Sundström & J.A. Åkesson

Innovative support system for Australia’s longest road tunnel
P.W. Gibbs

A new numerical model of rock bolts used in jointed rock
X.R. Ge & Y. Xiang

Feasibility of developing the Underground Science City in rock caverns under Kent Ridge Park, Singapore

A theoretical method for estimation of loosening pressure on tunnels in soft rocks
Y. Jiang, Y. Tanabashi & H. Yoneda

Considerations for ground vibrations in underground blasting

The use of bulk emulsion explosives at the Mandai underground storage caverns
P.F. Ong, M. Myklatun, C. Yeung & A. Labriola
Performance improvement of roof support system in longwall gate roads
S.Naik, F.P. Shende & R. Venugopala Rao

Three dimensional finite element analysis on construction process
of large span tunnel of Guangzhou Metro
X.J. Zhou, B. Gao, S. Hu & D. C. Li

Rock engineering system approach in tunnelling and underground excavation
J.G. Cai, H.Y. Bian, J. Zhao & X.T. Feng

Applicability of seismic geotomography to rock classification of Okawara
Tunnel, Kyushu, Japan
H. Kochihira, T. Nakazuka & Y. Yokoi

Quality recommendations on segmental lining for shield drive in hard rock
D. Kolic

Two cavern schemes in the Jurong Formation of Singapore
J. Zhao & J. Bergh-Christensen

Vibration isolation of cutter picks on mining machines
Z.C. Liu, F. F. Roxborough & B. B. Lin

Optimisation of operating and design parameters of shearer drums
by computer
Z.C. Liu, F. F. Roxborough & B. B. Lin

Discrete element modelling of rock cavern stability subjected to shock loading
S.G. Chen, J. Zhao, A. M. Hefny & Y. X. Zhou

Application of energy-dissipation model to majorization analysis
of construction sequence of large-scale underground openings
W. Zhu, S. Li & F. Chen

Simulation of thermal deformation around an underground opening
K. M. Neaupane, N. Gurung & T. Yamabe

5 Deep excavation

Geotechnical design and construction aspects of the Clarke Quay station
G. V. R. Raju, K. Lim & L. J. Endicott

Some observations during excavation on the behaviour of old alluvium soils
in Singapore
K. Jeyatharan & T. W. Song

Changi Airport station design and construction
C. P. Whiting & P. A. Gasson

Semi top-down construction method for Singapore MRT, NEL
A. R. Mitchell, C. Izumi, B. C. Bell & S. Brunton
Construction of the northern end of Outram Park Station  
C.Y. Hsung, B.H. Lim, N.Osborne & S.G. Chia  
An observational approach to the monitoring of the excavation  
at Harbour Front Station, Singapore  
D.C. Chen, N.Osborne, J.D. Shim & E. Hong  
Effect of horizontal soil movement on vertical piles  
C.S. Ong & C.L. Teh  
Behavior and performance of deep excavation in residual soils near sensitive structures  
S.K. Kong, K.S. Lai & D.Q. Yang  
The monitoring and analysis of results for two strutted deep excavations in Singapore using vibrating wire strain gauges  
D.R. Coutts & J. Wang  
Instrumentation for the North-East MRT project at Clarke Quay  
P. Nadarajah & P. Sebastian  
Reliability based design of sheet pile wall in excavation  
G.J. Li

6 Settlement and structures

Planning the monitoring required to confirm the movement and rotation of tunnels and trackwork due to excavation and tunnelling  
The assessment of limits for the movement of subway tunnels and trackwork due to adjacent construction  
Effect of adjacent excavation on MRT tunnels  
J.S. Sharma, J. Zhao & C.W. Chan  
An estimate of subsurface settlement trough width parameter for G4 material  
P.C. Lim & O. Sigl  
Ground control of tunnelling beneath an operating railway tunnel in Singapore  
N.H. Osborne, O.I. Williams & W.B. Lim  
Effect of deep excavation on piled foundation  
B. Chandrasekaran, S.K. Tang & T.L. Lim  
Deformation analysis based on shield tunnelling and soil conditions with case studies from Shanghai Metro tunnels  
Y. Bai, Q.W. Liu & J. Zhao
NATM – Effect of shotcrete setting time and excavation sequence on surface settlements  
*J.S. Sharma, J. Zhao & A.M. Hefny*

Monitoring of reinforced concrete piles under horizontal and vertical loads due to tunnelling  
*D.R. Coutts & J. Wang*

Tunnelling under shop-houses along Serangoon Road, Singapore  
*R.S. Nair & D. Wen*

Stability and settlement due to bored tunnelling for LTA, NEL  
*C. Izumi, A. Norrish, N.N. Khatri & R. Davies*

Soil disturbance and stability control of shield tunnelling in urban environment  
*J. Sun*

Safety in tunnelling is far too important to be left only to safety officers  
*J.M. Anderson & N.G. Terezopoulos*

### 7 Planning, investigation and ground improvement

How the Zimmerberg-Base Tunnel is being built in the City of Zürich  
*M. Bosshard & J. Matter*

Initial geotechnical considerations of Delhi Metro  
*J. Gahir, H. R. Yadav & R. N. Choubey*

Engineering properties of fluvial sand at Race Course Road  
*J. Chu, D. Wen, R. E. Kay & T. H. Tay*

Hydraulic fracturing stress measurements for the design of underground de-silting chamber  
*R. Singh & A. K. Dhawan*

Hydraulic three-dimensional tests – Comparison of concepts and results with single packer tests  
*E. F. de Quadros, D. Correa Filho & A. A. de Azevedo*

Engineering geology and geo-information system for cavern construction in the Bukit Timah Granite of Singapore  
*Y. K. Wu, Y. X. Zhou & C. C. Seah*

Geomechanical investigation plan in an underground research laboratory for feasibility study of radioactive waste repository in deep argillaceous rock  
*K. Su, N. Hoteit & O. Ozanam*

Risk assessment for tunnelling in adverse geological conditions in Asia  
*I. McFeat-Smith*
Tunnelling through challenging ground conditions in Singapore
C.K.Knight-Hassell & K.B.Tan
633

Construction issues related to jet grouted slabs at the base of excavations
J.N.Shirlaw, D.Wen, P.Nadarajah, S.I.Yoon & S.Sugawara
639

On site production of pre-cast tunnel segments in Singapore
K.B.Tan, S.T.Poh & S.B.Tay
645

Design issues related to jet grouted slabs at the base of excavations
J.N.Shirlaw, D.Wen, P.Nadarajah, S.I.Yoon & S.Sugawara
653

Planning the construction of an underground high energy physics facility
dedicated to the study of neutrino particles
C.Laughton
659

Modelling of injection in sand
S.W.Lee, M.D.Bolton, R.J.Mair, K.Soga, G.R.Dasari & T.Hagiwara
665

Crushing and conveying in tunnel construction – An overview of the principles
and operational benefits
E.Trueman
671

Author index
679
Foreword

The Tunnelling and Underground Construction Society (Singapore), TUCSS, was formed in 1998, to provide a forum for the discussion of topics relevant to tunnelling and underground construction. The formation of the society coincided with, and was largely a result of, the start of a number of major underground projects in Singapore. These projects included the North East and Changi Airport Lines for the Mass Rapid Transit System and the Deep Tunnel Sewerage System. Since 1998 a number of further major projects have been announced. These include the Marina Line (transit), the Kallang Expressway (road) and cable tunnels (power).

The society organises regular monthly meetings, and occasional workshops, to encourage the sharing of experience about tunnelling and underground construction.

This conference, the International Conference on Tunnels and Underground Structures, ICTUS2000, is another major step in the Society's efforts to provide a forum for the exchange of experience. The conference is built out of three main elements. The first element involves the documentation of the experience gained during the planning, design and construction of recent projects in Singapore. The second element relates to work in South, Southeast and East Asia, and involves both recent experience and an overview of recent and planned major projects. The third element is the international element. This includes well known keynote speakers, who will share their great experience and knowledge, and offer speakers from 24 countries worldwide.

The conference is supported by the International Tunnelling Association, of which the society is an affiliated member, and the Land Transport Authority of Singapore. The organising committee wishes to take this opportunity to thank them for their support.

The organisation and success of the conference is due to mainly the efforts of many individuals, including the authors, keynote speakers, plenary and technical session speakers, and conference chairpersons. The Organising Committee wishes to thank all the organisations and individuals for their contributions to the society and the conference.

Organising Committee
International Conference on Tunnels and Underground Structures
Organisation

ORGANISER
Tunnelling and Underground Construction Society, Singapore

SUPPORTERS
Land Transport Authority, Singapore
International Tunnelling Association

ORGANISING COMMITTEE
Chairman
Kok Siong Chan
PB Merz & McLellan Pte Ltd

Co-Chairman
Rajan Krishnan
Land Transport Authority

Honorary Secretary
Jian Zhao
Geotechnical Research Centre, Nanyang Technological University

Members
Soew Kiak Ang-Tan
Sewerage Department, Ministry of Environment
Yang San Go
PB Merz & McLellan Pte Ltd
Kenny Lim
Maunsell Consultants (S) Pte Ltd
Kee Nam NG
Land Transport Authority
Jitendra Sharma
Geotechnical Research Centre, Nanyang Technological University
J. Nicholas Shirlaw
Land Transport
Ing Hieng Wong
Mitic Consultants
Yingxin Zhou
Defence Science and Technology Agency

XV
TECHNICAL REVIEW BOARD

Soew Kiak Ang-Tan
Peter Copsey
Richard F. Flanagan
Ashraf M. Hefny
Terence W. Hulme
Rajan Krishnan
Kenny Lim

Jitendra Sharma
J. Nicholas Shirlaw
Oskar Sigl
Ing Hieng Wong
Jian Zhao
Yingxin Zhou

CONFERENCE SECRETARIAT

Conference & Travel Management Associates
425A Race Course Road, Singapore 218671
1 Keynote papers
ABSTRACT: The use of underground space is winning more and more importance all over the world. This development is justified by the proven positive impact of subsurface construction especially to densely built-up areas. ITA - the International Tunnelling Association - is supporting those activities as one of the key tools for getting our cities more worthwhile to live in as well as more loveable and to form the social and hygienic basis for the increasing number of megalopolises.

1 SIGNIFICANCE OF SUBSURFACE CONSTRUCTION

Generally speaking, we experience our cities from the surface. We can find our way around here, can recall certain groups of buildings and are thus aware at any time just where we are. In cities with which we are unfamiliar, we can obtain decisive initial impressions when encountering it for the first time and compare and evaluate the character of the place we are visiting with towns we have got to know before. This normal pattern of behaviour also explains why so many of our fellow human beings prefer transportation systems which are on the surface.

Most inhabitants of a city as well as its visitors are far more familiar with the structure above ground than the multifareous infrastructure below the surface of the earth. Supply lines for gas, water, electricity, telecommunications and distance heating are located here along with a diversified network of disposal lines (Fig. 1). In large cities, there are also transport tunnels for rail commuter traffic, long-distance trains, motor vehicles and pedestrians. In many cases, this subsurface urban landscape is rounded off in built-up areas by private transport tunnels, underground garages, with as many as four or five storeys in the case of large administrative buildings, subterranean shopping malls and storage rooms, covered watercourses and many other special facilities.

Should local conditions demand and facilitate this, even production halls, offices, sports facilities and churches are set up underground. In this connection, especially impressive examples are to be found in North America, Japan and Scandinavia.

Our modern cities are almost incapable of sustaining themselves without this subsurface infrastructure, which is not identifiable at first glance. This very soon becomes evident when the chaotic conditions prevailing in some cases in the multimillion cities on the African, Asian and South American continents are taken into consideration. This does not simply apply to the hopelessly congested streets in the downtown areas. If anything, it is shown here too that a subsurface infrastructure represents an important prerequisite for public health right up to banishing the danger of disease. Even during the 1990s, this has been clearly underlined through examples of cholera and plague epidemics in parts of Central and South America as well as on the Indian sub-continent.
The overriding significance of an inner urban subsurface infrastructure in order to create decent conditions in the major built-up areas was once again emphasised not all that long ago at the United Nations HABITAT-II Conference in Istanbul, Turkey, in June 1996. More than 15,000 delegates from all over the world mulled over and discussed the prerequisites for humane living conditions in human settlements taking the varying climatic, topographical and cultural marginal conditions in different regions of the globe into account.

Apart from the built-up areas themselves, the utilisation of underground space is experiencing high and ever increasing significance in less densely populated regions. Attractive and fast transport links between industrial centres call for high-performance transport arteries for the economic, speedy and unhampered carriage of people and goods. Important impulses for the economic power of a region or nation are provided by transport development and links. As a consequence, tunnels for roads and railways are being built or planned to a great degree for crossing mountain ranges, rivers and straits.

Let us briefly mention at this point that apart from the use of underground space for civil purposes, there is in some cases, exploitation world-wide for all kinds of military facilities. The construction and maintenance of these facilities possess a not inconsiderable economic importance.

There is no doubt that the construction of transport tunnels and subsurface construction in general has reached a high standard in many countries. In more than 100 cities with populations in excess of 500,000, metros, urban railways or rapid transport systems travelling beneath the surface in inner urban areas have been built or further developed during the last 30 to 40 years. In Europe, Berlin, Budapest, Hamburg, London and Paris are numbered among the first cities starting with such modern rail commuter systems at the end of 19th, beginning of 20th century.

In conjunction with building tunnels for long-distance road and rail links, in Europe, first and foremost, the efforts which started in the early 1980s to develop high-speed rail traffic deserve mention (Fig. 2). A number of these new lines possess a very high proportion of tunnels between say 30 and 40 per cent with overall section lengths of 100 to 350 km. Basically, the situation world-wide is similar as e.g. in Japan, or plans drawn up in Taiwan, South Korea as well as other countries.
In summing up, it can be established that currently there are a number of countries which are extremely active in tunnelling (Fig. 3). In Germany for instance, contracts were awarded for roughly 25 km of transport tunnels annually on average during the last ten years, which were then completed following a commensurate length of time. 10 to 12 km of this total is accounted for by metro, urban and rapid transit system tunnels, some 5 km by long-distance rail tunnels and around 10 km by road tunnels. For the years to come, an increase especially with respect to long-distance rail tunnels can be anticipated. Mining has not been included in this study.

Currently, the overall length of operational transport tunnels in Germany alone can be accepted to amount to roughly 1,200 km. Throughout Europe, the figure is well in excess of 10,000 km, in other words, more than from Lisbon to Moscow and back! The situation elsewhere in the world, for instance in North America or in South-East Asia is similar.
"Till the earth and subdue it!" This biblical saying from the First Book of Moses (Genesis), Chapter 1, Verse 28 calls for a high degree of responsibility not only vis-a-vis one's fellow human beings but also with regard to dealing with nature and the world around us in a responsible fashion. Tunnelling and underground construction in general can afford a considerable contribution in this respect. Many examples from all over the world have been able to underline this, particularly over the past years. Thus the financial efforts which have gone on in Europe, North America and Japan for some three to four decades now in conjunction with constructing metros, the relocating of especially busy roads in inner urban areas at greater depths, the conversion of railway lines into high-speed routes, and finally the expansion or renovation of many main collectors for sewage in the core areas of major cities have considerably enhanced their vitality and their acceptance by the citizen.

As outstanding recent examples in this connection, let us mention: the subterranean shopping centres in Toronto and Montreal, the Washington and San Francisco metro systems as well as those in Seoul, Beijing and Shanghai, expansion of the rail networks in Berlin, London, Paris and Tokyo. At present, enormous efforts are being undertaken in the densely populated cities of Asia, Africa and Latin America aimed at establishing properly functioning sewage disposal systems. Examples of this are New Delhi, Calcutta, Cairo, Mexico City and Sao Paulo.

Apart from the direct positive effects for coming to grips with traffic flows, tunnels also generally have considerable effects with regard to reducing loads on the environment caused by traffic. This immediately becomes evident in downtown areas with underground rail systems, in which extensive pedestrian zones could be set up on the surface (Fig. 4). Indeed, the effects are so far-reaching that complete regions have been freed from the loads imposed by road traffic. This is for example, an important objective also for the major arteries crossing through the Alps, by means of which in Austria and in Switzerland, through lorry traffic between central and southern Europe is to be transferred to rail.

In conjunction with the construction of tunnels on new long-distance connections for road and rail, protection of landscape and environment has gained special and ever increasing significance. Engineers are called on to pull out all the stops here. For the ICE new route between Frankfurt and Cologne for instance, some 33 hectares of woodland had to be destroyed in the Greater Frankfurt area; however, in order to compensate for this, the Deutsche Bahn AG planted 142,500 new trees on a similarly large area. This represents one of the largest compensatory projects ever undertaken in the German federal state of Hessen and at the same time is the biggest reforestation undertaking in this region for centuries. Alongside such highly positive effects, unfortunately, mistakes are also made. Thus it should not happen - as it did in Europe recently - that in conjunction with the constructing of a two tube rail tunnel several km in length that grouting materials were used for closing the fissures in the rock, which to a large degree
contaminated surrounding springs and brooks. As a consequence, cattle grazing there died of poisoning when they used their customary watering places. The population of that area had to be supplied with drinking water transported there in tanks for months on end. In another case, a number of lakes above a tunnel route discharged into the tunnel tube that had been headed because fissures were either closed insufficiently or too late. These examples reveal the balancing act between what is strived for and what is actually achieved that is encountered in some places. Also as far as tunnelling is concerned, in the end, you must depend on the individual and the care he takes in planning and executing a project.

3 ITA - INTERNATIONAL TUNNELLING ASSOCIATION

In all the cases put forward as examples, tunnelling has decisively contributed to enhancing the quality of life in urban centres. This is also numbered among the declared aims of the ITA - International Tunnelling Association. This international tunnelling organisation currently has about 50 members throughout the world. It is not simply made up of industrial nations, many developing countries also belong to it, for which the advantages of subsurface construction are also evident: As far as these countries are concerned, however, the construction of supply and disposal lines below the surface initially create the most urgent prerequisites for a decent life in these multimillion cities which are concentrated in constricted areas, free of the danger of disease and social tensions. First, once these basic needs have been fulfilled, will it be possible that in the long run the improved and extended exploitation of subsurface space will come to terms with the immense traffic problems besetting the built-up areas of Asia and Latin America.

In order to promote the utilisation of subsurface space to the advantage of the populations of the developing countries as well, the ITA is co-operating closely with the United Nations and its sub-organisations. This, first and foremost, applies to the field of activities of the UNCHS - United Nations Centre for Human Settlements. In internationally composed working groups, the ITA provides experts from its member countries as well as from other interested countries, the opportunity for a comprehensive exchange of experience. The individual working groups are engaged in the following activities: Issues relating to subsurface construction management planning, direct and indirect advantages of subsurface construction, health and safety in tunnelling, mechanised tunnelling, the application of shotcrete, underwater tunnels, long tunnels at major depths, maintenance and repair of subterranean structures, tunnelling and the environment, contractual procedures for subsurface construction as well as research and development.

4 CONSTRUCTION METHODS - SAFETY ASPECTS AND RESPONSIBILITIES

The geology and topography which are encountered decisively influence the construction methods chosen to build a tunnel. In this connection, we have to distinguish between tunnelling in soft ground and in solid rock.

For soft ground tunnelling, there are typical methods which are applied. These include all kinds of variants of cut-and-cover construction methods (Fig. 5), shotcreting in combination with additional supporting measures geared to improve the bearing capabilities in the surrounding ground as well as mechanised, shield-supported tunnelling. In such cases, the ground is removed by excavators, in special cases, possibly by means of roadheaders, whereas tunnel boring machines are generally applied in the event of a shield-supported heading. The latest most spectacular examples for the application of shield-supported tunnel boring machines are the drives for the Trans Tokyo Bay Tunnel in Japan as well as the 4th Elbe Tunnel Tube in Hamburg. The last-mentioned project is being headed over a distance of 2.6 km with the biggest shield diameter ever used amounting to 14.2 m (Fig. 6).

Tunnels in solid rock are usually driven as drill + blast projects making use of the shotcreting method. For long-distance links, the cross-sections amount to maximum excavated areas of 100 to 150 m². The heading is undertaken in a number of sections depending on the strengths of the rock encountered, should the conditions be especially tricky, then divided up into several wall, roof and base tunnels (Fig. 3). However, mechanised tunnelling with boring machines is being increasingly applied for tunnels through rock as well. Alongside high rates of advance, it, above all, caters for improved safety for the tunnelling crews.
An important aspect in the construction of transport tunnels is ensuring that they function properly. Alongside the technical installations which are required and optimised routing and alignment, these, above all, include adequate sealing. Various methods are necessary to achieve this goal depending on the construction method applied. With regard to inner urban tunnels, watertight concrete in conjunction with joint strips and joint plates is mainly utilised. In the case of shield-driven tunnels, the joints between the prefabricated reinforced concrete elements are sealed by means of special elastomer profiles. Underground tunnels which are not shield-driven for commuter and long-distance links are, by and large, provided with membrane seals on the basis of plastic sealing materials (Fig. 7). These are created in the form of so-called umbrella seals if they are only required to ward off seepage water. On the other hand, if groundwater has to be contended with, then the membrane seal must completely encase the tunnel cross-section (Fig. 8). During the last 20 to 30 years, the processing technology for such membrane seals has achieved a high standard of development.

It goes without saying that underground construction measures pose high demands on technological experience as well as call for a highly responsible approach. Considerable differences exist in this respect compared with building activities on the surface. The geologists, geotechnicians and engineers, involved in planning and execution, must on no account succumb to the temptation of constantly further extending the limits of what is possible or supposedly possible. Over-assessment of one's own capabilities, cost and time pressure can then easily lead to setbacks. Such experiences have been made repeatedly of late. In this conjunction, let us recall the tragic tunnel cave-in in Munich as a result of which an articulated bus fell into the ensuing crater as well as the major earth collapses at London's Heathrow Airport or during the building of the Sao Paulo metro in Brazil.

Against this background, tunnellers must recognise their limits well in time and keep their sights trained on the high degree of responsibility they bear for the crews working underground as well as for the residents and road-users above the tunnel route. Accidents, such as those that
were mentioned, can all too easily result in tunnelling, which from its very nature represents an effective and beneficial tool designed to improve traffic and living conditions in our cities, receiving a bad reputation. Such a state of affairs can occur very rapidly even if no tunnelling accidents worth mentioning have taken place for years or decades on end. The main task of the ITA as well as the national tunnelling associations in the years ahead will thus be directed at - in addition to technical improvements - bettering the image of subsurface construction for the general public and consolidating confidence in tunnelling techniques and their application.

Fig. 6: Mounting the TBM for the 4th Elbe Tunnel Tube in Hamburg, Germany with an outside diameter of 14.2 m

5 FUTURE PROSPECTS OF TUNNELLING

At the beginning of the third millennium there are many questions: What should and can we expect from politics, economics, social development, growth of population, nutrition, technological inventions for our daily life, impacts of the fast developing electronic and telecommunication world and, last but not least, concerning the mode of our mobility? Will we still use conventional railways, subways, and roads - all these traffic routes with tunnels and bridges to cover the distance between home and office in our cities? Will we, at the end, still have to leave home for our work, for shopping, for administrative necessities - or will we manage all these things using our PC? Will we undertake our weekend tours and holiday trips by using tunnels all the way between the cities and the recreation areas in super-fast containers rushing through vacuum conditions to reduce air friction and air resistance? Progressive ideas in that direction already exist in form of the plans the Swiss Metro or the pipe mailing via compressed air. Or
will those vehicles be floating in fast running liquid or magnetic currents where the transport units do not touch any supporting structure like these old fashioned rails or asphalt roads (Fig. 9)?

Fig. 7: Installing a membrane seal on the basis of plastic material

a) umbrella system

b) full round system

Fig. 8: Principle of a membrane seal as protection against
a) seapage water (umbrella system)
b) groundwater (full round system)
Can we expect tunnelling or underground activities in general for living, storage, transport means or waste disposal on the moon or even on other planets close to our globe? Could it be necessary to plan these subsurface facilities in principle and from the very beginning to avoid spoiling those neighboured planets and to conserve their nature and original environment? And will we use ultramodern excavation technologies applying rocket engines (Fig. 10) to melt the rock masses along the planned alignment producing in the same step the clearance as well as the lining by vitrifying the surrounding rock material?

Leaving those science fiction dreams and turning again to the earth, we surely have to concentrate more systematically on a design for our traffic tunnels involving safety aspects from the very beginning. This concerns the geometry of the tunnel as well as its emergency installations.
In addition we can expect more automatically controlled car driving on our roads. Sensors will warn the drivers and eliminate risky short distances to other cars or to the tunnel walls. This could also ensure sufficient distance between cars, lorries and trucks themselves in case of a traffic jam inside a tunnel. Stopping bumper-to-bumper as usual nowadays outside as well as inside a tunnel extended the risk in the Mont Blanc Tunnel and the Tauern Tunnel during the two recent catastrophic fire accidents. Normal driving behaviour made it easier for the fire to spread from one vehicle to the next and thus contributed to the horrifying outcome. In the near future advanced guidance systems will warn the driver long before he enters a tunnel or a specific road section and recommend alternative routes as soon as an accident occurs in that section or a major traffic jam builds up.

Long distance train systems will become faster and need more and more tunnels. Their speed will increase to 300 to 350 km/h. In our cities, mass transit will be continuously automated and remotely controlled as it is already the case with the VAL-System or METEOR, both in France, the Dockland light railway in London, US or the PUTRA system in Kuala Lumpur, Malaysia.
Further development of people movers we know from some airports is already going in the same direction. Those systems will certainly spread to a greater extent into our urban centres, using underground ways in particular.

In general, the use of the underground in the form of covered and weather-protected shopping malls, cultural facilities, housing, offices, car parks or even underground walkways, possibly mechanised by the installation of conveyor belts like those occasionally encountered at airports will become more frequent. This is to save room for better urban landscape, more greenery in the cities and higher life quality on the surface with reduced pollution as regards noise, dust, fumes etc.

The growing trend for tunnelling and the multi-purpose use of the underground can be observed world wide. In all continents, the numbers and lengths of tunnels are increasing. Taking Europe as an example, there are more than 10,000 km of traffic tunnels in operation and many tunnels under construction at present. In Germany alone, the average annual production rate during the last 10 years has been 12 km for subways, 5 km for railways and 11 km for roads. Similar situations are to be found in other parts of the world like in South East Asia especially in Japan, Hong Kong and Singapore as well as in North and Latin American.

Concerning tunnelling technology we certainly have also to expect a continuing development. Starting with small diameter tunnels, trenchless technologies for the construction of service and disposal lines will without any doubt gain more and more importance (Fig. 12). This will be a significant contribution to the protection of our environment. Additionally, these technologies contribute to the saving and conserving of historical city architecture as well as to the reduction of the disturbances usually connected with cut-and-cover methods in this field unavoidably combined with all the negative impacts for local residents and for surface traffic. Finally, trenchless technologies improve the situation concerning the city landscape in general, if for example public parks or central places or even large or historical building complexes have to be passed under.

For transport tunnels with their larger cross-sections the methodologies also will undoubtedly improve during the years and decades ahead. The tendency to ever increasing cross sections will continue (Fig. 13). Especially the mechanisation of tunnelling will progress. Certainly the diameter of 14.2 m for TBM cutter wheels like for the 4th tube of the River Elbe Tunnel in Hamburg (Germany, Fig. 6) currently under construction will not stay as the final bench mark. Plans in Japan and Germany are ranging far ahead and extending the excavation diameter to somewhere between 15 and 16 m as a next step. The highly sophisticated pre-running ground investigation methodologies over a distance of 30 to 50 m ahead of the face will be improved and become more and more generally applied. Furthermore, robotics will progress significantly during the next decades both in the field of tunnel excavation as well as placing the tunnel lining. In the field of conventional tunnelling we surely have not reached the final stage of development. So, more sensitive explosives and ignition methods will be developed to save to a greater extent the environment and to produce less impact on adjacent rock parties. All those developments will certainly contribute to safer tunnelling, better occupational health conditions for the working crews, less effect on to the surface and generally to reduced risks during the construction phase underground as well as above ground.

Another field in tunnelling will also gain more and more importance: the linking of neighboured countries and even continents. Thus the countries in the region of the Alps, Austria, France, Italy and Switzerland are very soon going to excavate mega-tunnels with lengths between 50 km and 60 km like the Gotthard, the Lütschberg, the Brenner and the Mont Cenis base tunnels. The huge projects of strait crossings between Europe and Africa via the Gibraltar Tunnel or Asia and North America via the Behring Strait Tunnel etc. are no longer purely technical phantasies of crazy engineers, but in principle feasible projects.

6 SUMMARY AND CLOSING REMARKS

Cities which are capable of functioning both in social and hygienic terms form the prerequisite for a decent life in built-up areas. This also necessitates the utilisation of underground space to an ever increasing extent. The optimised translation of systematic underground development planning in our cities is only possible through applying the means presented by modern tunnel and line construction.
All in all, it can thus be determined that subsurface construction has lost none of its topicality world-wide, indeed it is actually gaining in significance. In economic terms, it represents a growth branch of industry, which is orientated to the future.

In order to avoid possible misunderstandings, it must be clearly stated at this point that we are not concerned with building tunnels at all cost. However, there is no real alternative to constructing tunnel in most cases when it comes to traffic links and the safe use of congested areas in large cities. This is impressively reflected by the extremely positive examples of a large number of downtown areas in European, Asian and North and Latin American built-up areas. However, it is not at all essential to set up straddling rapid transport systems underground in medium-size cities. Instead considerable improvements can already be achieved by ensuring that public transportation is operated underground along central lines in the core of a city only.

In a nutshell, it can thus be said that the development of core areas in many big cities through the routing of public commuter traffic as well as important road links via underground facilities clearly reflects the positive effects of subsurface construction. ITA working groups, which examined such issues on an international basis, have been able to compile numerous examples of this. In a well considered fashion and taking cost-benefit aspects into account, these opportunities should therefore also be exploited free of ideologies in future so that our cities become more worthwhile to live in and more loveable.

Often tunnels represent the sole alternative for crossing mountain ranges and waterways if large-scale transport links have to be established. In many cases, cross-border projects are at stake. As a consequence, effective co-operation on a political level as well is thus of decisive importance.
The challenges of urban tunnelling

Rock mass classification for choosing between TBM and drill-and-blast or a hybrid solution

Planning for cost-effective underground space use in urban areas
Design of substratacures against hydrostatic uplift
73 Anand, S. 1997. Design of basement slabs against hydraulic uplift, MSc dissertation, Nanyang Technological University, Singapore

Current issues regarding mechanised and automated tunnelling
Minoru, Yamamoto. The Latest Shield Tunnelling Technology. P.83.

Tunnelling and underground projects in Singapore
T.W. Hulme, R. Krishnan 1998. Singapore MRT: A construction challenge. Geotechnical special publication No 86. ASCE

Current and future tunnelling works in Hong Kong for the years 2000-2010
115 Broomfield J.D. Pipejacking and Micro tunnelling in Asia Proceedings 3rd Asia Tunnelling Summit-Hong Kong. IBC, Hong Kong 1999.
McFeat-Smith I. Mechanized Tunnelling For Asia Pub. IMS Tunnel Consultancy, Hong Kong 1998 pp. 17-21 (e-mail http://IMS@netvigator.com)

Tunnelling and underground projects in Korea
Tunnelling and underground construction in India: Present status and future potential


Tunnelling and development of tunnelling technologies in Japan

Committee on Tunneling Engineering, Japan Association of Civil Engineers 1966. Application of Tunnel Boring Machines in Japan. Tokyo: Japan Association of Civil Engineers


Study Committee on Transportation 1999. Transportation(Railways). Tokyo: Industrial Press


Delhi Metro Tunnels and stations on the 11km underground metro corridor


Design criteria for large tunnels in soft ground


Determining the parameters of double-layer linings of shallow tunnels


Construction of North East Line tunnels at Singapore River Crossing


Evaluation of face stability with the consideration of seepage forces in shallow tunnels

Lining design and ground response to the construction of the Clarke Quay tunnels

Tunnel linings for Contract C705, Singapore Northeast Line

Tunnelling under Woodleigh WorkersQuarters on Contract 705

Special shield tunnelling methods in Japan

Application of neural network in estimation of air losses in compressed air tunnelling
Use of rock caverns in urban areas


Innovative support system for Australia's longest road tunnel


A new numerical model of rock bolts used in jointed rock


Feasibility of developing the Underground Science City in rock caverns under Kent Ridge Park, Singapore


A theoretical method for estimation of loosening pressure on tunnels in soft rocks


Considerations for ground vibrations in underground blasting


The use of bulk emulsion explosives at the Mandai underground storage caverns


UDEC 3.0 (1996), User□□□s Manual, Itasca Consulting Group Inc., USA

Performance improvement of roof support system in longwall gate roads


Rock engineering system approach in tunnelling and underground excavation

Applicability of seismic geotomography to rock classification of Okawara Tunnel, Kyushu, Japan

Quality recommendations on segmental lining for shield drive in hard rock
Kolic D., 2000: IBM progress at the Great Wall. Tunnels & Tunnelling International No. 5, May 2000, pp.9

Two cavern schemes in the Jurong Formation of Singapore

Vibration isolation of cutter picks on mining machines

Optimisation of operating and design parameters of shearer drums by computer
Discrete element modelling of rock cavern stability subjected to shock loading


Application of energy-dissipation model to majorization analysis of construction sequence of large-scale underground openings


Simulation of thermal deformation around an underground opening

Xue Z., Permeability and Microgeometry of Sandstones under Hydrostatic Pressure, Ph.D. Thesis, Faculty of Engineering, Hokkaido University, Japan (1992)
Geotechnical design and construction aspects of the Clarke Quay station

Some observations during excavation on the behaviour of old alluvium soils in Singapore

Changi Airport station design and construction

Construction of the northern end of Outram Park Station

An observational approach to the monitoring of the excavation at Harbour Front Station, Singapore

Effect of horizontal soil movement on vertical piles
Behavior and performance of deep excavation in residual soils near sensitive structures

The monitoring and analysis of results for two strouted deep excavations in Singapore using vibrating wire strain gauges
Hwang, R., Quah Hong Pin, and Butling, S. Measurements of strut forces in braced excavations. Publication details unknown
Poh Kong Beng, Butling, S. and Hwang, R. Some MRT experiences of soils and geology of Singapore. Publication details unknown.

Instrumentation for the North-East MRT project at Clarke Quay
Lim, H.T. & Glenville, M. 1999, System to monitor the existing station and tunnels & surrounding building during the construction of NEL Dhoby Ghaat Station, International Conference Rail Transit: 525-526, Singapore.

Reliability based design of sheet pile wall in excavation

Planning the monitoring required to confirm the movement and rotation of tunnels and trackwork due to excavation and tunnelling

The assessment of limits for the movement of subway tunnels and trackwork due to adjacent construction


Effect of adjacent excavation on MRT tunnels


An estimate of subsurface settlement trough width parameter for G4 material


Ground control of tunnelling beneath an operating railway tunnel in Singapore


Mair, R.J. Taylor, R.N. & Bracegirdle, A. 1993 Subsurface settlement profiles above tunnels in clays Geotech-mque


Effect of deep excavation on piled foundation


Deformation analysis based on shield tunnelling and soil conditions with case studies from Shanghai Metro tunnels

Li, Q. 1991. Construction method by series of earth pressure shield. Shanghai Qiaotong University Publisher, Shanghai.
Tan, J. W. 1993. The study and measurement for ground movement after separation of shield tail during shield driving. Tongji University, Shanghai.
Wuhan Rock and Soil Mechanics Research Institute, Chinese Academy of Sciences. 1979. The survey and determination for the single shear creep characteristics of Shanghai shallow layer soil. Wuhan.
Ye, X. J. 1993. A research on the construction mechanism of large size mesh type shield machine. Tongji University, Shanghai.

NATM Effect of shotcrete setting time and excavation sequence on surface settlements

ICE 1996. Sprayed concrete linings (NATM) for tunnels in soft ground. Institution of Civil Engineers (London) Design and Practice Guides, Thomas Telford, London, UK.

Monitoring of reinforced concrete piles under horizontal and vertical loads due to tunnelling

Broms, B. B. and Pandey, P. C. Influence of ground movements from tunnelling on adjacent piles and remedial measures. Publication details unknown.

Stability and settlement due to bored tunnelling for LTA, NEL


Soil disturbance and stability control of shield tunnelling in urban environment


Safety in tunnelling is far too important to be left only to safety officers


Construction Industry Research and Information Association (CIRIA) 1998 Selecting contractors by value London. CIRIA.


European Commission 1992 Temporary or Mobile Construction Sites Directive 92/57/EUC.


Inokuma A. et al 1994 Studies on the present state and mechanism of trouble occurrence in tunnel construction in Japan Proc. International Tunnelling Association Conference in Cairo Tunnelling and Ground Conditions\textsuperscript{399\textsuperscript{F}}. Rotterdam, Balkema.

International Tunnelling Association 1992 Recommendations on the contractual sharing of risks Oslo, Norwegian Tunnelling Society.

Kuhnennh K. 1995 The New Austrian Tunnelling Method Tiefbau 5, 202\textsuperscript{E}.


Melis M.M. et al 38km of Madrid Metro extension in tunnel, designed and constructed in 40 months. Proc. International Tunnelling Association Conference in Durban, South Africa\textsuperscript{Tunnels underpressure\textsuperscript{295\textsuperscript{D}1}. Durban. South African Institution of Mining and Metallurgy.

McCormack S. (Ed) 1999 Madrid Metro Extension\textsuperscript{Blueprint for success}. Tunnels and Tunnelling International 31, 3: i\textsuperscript{vi} Miller Freeman Ltd, London.

Oliver A. 1999 Heathrow Express- the cost New Civil Engineer edition of 18 Feb. page 4.


Tait J.C. and Hoj N.P. 1996 Storebaelt Eastern Railway Tunnel\textsuperscript{IBM fire, analysis and recovery}. Proc. Institution of Civil Engineers 114, (Special Edition) 402\textsuperscript{E}.

Tesar O. 1996 Assessment of untoward events and accidents in underground tunnels in Prague 1969998 Tunel 27/96, 252\textsuperscript{E} (in Czech).

Vlassov S. , Merkin Y.Y. and Makovsky L.V. 1997 Emergency cases in the construction of transportation and subway tunnels Moscow, Russian Tunnelling Association (in Russian).


Wallis S. 1995 What is going on in Los Angeles ? Tunnel 6/95, 8\textsuperscript{I}.

Wallis S. 1999 Heathrow failures highlight NATM misunderstandings Tunnel 3/99 66\textsuperscript{E}.

Waninger K. 1982 Accident blackspots associated with the New Austrian Tunnelling Method Tiefbau 2/82, 74\textsuperscript{D}.


Zaslonov I. 1998 Chasm swallows Moscow Street. Moscow Tribune edition of May 15th, 12\textsuperscript{I}.

\textbf{Initial geotechnical considerations of Delhi Metro}


Singh, M. 2000 Delhi Metro\textsuperscript{T}unnels and stations on the 11km underground metro corridor. International Conference on Tunnels and Underground Structures, Singapore, Balkema.

\textbf{Engineering properties of fluvial sand at Race Course Road}


Hydraulic fracturing stress measurements for the design of underground de-silting chamber

Hydraulic three-dimensional tests: Comparison of concepts and results with single packer tests

Engineering geology and geo-information system for cavern construction in the Bukit Timah Granite of Singapore
LEO-STAE 1996. 1998, Geological reports for site characterisation Phase I & II.

Geomechanical investigation plan in an underground research laboratory for feasibility study of radioactive waste repository in deep argillaceous rock

Risk assessment for tunnelling in adverse geological conditions in Asia

Construction issues related to jet grouted slabs at the base of excavations

Design issues related to jet grouted slabs at the base of excavations
Planning the construction of an underground high energy physics facility dedicated to the study of neutrino particles


Modelling of injection in sand


Crushing and conveying in tunnel construction An overview of the principles and operational benefits

Continuous Belt Conveyor Mucking System at Tagami Tunnel Yukio Yoshitomo
Application and Benefits of Track Mounted Crushing Equipment Trueman
Tunnel Crushing & Conveying Pasi Merilainen
Tunnelling Article World Highways Magazine
Mobile Crushers Underground- Jorma Kempas