Cascadia Center

Large Diameter Soft Ground Bored Tunnel Review

Review of current industry soft ground bored tunnel practice

Document ref REP/208085/S001

Cascadia Center

Large Diameter Soft Ground Bored Tunnel Review

Review of current industry soft ground bored tunnel practice

November 2008

This report takes into account the particular instructions and requirements of our client.
It is not intended for and should not be relied upon by any third party and no responsibility is undertaken to any third party

Arup North America Ltd
403 Columbia Street, Suite 220, Seattle, WA 98104
Tel +1 206 749 9674 Fax +1 206 749 0665
www.arup.com

Job number 208085-00

Contents

		Page
1	Introduction	1
2	Large Diameter Tunnels	2
	2.1 Recently completed tunnels	2
	2.2 The Future	3
3	TBM technology	5
4	Versatility of tunnel configurations	7
5	Whole life costing	8
	5.1 ‘Like-for-like’ comparison	8
	5.2 Project construction costs	8
	5.3 Whole-life cost estimate	10
	5.4 Broader benefits	11
6	Conclusions	12
7	References	13

Appendices

Appendix A

Large bored tunnel survey

Appendix B

Tunnel cross-sections

Appendix C

Extracts of referenced reports

1 Introduction

The Alaskan Way Stakeholder Advisory Committee is considering a number of options for the replacement of this important transportation corridor through Seattle.

Arup were commissioned by the Cascadia Center at the Discovery Institute to report on recent developments in the implementation of large diameter highway tunnel projects around the world.

This document reports on the technological advances that have made it common place to use large diameter bored tunnels for urban highway projects in difficult ground conditions, and reports on how increasing tunnel diameters make these subsurface corridors more versatile in terms of their function.

A discussion on costing highlights the importance of a whole life approach for such projects and how when considered in this way tunnels are typically more economic than other highway alternatives. Reported analyses publically available project construction cost data for tunnel projects around the world and in the United States also indicates that tunnel alternatives are competitive when compared with above ground options that provide similar capacity.

The document also highlights the wider economic, community and environmental benefits of tunnels that should be included in the assessment of replacement options.

2 Large Diameter Tunnels

2.1 Recently completed tunnels

The successful completion of two highway tunnels beneath the Yangtze River in Shanghai China in September this year represents another milestone in the development of large diameter bored tunnel projects around the world. The tunnels, the largest in the world to date at 51 ft diameter, will carry three lanes of vehicular traffic and a transit line in each direction between Pudong in Shanghai and Changxing Island (Figure 1), a distance of 4.7 miles. They were constructed in difficult ground conditions comprising sands and clays under high groundwater pressures some 200 ft below ground level. The tunnels were completed in 20 months and the project is expected to be open in 2010, one year ahead of schedule.

Figure 1 - Shanghai River Crossing (2 x 51ft tunnels)

This success with TBM's of over 50 ft diameter comes on the back of the completion of the M30 tunnels in Madrid in 2008. These tunnels, at a diameter at 50 ft diameter, form part of a ring road around Madrid carrying three traffic lanes in each direction and were completed 4 months ahead of schedule. This subsurface project allowed the removal of highways from the banks of the Manzanares River and their development as a public amenity.

The 1.4 km Serebryany Bor tunnel (46 ft) in Moscow was also opened on December 27, 2007 becoming the first tunnel in the world to combine road traffic and metro transit.

These achievements reflect the improvements that have been made in tunnel boring technology over the last few decades and the increases in diameter that have recently been achieved. Table 1 indicates a selection of tunnels that are under construction or have been recently completed. This reflects the fact that such technology is widely used across the world. It is also becoming more commonly used or proposed in the US for highway traffic such as the Port of Miami tunnels and the proposed I-710 project in Los Angeles.

Completed large diameter highway tunnels						
Name	**Length**	**Dia.**	**Bores**	**Reported cost per *mile* of tunnel ($)**	**Soils**	**Function**
Shanghai River Crossing, China	4.6 mi	50.6 ft	twin	$27m	sand, clay, rubble	Road
Madrid M-30 - north tunnel of the south bypass, Spain	3.65 mi	50 ft	twin	$131m	marly clays of the Madrid Tertiary penuela and gypsum	Road
Serebryany Bor Tunnel	1.5 mi	46.6 ft	twin	*no data*	*no data*	Road/Metro
Lefortovo, Moscow	1.3 mi	46.6 ft	twin	$439m	fine to coarse sand, clay, limestone (medium strength, partially very fissured)	Road
4th Tube of the Elbe Tunnel, Germany	1.6 mi	46.5 ft	single	$303m	sand and mud, rock and pebbles, marly till and mica schist	Road
SMART Tunnel, Kuala Lumpur, Malaysia	1.86 mi	43.3 ft	single	$85m	*no data*	Water/ Road
Wesertunnel, Kleinensiel, Germany	1 mi	38.3 ft	twin	$180m	clay, sand, turf, till, silt	Road
Westerschelde, Terneuzen, Netherlands	4.1 mi	37 ft	twin	$60m	soft, permeable ground	Road
A-86W East Tunnel, Paris France	6.2 mi	34 ft	single	$242m	limestone, sand, clay, marl, chalk	Road

Table 1 - Completed large bore tunnels

See Appendix A for a list of completed, in construction and proposed large bore tunnels.

2.2 The Future

Looking to the future, large tunnels will become more commonly used and of larger diameter. On 27th March 2008, Moscow based ZOA Infrastruktura announced a deal to acquire a 62.3ft diameter tunnel boring machine. The ultimate project this is to be used for is undisclosed, but it will be the first bored tunnel capable of accommodating a four-lane highway.

Other projects now on the drawing boards around the world include bored tunnel alternatives up to 58 ft in diameter for the 4.5 mile long I-710 project in Los Angeles, three 50 ft TBM tunnels in Austria, a 50 m diameter 5th Elbe crossing tunnel, several large diameter transit tunnels for systems at Tysons Corner in Virginia, Sao Paulo and Barcelona. Figure 2 shows the increases in tunnel diameters that have been delivered over the last two decades alongside proposals which have been announced for the next 5 years.

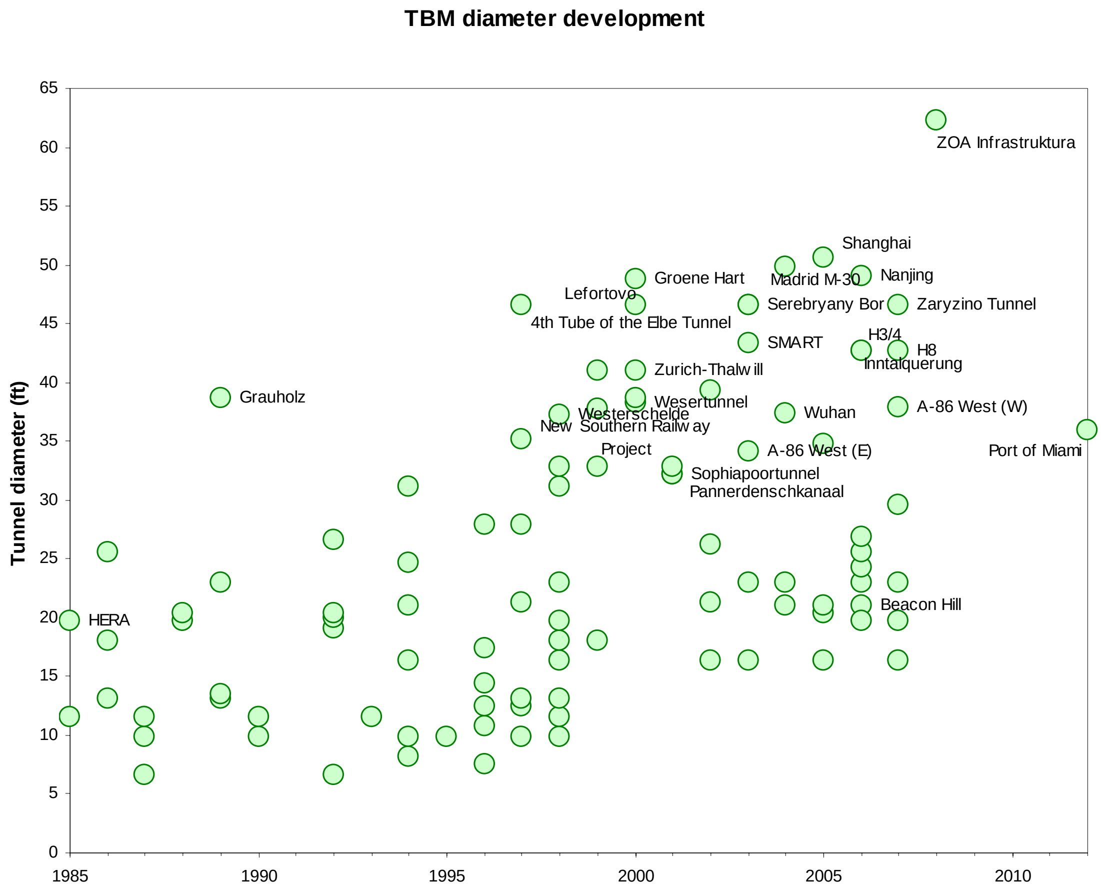


Figure 2 - Increasing TBM diameters over the last 20 years

3 TBM technology

Over the last two decades, the ability of TBMs to construct large diameter tunnels in weak ground and in significant groundwater pressures has increased significantly. Historically, tunnels in these ground conditions were constructed with the use of compressed air to provide support to the ground. Modern TBMs use a pressurized, or closed, face at the front of the machine to maintain stability in the ground while allowing workers to operate in safe conditions within the tunnel.

There are two main types of soft ground TBMs. An Earth Pressure Balance Machine (EPBMs) controls the rate at which the excavated ground is removed through the pressured face so that an appropriate level of support is provided to the ground around the tunnel, maintaining stability. A Slurry, or Mixshield, TBM uses a bentonite fluid to maintain the support and to carry the excavated ground in suspension. The choice between the two types of machine depends on the exact nature of the ground, with EPBMs more suited to clays and silt and Slurry machines to sandy ground or gravels. In complex projects, with varying ground conditions, a hybrid machine which has the ability to work in both modes can be used.

As a track record of successful tunneling with soft ground TBMs has been built up, and more sophisticated control systems have become available, the ability to excavate larger diameter tunnels in more challenging ground has increased. Some specific areas of improvement that have allowed soft ground tunneling to be carried out with less risk, lower impacts and with greater efficiency include:

- The motors used to rotate the cutting head at the front of the machine have been developed to become more powerful and can be controlled much more accurately, allowing larger TBMs that can operate in more complex ground.
- Modern soft ground TBMs can collect and process a vast amount of data in real time so that the operator has a good understanding of how the machine and the ground around it are performing, allowing a high level of control. This particularly allows very close control of ground movements above the tunnel, permitting the construction of tunnels in dense urban environments without damage to buildings or subsurface utilities.
- Increased scientific understanding of foams and additives that can be added into the excavated soil in the pressurized area at the front of the TBM, allowing the ground to provide a uniform support to the ground around the tunnel.
- Increased understanding of the abrasive effects of the ground on machines, allowing TBMs to be designed to suffer less wear and increase in reliability.
- Improved design of the cutting tools that are mounted on the front of the TBM, which provides better performance. Electronic sensors can also be incorporated in the cutting tools to detect when the tools are becoming worn down, which allows maintenance to be scheduled.
- On large diameter TBMs, the machines have been designed to allow the cutting tools to be replaced without sending workers into the pressurized zone in front of the machine, simplifying maintenance procedures.
- Improved design of seals in bearings and between the TBM and the tunnel lining have allowed tunnels to be constructed under higher ground water pressures.
- Ground penetrating radar has been used on some TBMs to help identify the location of boulders or other obstructions ahead of the tunnel, reducing the risk of unplanned stoppages.

These developments continue to evolve allowing ever more challenging conditions to be successfully tunneled.

4 Versatility of tunnel configurations

With these increases in tunnel diameter, innovative configurations of corridors within the tunnels have been developed to optimize the usage of this underground space. These include double stacked traffic decks, separation of vehicle traffic from heavy goods vehicles, provision of transit corridors through highway tunnels and, in the case of the SMART tunnel in Malaysia, the use of part, and under some conditions all of the tunnel as a storm-water overflow tunnel. Figure 3 shows cross sections through three built tunnels which show this versatility. Appendix B contains figures from other tunnels referenced in this report.

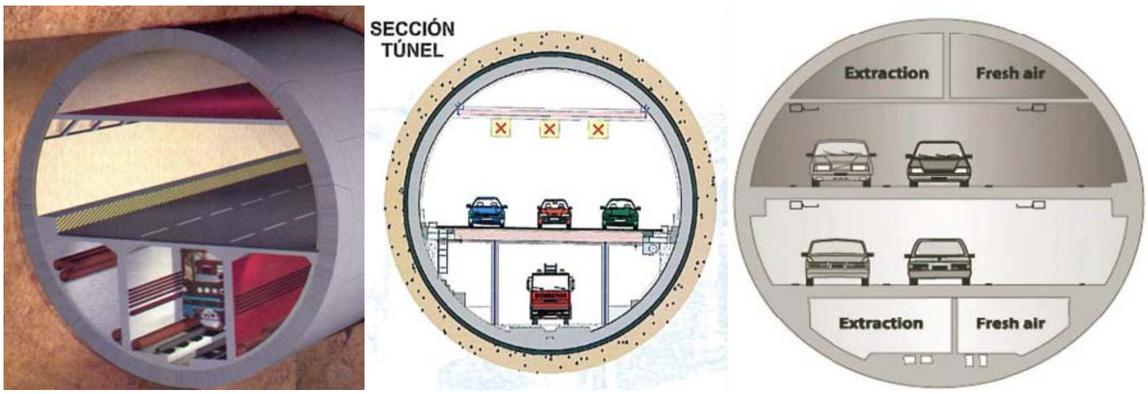


Figure 3 – Road tunnel configurations (left Serebryany Bor, middle M-30, right A-86)

5 Whole life costing

5.1 'Like-for-like' comparison

Cost estimating for large infrastructure projects is a complex process and is impacted by many variables. Cost comparisons of project alternatives in the US are typically carried out on the basis of construction cost only, however it is becoming more widely recognized that the longer term costs to an owner are also heavily influenced by the maintenance and operational costs and the eventual replacement costs or residual asset value. This type of analysis is common place in the manufacturing industry and is the approach taken by private investors when considering the construction or purchase of an infrastructure facility such as a highway.

The paper 'Compiling real costs for true infrastructure construction comparison' prepared for Tunnels and Tunneling magazine in December 2005 (Appendix C) reports that while the project cost for a bored tunnel may be slightly more than that of a viaduct and substantially more than a surface street option, when whole life costs are considered the tunnel becomes the most cost effective solution.

5.2 Project construction costs

Reported project construction costs for a number of tunnel projects are provided in Table 2. These figures have been compiled from a literature survey of completed and proposed projects. Data on major infrastructure projects is readily available. However, the basis of the estimates is often unclear. Tunnel project costs fall into the following categories:

- Tunnel contract cost (including cost of TBM and TBM operation)
- Project cost (including tunnel contract cost, support infrastructure, access roads, highway surfacing, etc.)
- PPP cost (includes project cost, operating and maintenance cost, cost of financing)

It is often difficult to arrive at a realistic cost estimate without some engineering defined criteria on which to base the costs. Baseline cost data from similar projects around the globe are useful but not always illustrative of the eventual costs of a project that do not contain the same combination of features that are required for the construction of a specific project.

With the above caveats in mind, Table 2 and Figure 4 summarize a literature survey of global large bore tunnel costs. As some projects comprise a single bore solution and others a twin bore solution the data is presented in dollars per tunnel mile. The calculation for a twin bored tunnel would be double the presented price per alignment mile. The highlighted projects form a cluster of projects which suggest a typical cost range per mile of a twin bore project of approximately $200M to $700M. It can be seen that projects at the lower end of the cost scale are often in Asian countries where labor and material costs are significantly lower. Higher costs per mile are reported in western European countries and in the US where the Port of Miami tunnel is approximately $1,000M for a 0.7 mile twin bore project. The shorter length of this project may have an upward impact on the cost per mile as economies of scale are smaller.

This data indicates that construction costs for tunnel projects larger than a 2 mile Alaskan Way by-pass tunnel are somewhat less than previously published estimates for the Alaskan Way Viaduct replacement.

In comparing these costs with estimates produced for the Alaskan Way project it should also be noted that project costs developed by WSDOT use a statistical approach to construction costing (See 'Probable cost estimating and risk management' presented in Appendix C) which recognizes the various risks that may impact the project cost and applies a differing amount of contingency dependent on the certainty of the cost estimate. During project development, costs reported for a high level of certainty of non exceedance may be higher than those determined by more traditional methods.

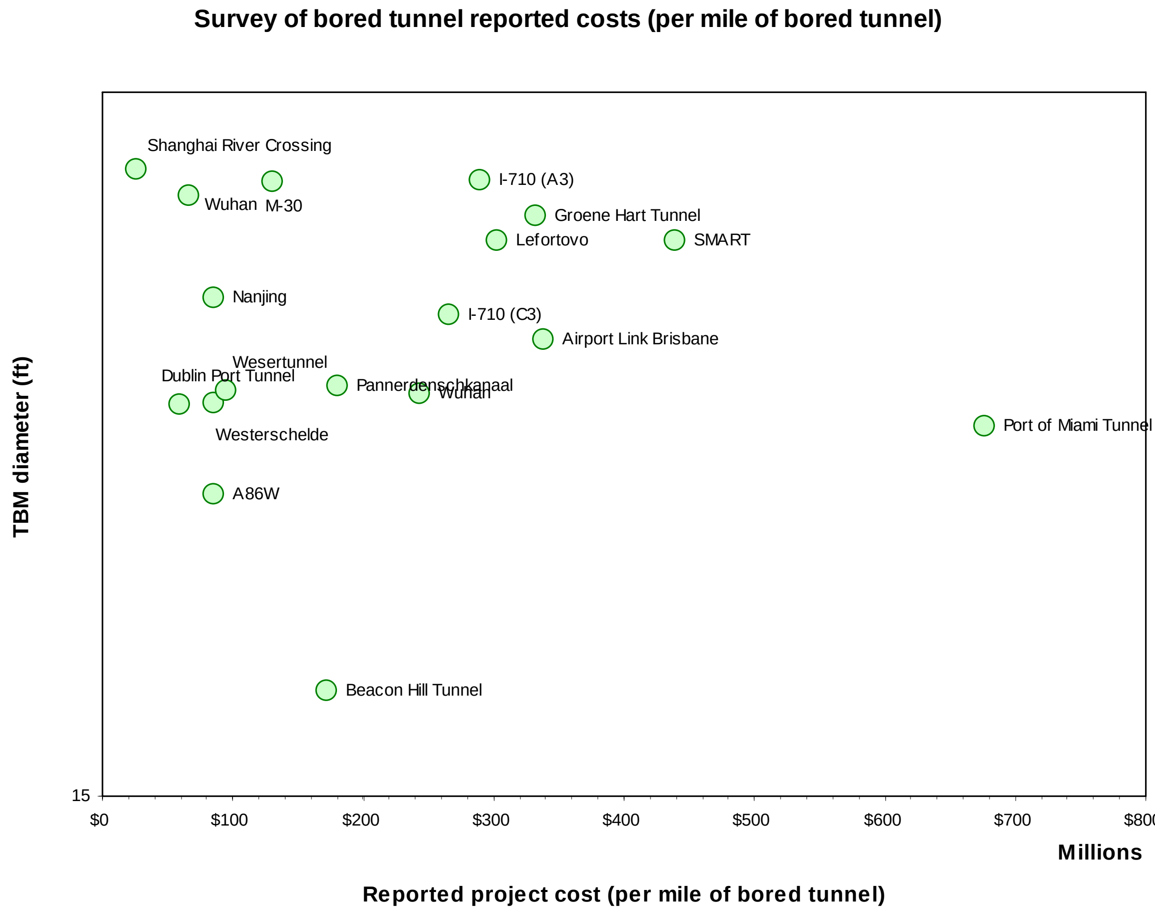


Figure 4 - Survey of tunnel costs

Tunnel	Year completed	Diameter (ft)	Bores	Alignment length (miles)	Total length of tunnels (miles)	Reported cost ($ million)	Cost per mile of tunnel (million $/mile)
Port of Miami Tunnel	proposed	36	twin	0.7	1.5	1,000	$677
Lefortovo	2005	47	single	1.4	1.4	600	$439
Airport Link Brisbane	2012	41	twin	3.3	6.5	2,206	$338
Groene Hart Tunnel	2006	48	single	1.4	1.4	450	$332
4th Tube of the Elbe	2002	47	single	2.6	2.6	775	$303
I-710 (A3)	proposed	50[1]	triple	4.1	12.4	3,585	$290
I-710 (C3)	proposed	42[1]	triple	4.0	12.0	3,195	$266
A86W	2010	37.9[1]	single	10.9	10.9	2,641	$242
Wesertunnel	2001	38	twin	1.0	2.0	358	$180
Beacon Hill Tunnel	2009	21	twin	0.8	1.6	280	$172
M-30	2008	50	twin	2.2	4.3	570	$131
Dublin Port Tunnel	2006	38	twin	2.8	5.6	530	$94
Pannerdenschkanaal	2003	32	twin	1.0	2.0	173	$86
SMART	2007	43	single	6.0	6.0	515	$85
Wuhan	2008	37	twin	1.7	3.4	288	$85
Nanjing	2013	49	twin	1.9	3.7	245	$66
Westerschelde	2002	37	twin	4.1	8.2	490	$60
Shanghai River Crossing	2008	51	twin	4.6	9.3	245	$27

[1] This scheme contains multiple tunnel diameters. This number presented is the average tunnel diameter.

Table 2 - Survey of tunnel costs

5.3 Whole-life cost estimate

As indicated by the Tunnels and Tunneling paper (Appendix C) maintenance and operational costs for a road tunnel are likely to be similar to that of a surface street option and significantly lower than that of an elevated highway. The maintenance of way costs will be similar, however maintenance and operation of ventilation systems can be an additional cost of longer tunnels while structural repair cost for viaducts typically increases that of an above ground structure.

The largest whole life benefit of a tunnel is its longer design life. The life span of tunnels can be up to 150 years against 50 years for an elevated structure. This is evidenced in Seattle by the BNSF tunnels which are over 100 years old against the existing Alaskan Way viaduct and SR-520 which are reaching the end of their life span after approximately 50 years.

It should also be noted that, given the potential for seismic events in the Pacific North West, tunnels perform better in earthquakes as evidenced by the damage caused to the Bay Bridge and the Embarcadero highway in San Francisco against the performance of the BART transit tunnels below the bay which remained largely unaffected by the Loma Prieta earthquake in 1989.

The importance of whole life costing is demonstrated in Table 3 below which illustrates that the “conventional” cost of an infrastructure project could amount to only 26% of the whole life cost. A full whole-life cost of any infrastructure replacement option is therefore the most appropriate approach to generate a fair and comparable assessment.

2400 meters of 11 meter TBM Bore 2 Lane Road Tunnel												% of TOTAL
EIS, Preliminary Design, Scoping, Procurement	100	100	100	100	100	100	100	100	100	100	100	4%
Supply TBM		71	71	71	71	71	71	71	71	71	71	3%
Construct Tunnel - Fixed Cost			83	83	83	83	83	83	83	83	83	3%
Construct Tunnel - Variable Cost				419	419	419	419	419	419	419	419	16%
Connectors, Stations, Etc					119	119	119	119	119	119	119	4%
Detail Design Engineering						53	53	53	53	53	53	2%
ROW acquisition							50	50	50	50	50	2%
PPP financing and fees								300	300	300	300	11%
Agency inspection and Construction Management									150	150	150	6%
O&M Costs- 100 years $8.5 million per year										850	850	32%
Decomission and Deconstruct											500	19%
TOTAL	$ 100	$ 171	$ 254	$ 673	$ 792	$ 845	$ 895	$ 1,195	$ 1,345	$ 2,195	$ 2,695	100%
Duration- Years	3	2		1.5	1.5					100	3	111

in millions of 2008 US$

Table 3 - Whole life cost

5.4 Broader benefits

Major infrastructure projects typically have a wider benefit to the community and as such these benefits should be fully considered in the assessment of options. The benefits of a tunnel option, when compared with above ground options include increased property values, reduced congestion and associated pollution, and reduced disruption to businesses, pedestrians and traffic during construction. Land freed up by placing the facility below ground presents opportunity for improved public amenity and development opportunities particularly at the portal locations. These benefits can be assigned a monetary value which should be included in a detailed assessment.

The impacts of these issues in relation to comparing a tunnel with a surface street and a viaduct are discussed in the Tunnel and Tunneling article presented in Appendix C. This article makes two significant points:

a) tunnels have the lowest pro-rate cost taking into account the longer design life of tunnels.

b) when the cost of environmental pollution, loss of property taxes, social divide and maintenance cost is taken into account, the annual costs of a typical tunnel is half that of the at grade option and a third that of an elevated structure.

6 Conclusions

Bored tunnel technology is continually developing and larger and more safely constructed tunnels are becoming more and more common. This additional size allows more versatile configurations of uses within the tunnel to allow stacking of traffic lanes and the combination of different uses such as highway and transit usage.

The total whole life cost for a project, rather than construction costs alone, better reflect the overall costs incurred by an owner for a transportation facility. Methods for assessing whole life costs are available and are commonly used in the private sector for assessing such projects.

Major transportation projects have a wider impact on the surrounding community. Tunnels typically provide greater benefits than other alternatives as a result of:

- Reduced disruption to businesses during construction
- Reduced utility relocations,
- Reduced street impacts to pedestrians and vehicles during construction
- Increased property values as result of the infrastructure being below ground
- Greater opportunity to provide public amenity
- Development opportunities where land is released by placing facility below ground particularly at portals
- Providing capacity below ground moves congestion and pollution from downtown streets.

7 References

"Tunnel Boring Machine Development", Martin Herrenknecht and Karin Bäppler, North American Tunneling Conference 2008

"State of the Art in TBM Tunneling", Martin Herrenknecht and Karin Bäppler, North American Tunneling Conference 2006

"Current Issues Regarding Mechanized and Automated Tunneling", G.Ishii, Tunnels and Underground Structures 2000

"Lifting the lid on Mixshield performance", Werner Burger and Gerhard Wehymeyer (Herrenknecht AG), Tunnels and Tunneling International June 2008

"Compiling real costs for infrastructure construction comparison", T&T North America, December 2005

"Probable Cost Estimating and Risk Management", John Reilly

"Bold and Visionary Planning of Tunnels and Underground Space", Harvey W. Parker

Appendix A

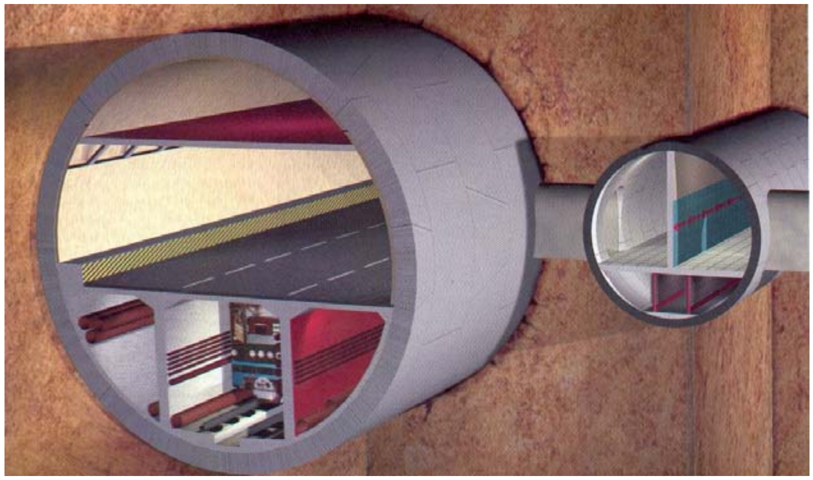
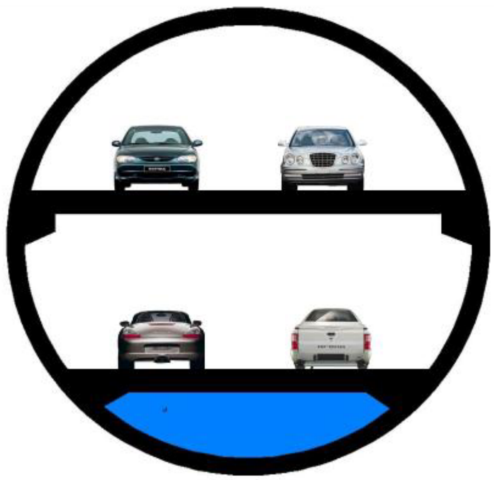
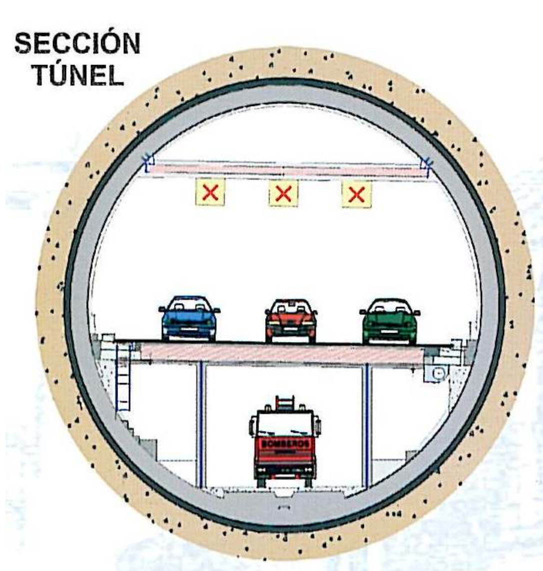
Large bored tunnel survey

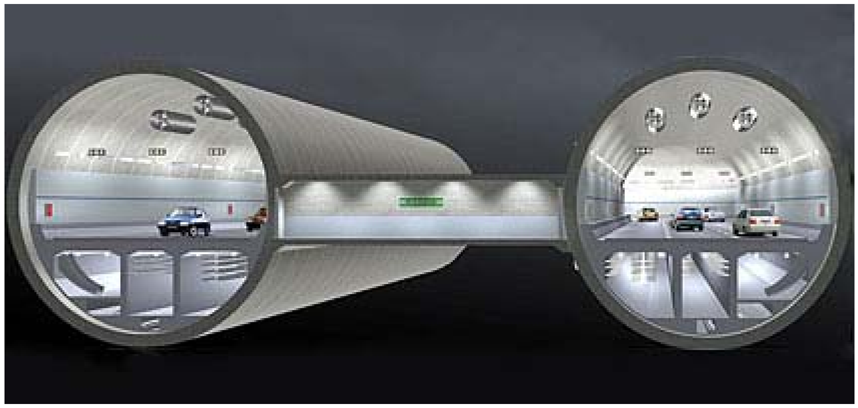
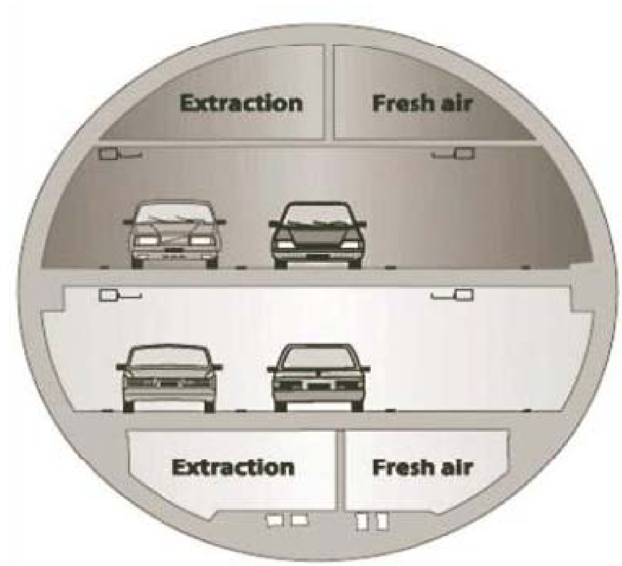
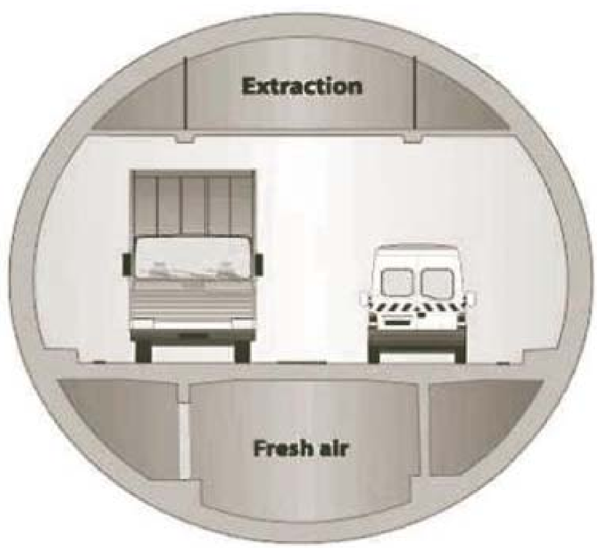
Name	Length	Diameter	Bores	Status	Period	Soils	Function
I-710 Option A3	4.12 mi	58 ft	triple (1 x 58' and 2 x 46')	proposed		shale, sandstone, siltstone, and conglomerate, with soft alluvial soils	Road
I-710 Option A1	4.12 mi	57 ft	twin	proposed		shale, sandstone, siltstone, and conglomerate, with soft alluvial soils	Road
Shanghai River Crossing 15.5 meter Soft Ground (Bouygues Job) (just finished)	4.6 mi	50.6 ft	twin	tunnels completed	2008	sand, clay, rubble	Road
Madrid M-30 - north tunnel (left carriageway) of the south bypass	2.2 mi	50 ft	single	completed	2004 - 2008	marly clays of the Madrid Tertiary penuela and gypsum	Road
Nanjing Yangtze Crossing	1.8 mi	49 ft	twin	contract awarded	- 2013	oft river deposits of clay, silt and sand	Road
Groene Hart Tunnel	5.3 mi	48 ft	single	completed	2000-2006	highly permeable sand below a very soft peaty clay layer	Rail
Zaryzino Tunnel	1.5 mi	46.6 ft	single	proposed	no data	*no data*	Road
Serebryany Bor Tunnel	1.5 mi	46.6 ft	twin	tunnel complete	-2007	*no data*	Road+/Metro
Lefortovo, Moscow	1.3 mi	46.6 ft	twin	complete	2000 - 2005	Fine to coarse sand, clay, limestone (medium strength, partially very fissured)	Road
4th Tube of the Elbe Tunnel, Hamburg	1.6 mi	46.5 ft	single	complete	1997 - 2002	sand and mud, rock and pebbles, marly till and mica schist	Road
SMART Tunnel, Kuala Lumpur, Malaysia	1.86 mi	43.3 ft	single	completed	- 2007		Water/ Road
Tyson' Corner	3.38 mi	43.3 ft	single	proposed	*no data*	residual soil, decomposed rock, and rock	
Inntalquerung	3.6 mi	42.6 ft	single	in construction	*no data*	Pebble stones, sand, coarse clay, brash, gravel	Rail
Airport Link Brisbane	3.3 mi	41 ft	twin	tendered	- 2012	*no data*	Road
San Vito	0.6 mi	40.3 ft	*no data*	*no data*	*no data*	*no data*	Rail
Rennsteigtunnel	5.6 mi	40.3 ft	twin	complete	1998 - 2003	*no data*	Road
Metro Barcelona Line 9	5.3 mi	39.6 ft	single	completed	no data	Granite, sand, clay, gravel, gravel with boulders	Metro

Name	Length	Diameter	Bores	Status	Period	Soils	Function
Hsuehshan (also known as Pinglin), Taiwan	8.0 mi	38.5 ft	twin	complete	1993 - 2006	strong, hard, abrasive and intensely fractured Szeleng Sandstone on the east and indurate sandstone and siltstone on the west	Road
Wesertunnel, Kleinensiel, Germany	1 mi	38.3 ft	twin	complete	2000 - 2001	clay, sand, turf, till, silt	Road
Wuhan, China	1.7 mi	37.3 ft	twin	in construction	2004 - 2008	sand stratum, gravel, and shale rock.	Road
Westerschelde, Terneuzen, Netherlands	4.1 mi	37 ft	twin	complete	1998 - 2002	soft, permeable ground	
Katzenberg	5.6 mi	36.5 ft	twin	complete	2003 - 2008	Mudstone, marl, limestone and sandstone, approx. 800m of Oxford Coral Limestone	Rail
Port of Miami Tunnel	3900 ft	36 ft	twin	proposed	no data	no data	Road
A-86W West, Paris	4.7 mi	35.8 ft	single	in construction	2007 - 2010	limestone, sand, clay, marl, chalk	Road
Finnetunnel	4.23 mi	35.5 ft	twin	in construction	2008 - 2009	loose rock formations in the first section of around 1,500-m-long and unsupported rock on the remaining line (sandstone, claystone)	Rail
New Southern Railway Project	3 mi	35 ft	single	complete	1996 - 2000	Clay, sandstone	Metro
Metrotren Gijon	2.4 mi	34.6 ft	single	completed	- 2006	Clay, dolomit, limestone	Metro
A-86W East	6.2 mi	34 ft	single	complete	2003 - 2008	limestone, sand, clay, marl, chalk	Road
Sophiaspoortunnel, Rotterdam, Netherlands	2.6 mi	32 ft	twin	complete	2001 - 2002	clay, sand, till	Rail
Pannerdenschkanaal Tunnel, Netherlands	1 mi	32 ft	twin	tunnel structure complete	2000 - 2003	sand, clay	Rail
Sao Paulo metro , Linea 4	4.7 mi	31 ft	single	in construction	- 2008	no data	Metro
Leipzig , Germany	0.9 mi	29.5 ft	no data	in construction	2006 - 2008	no data low subsidence requirement below existing buildings	Rail
Beacon Hill Tunnel	4,300 ft	21 ft	twin	in construction	-2009	glacial soils	Metro

Appendix B

Tunnel cross-sections

Serebryany Bor Tunnel Moscow, Russia 1.5 miles 46.6 ft diameter	
SMART Tunnel Kuala Lumpar, Malaysia 1.86 miles 43.3ft diameter	
M-30 Madrid, Spain 3.65 miles 50 ft diameter	

Nanjing Yangtze Crossing China 1.8 miles 49 ft diameter	
A-86W East Paris, France 6.2 miles 34 ft diameter (note double deck configuration is limited to cars only)	
A-86W West Paris, France 4.7 mi 35.8 ft diameter	

Wuhan China 1.7 miles 37.3 ft diameter	

Appendix C

Extracts of referenced reports

Compiling real costs for true infrastructure construction comparison

Is tunneling really the most expensive option of providing public transportation infrastructure? These research data compiled by a consulting engineering firm in the US suggest not. They bust the long-held axiom by considering more than construction cost alone.

What is the true cost of constructing transportation infrastructure? What is included in 'true cost'? How do the different transportation structures compare?

Answering these questions has consumed many feasibility-study man-hours over the decades and often with unsatisfactory results. Once compiled, the difficulty of expressing the data in a readily appreciated manner is often the task that renders the information indigestible, too difficult to fathom, and the whole exercise some what futile.

In an effort to address this deficiency, a consulting engineering practice in the US has compiled these three tables that present a different take on cost comparison. Without publishing the name of the firm for the moment, what is your opinion of the data presented? How does your experience conflict or comply with these suggestions?

As part of this comprehensive tabular and graphic comparison, the researchers not only compare 'soft' as well as 'hard' construction costs, as a percentage of the at-grade baseline, but include also the impact each method of procurement has on property values within the traffic corridor, an aspect that is often ignored in project planning and estimating, or considered in only a cursory fashion.

With such data in hand, how to

Table 1: Project cost

	Soft cost					Construction cost			Total project cost (1)
	EIS/EIR	Design fee	Right of way	Productivity loss	Construction management	Traffic relocation & maintenance	Utility relocation & support	Structures	
Weighted % Average Range	4.5 3 - 6	13.5 12 - 15	11.5 8 - 15	3.5 2 - 5	13.5 12 - 15	16.5 8 - 25	11.5 8 - 15	25.0 15 - 35	100
At grade = baseline	1	1	1	1	1	1	1	1	1.0
Elevated structure/viaduct bridge	1.4	1.4	1.8	1	2	1	1.2	7	2.8
Tunnel cut & cover	1.4	1.6	1	1.5	1.6	1.5	2	10	3.7
Tunnel mined (NATM, TBM)	0.3	1.4	0.3	0.3	0.7	0.3	0.3	11	3.2

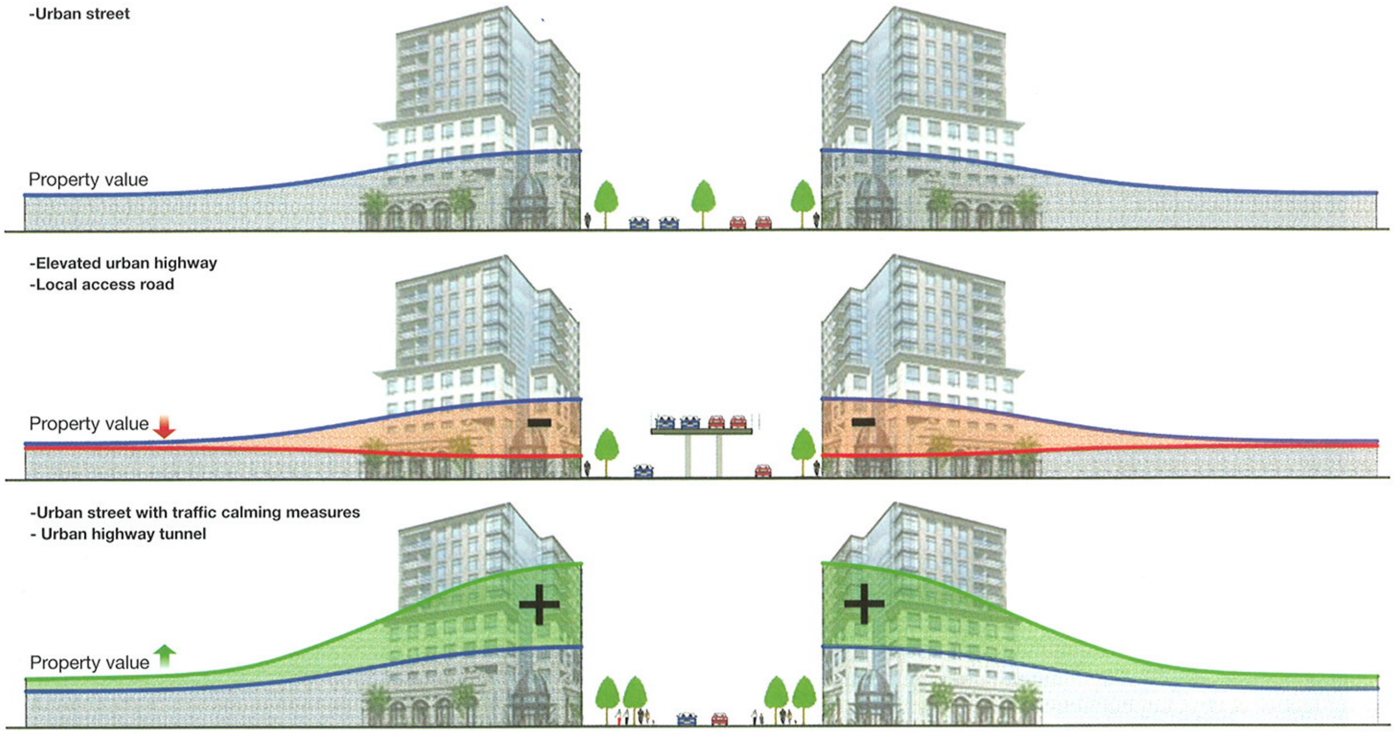
Notes: (1) Refer to Table 2 for life time costs (Environmental pollution, property tax, maintence costs, social divide, life time factor)

Table 2: Annual cost

Life span in years	Project cost per annum (1)(2): Life span relation	Project cost per annum (1)(2): Total project cost	Project cost per annum (1)(2): Total		Annual costs: Environmental pollution	Annual costs: Loss of property taxes	Annual costs: Social divide	Annual costs: Maintenance cost	Annual costs: Total
	-	-	100	Weighted % Average Range	25 20 - 30	25 20 - 30	15 10 - 20	35 30 - 40	100
100	1	1	1	At grade = baseline	1	1	1	1	1
50	2	2.8	5.7	Elevated structure/viaduct bridge	1.2	1	0.8	2	1.4
100	1	3.7	3.7	Tunnel cut & cover	0.05	0.2	0	1.3	0.5
150	0.66	3.2	2.1	Tunnel mined (NATM, TBM)	0.05	0.2	0	1.1	0.4

Notes: (1) Refer to Table 1 (2) Interest not included

Based on international experience in urban areas



use it? How are the suggestions received by owners of transportation infrastructure? The data suggests that long-held conceptions about the costs of procuring public infrastructure need to be completely reversed, that tunnels are after all less expensive that all other alternatives – providing life cycle costs and social impacts

are included. What is your reaction? To respond, either on the record as a 'Letter to the Editor', or anonymously to our 'OFF THE RECORD' column, please send your comments to the Editor of T&TNA at HWallis403@aol.com. All contributions will be published in the next issue of T&TNA in March 2006. ■

Bold and Visionary Planning of Tunnels and Underground Space

Harvey W. Parker
Harvey Parker & Associates, Inc., Bellevue, Washington

INTRODUCTION

Our industry has developed to the skilled, experienced and productive industry that we now enjoy as a result of the visions of great engineers throughout history, but, in particular for their visions in the last 1 centuries. Unfortunately for our forefathers, the technology lagged so far behind that these exceptional visions could not be realized for decades, sometimes for a century. All that has changed in recent time and many bold and visionary projects can now be constructed and operated because of dramatic advances in technology. Before, say, 1950, tunnel technology developed very slowly. However, technology is now developing at such a fast rate that planners and decision makers are challenged to stay ahead. Moreover, new technology will develop during the lifetime of any project that can dramatically improve underground space projects. One of the best examples of this technological advancement is that of closed-face TBMs which now make tunneling feasible in previously impossible ground conditions.

Since it usually takes a decade or more to plan, overcome environmental and political issues, construct, and put into service major projects, planners and designers are challenged by the changes in technology that occurs during the long time span of planning and construction. This is particularly true of large infrastructure projects such as transportation, water and wastewater systems and other major underground schemes. Also, since the serviceable life of many of these tunnels is often over one century, planners must consider not only lessons learned from the past but also what new concepts and innovations may develop over an extremely long time. These and other issues create a great challenge to planners and illustrate the great importance of careful but creative vision and flexibility during planning of long-term tunnel and underground space projects.

PLANNING CHALLENGES POSED BY WORLD POPULATION

The world's population is increasing and is re-grouping at a staggering pace. In October, 1999, the world population passed the 6 Billion mark. However, a major factor in world demographics that is extremely important to planning of underground space is that, in the future, most of the world's population will live, not in rural areas, but will live in urban cities. In 1950, only about ⅓ of the world's population lived in urban areas but that is changing at a rapid rate. By October, 1999, about of the 6 Billion people lived in urban areas. The trend continues to accelerate and cities are becoming extremely large. So large, that the United Nations and other world bodies have given special attention to those Megacities in which more than 10 Million people live. In 2001, there were only 19 Megacities around the world. By 2015 it is estimated that there will be about 60 Megacities and most of these new Megacities will be in the Developing World. The trend will continue. By 2030, it is estimated that 4.9 Billion people will live in cities which is 60% of the estimated 8.1 Billion world population.

Planners and decision makers must realize that an enormous amount of infrastructure must be constructed not just for the urban framework of large and very large cities to be sustainable, but just for them just so they can survive. In fact, there may not be enough trained and experienced planners and tunnelers to safely construct and operate such a large number of underground facilities in such a short time.

Fortunately for the underground space industry, the underground is often the best location for much of the infrastructure required in urban areas, especially if the environment and sustainable development are considered. It is essential that those of us in the tunnel and underground space industry be proactive to inform the public, the media, city officials, and planners, at very early stages of a city's growth, of the importance of the underground to sustainable development and to quality of life.

Greater use of underground space will be beneficial to sustainability of cites. This is particularly true of essential infrastructure such as water, wastewater, other utilities and transportation. However, more planning and promotion of general underground space such as bulk storage, manufacturing, living, office spaces will be important but also long tunnels will be needed to maintain the efficiency of the transportation networks between these Megacities.

ENVIRONMENTAL BENEFITS AND THEIR IMPACT ON PLANNING

Tunnels and underground space play a dominant role in our standard of living and in the preservation of the environment. Moreover, they are increasingly recognized as being environmentally friendly and energy efficient. But the advantages of the underground are taken for granted by almost everyone. Tunnels and underground space are "Out-of-Sight, Out-of-Mind." At least within developed urban cities, every time someone turns on a faucet or flushes a toilet, an "environmental tunnel" is put into use. Yet the average person almost never makes this connection; even members of our industry take clean water in and wastewater out for granted because our tunnels have been doing such a good job for such a long time with so little maintenance that they are invisible to sight and to mind. As urban centers and megacities develop, underground space will play an increasing role in improving the quality of life. Underground specialists must play an important role in the future of our cities by advising urban planners on the advantages of underground space. In December 2008, ITA conducted a joint UN-ITA workshop at the United Nations titled "Underground Space, an Unexpected Solution to Promote Sustainable Development." There was considerable interest shown by the UN delegates and audience and subsequent cooperative events are being planned (ITA 2007). Some of the numerous environmental and societal benefits that are inherently associated with tunnels and underground space are given below (Parker 2004, ITA 2007).

- Tunnels play a vital role by conveying clean water to urban areas and by conveying waste water out. Most major urban areas depend on tunnels for these services, which function with a minimum of maintenance.
- The usable space off a parcel of land can, in some cases, be almost doubled by adding transport or other communication lines, floor space or bulk storage below the ground surface.
- Life-cycle cost and benefit methodologies are expected to reveal the underground alternatives to be much more competitive with surface facilities.
- It has been demonstrated by several recent events that tunnels behave very well in earthquakes. Underground space provides strong protection from natural and man-made hazards such as Earthquakes, Storms, and Violence so if you want to protect or preserve an asset for the future, put it underground.
- Underground space inherently conserves energy and thus promotes sustainable development and is an ally in the fight against Global Warming. Only a little energy is needed to bring underground space to a comfortable temperature both in winter and summer. Transportation Tunnels that reduce travel time over rough mountainous terrain also provide enormous fuel savings and reduction of emissions for decades.
  - Underground space provides significant environmental benefits by efficiently putting essential services underground leaving the surface to be used for more noble purposes.
  - Underground Space is Good for Sustainability and is an Ally in the fight against Global Warming.

These advantages are very compelling especially our industry's contribution to the fight against Global Warming. It will be up to the leaders of our industry to inform planners and decision makers of these advantages and benefits and, as they become better known, there will be an enormous demand for construction and utilization of tunnels and underground space.

CHALLENGES TO PLANNERS AND DECISION MAKERS

What are some of other challenges facing Planners and Decision Makers? They are not only numerous but they also change in significance with time as the process of planning develops and becomes more mature, detailed, and comprehensive. Selected planning challenges are outlined below:

- Population and Demographics
- Economic and Social Values
- Environmental Values
- Tunnel Technology likely to be available
- Non-Tunnelling Technology Developments
- Cost and Funding issues

These, and other issues, need to be addressed early in the planning of any underground project. Moreover, many of these issues are non-technical. Thus the planner is faced with multi-disciplinary decisions from the outset and throughout the rest of the project. For instance, in the decade that it may take to bring a project to construction, many of the basic decisions may change. Demographics may change and, in fact, may change just because the tunnel project is built and put in to service.

Changing environmental and social values are also likely to result during the planning and construction period of any project. With the rapid awareness of the environment, sustainable development and global warming, it is likely that environmental requirements for underground facilities will become stricter. On the other hand, the environmental benefits of tunnels may just make the project more acceptable to the environmental community.

Of great importance to the technical tunnel community will be the future changes of tunneling technology and in the non-tunnelling technology. These changes are likely to be very important to the planning and construction of underground facilities. The real challenge for planners will be to identify such technological improvements in time to apply them on the project.

Financial cost and funding issues are always the governing issues. These also change with time but, unfortunately, the general trend is more tightened budgets.

DEVELOPMENT OF UNDERGROUND TECHNOLOGY IN THE PAST

General Comments on Development of Underground Technology

Clearly, major mining and civil works schemes during ancient times and throughout the Middle Ages were bold and visionary feats in their own time. The development of tunnelling technology was very slow from 1850 to almost 1950. Before 1950, technological developments were slow to materialize and tunnel planners likely realized that there was not much chance of significant innovations that might impact their project. Now (2008), just the opposite is true; innovations are now expected and rapid development in technology and innovations must be taken into account by planners imposing a whole new set of visionary requirements for tunnel planners.

The author was fortunate to have been involved in pioneering work on innovative tunnel support systems in the late 1960s at the University of Illinois in Champaign-Urbana for a project for the U.S. Federal Railroad Administration (Parker and Semple 1972). The impetus for this work was the ambitious concept of a tunnel or series of rail tunnels from Washington DC to Boston, a distance of some 750 km. The concept was bold and visionary but was never constructed for many reasons including cost. As we undertook this project on innovations, the project team found that very few ideas were truly new; almost everything had been thought of and tried before. Planners should understand that many new ideas are not actually new ideas but are older ideas being revisited.

Since technological changes were slow to develop, tunnel planners probably recognized that there was not much chance of significant innovations that might impact their project. This made the planner's job easier but the situation is reversed now giving tunnel planners great challenges.

Pre-1950 Development of Underground Technology

Our forefathers were great engineers. Even prior to 1900, practicing tunnel planners, designers, and contractors were visionary in their development of some extraordinary concepts for tunnel construction and operation. They not only had great visions but they actually tried some of these great ideas. For no fault of their own, more frequently than not, they were unsuccessful, mainly because technology had not progressed far enough to support their ideas and visions. Often those same ideas were successfully put into practice decades or sometimes a century later (Parker, 1999). For instance, the Channel Tunnel took over a Century to realize the dream, not only for political reasons but also for technical reasons.

The first mechanized tunnel machine was tried unsuccessfully in the late 1840s on the 12 km long Frejus Tunnel (also known as the Mt. Cenis Tunnel) from Italy to France (Stack, 1982). The second mechanized tunnel machine, also unsuccessful, was built for the 8-km-long Hoosac Tunnel in Massachusetts, USA in the early 1850s. Over the next century many attempts to develop a mechanized tunnelling machine were unsuccessful. However, there was a time-span of over a century before TBMs began to become practical.

Gunite, the forerunner to shotcrete was first developed in the USA around the turn of the century when Carl Akeley invented the Cement Gun to apply mortar over skeletal frameworks of prehistoric animals for Chicago's Field Museum. Although tried in an experimental mine in Pittsburgh in 1914, it wasn't until 1952 on the Swiss Maggia Hydroelectric project before tunnels were solely supported by shotcrete (Parker, 2001). Again, there was a century span between vision and practical application.

Development of Technology: 1950 to Present

Technology is advancing now (2008) at an ever increasing rate. Around the 1950s and beyond, technology started to catch up with our vision which resulted in many of our forefather's ideas becoming a reality. James S. Robins built an 8-m-diameter rotary TBM which successfully excavated Pierre Shale at Oahe Dam in the USA. He then pioneered the use of solely using disc cutters on a TBM cutterhead on a small diameter tunnel in Toronto. Unfortunately, because of technological limitations, similar success was not possible in hard rock for a very long time.

About a century after Greathead's 1874 patent of a shield with water pressure on the face, pressurized-face TBMs became feasible. In the 1960s, several developments took place all over the world that made these machines more feasible technically. These took place in Japan, Germany, England, Mexico, USA, Canada and elsewhere. Earth Pressure

Balance and Slurry machines now are commonplace on routine projects. Now, there are various concepts for handling mixed-face conditions to make machines more feasible for rock tunnels that will also pass through fault zones with differing ground conditions.

Steel fiber reinforced shotcrete (SFRS) was developed in the USA around 1970. The author worked on the practical development of SFRS at the University of Illinois in the early 1970s (Parker 1976, Parker 2001). It only took a decade before SFRS became accepted and now (2008) SFRS is now routinely used in tunnel construction.

Accordingly, now, because of such great advancements in technology, the ideas and vision of the planners, designers, manufacturers and tunnelers in our industry are being realized in the field very quickly after the idea is conceived. This trend seemed to have started in Japan where some amazingly creative machine configurations and concepts have been built and used in practice but the trend is now beginning to spread worldwide. The message to the planners and designers is that our industry is very creative and can overcome any challenge. Thus, planners should be bold and daring in the planning of projects.

Previous Planners Lacked the Tools

In the 1950s and 1960s, planners hardly had any of the tools that we now enjoy (2008). It is interesting to reflect on the tunnels that could have been built if our predecessors knew that new and innovative tools would exist when their tunnel was finally constructed. In order to reflect on just how much our industry has changed in the last half-century, it is helpful to reflect on the progress our industry has made since 1950. Equipment such as rock TBMs, Pressurized-face TBMs, conveyor belts, microtunneling or directional drilling all have been developed in that time period since 1950. Methods of excavation and support such as the sequential excavation method (SEM/NATM), rock bolts and shotcrete, special ground improvement, single pass concrete segments and waterproof membranes also have been developed since 1950.

Each of these (and the many others not listed) make tunnels and underground construction today more technically and financially feasible. Had planners known that such innovations would become available, they could have been more bold and visionary and many more tunnel projects would have been proposed and built in increasingly more difficult conditions. Although this is Monday morning quarterbacking, it is proof of the strength and creativity of our tunnelling industry. If a planner can dream it up, our industry can get it done. Of course the difficulty is knowing what innovation is most likely to become practical during the decade or so of the planning process. This is a task that UCA and ITA should work on.

IDENTIFICATION OF OPPORTUNITIES AND RISK MANAGEMENT

Risk management has now become a buzz word in our industry and it is the subject of numerous conferences, books and papers. Tunnel owners and planners now have begun to use systematic risk management principles to identify all risks in a way that directs the rest of the planning and construction process to minimize those risks. This systematic procedure must be done as early as possible in the stages of a project (pre-conceptual or idea stage). This systematic risk management work then is carried on and updated all the way through design and construction. The risks to be considered should be broad and also include risks of cost, schedule, environment, public acceptance, adjacent owners and third-party intervention, politics, etc. in addition to the technical risks that always immediately come to mind.

Fortunately, the same concepts and tools can be used to identify value engineering ideas, as well as to identify broad ideas and opportunities including "thinking out of the box" (Parker and Reilly 2008).

PRINCIPLES OF LIFE-CYCLE COSTS AND BENEFITS

Tunnels often remain in service for over a century. Accordingly, decisions about whether a certain infrastructure should be a tunnel, or not, should be made on considerations of Life-Cycle Cost and Benefit and not Initial Capital Cost. This is a difficult concept to implement but it is important for planners and decision makers to avoid the pitfall of decisions based on initial capital cost. Using principles similar to those used in Risk Management, the likely cost of a tunnel or underground facility and also its planning and construction schedule should be developed and reported as a range, not as a single number (Reilly, 2006, Reilly and Parker 2007, Parker and Reilly 2008).

Obviously, the life-cycle costs should include future operational and maintenance costs. However, the cost analyses should also include realistic allowances for equivalent financial benefits from environmental and social improvements associated with tunnels which can be substantial.

Thus, the initial cost is mitigated and offset by significant savings attributed to the environment over the years of operation. It is imperative for planners to consider the financial aspects of tunnels from a Life-Cycle Cost standpoint that also takes into account the accumulative equivalent financial benefits from saving the environment. Planners and decision makers must be courageous and convincing as they present a clear message of the overall advantages of tunnels and underground space to the media, public, politicians, and fellow decision makers. UCA and ITA should take this challenge on as a major goal.

BOLD AND VISIONARY TUNNEL CONCEPTS

Visionary Concepts Currently Being Implemented

There are many projects around the world that fall into the category of bold and visionary. In Seattle, Washington, a 50-year-old viaduct along the waterfront was damaged by an earthquake and needs replacing. However, in addition, the old seawall along the waterfront and just beneath the viaduct also needs replacing. Both structures may not survive the next big earthquake. Planners and decision makers have designed a cut and cover roadway whose outboard wall will be designed to also function as the new seawall. This new structure would replace both the viaduct and the seawall with one structure with an overall reduction in cost, schedule, and especially in reduced disruption to the public. Moreover, the cost would be shared by both road and waterfront authorities. Of course, the initial cost of any such structure is considerable and, at the present time, other schemes are being considered. Unfortunately, the comparison of schemes has been, and will likely continue to be, on the basis of capital cost, not life cycle cost and benefits which also take into account the environmental and societal benefits of the underground option.

Another innovative out-of-the-box concept is the SMART tunnel project in Kuala Lumpur. It is a double-deck tunnel is specially configured to handle both auto traffic and floodwater. During low and medium flows, water flows beneath the lower deck while cars are still travelling through the tunnel. However, when a very big flood occurs, traffic is removed and the flood waters pass through the entire tunnel including the roadway. This way, the public gets two end uses for the tunnel for a price and construction disruption that is less than that of two separate tunnels. Moreover, the cost of the tunnel is shared by two groups making each easier to afford. The concept of using tunnels to store wastewater during a storm, such as the Chicago TARP project and other CSO storage projects, is another creative use of tunnels. Similar wastewater storage projects are being constructed worldwide.

A pioneering concept is the A86 road tunnel project in Paris. This project will not permit trucks and is strictly for cars less than 2-m-high. With this restriction, the owner/concessionaire is able to fit 4 lanes of traffic plus 2 breakdown lanes (in a double-deck configuration) in a 11.6 m-outside-diameter tunnel. In the USA and elsewhere in the world, geometrical restrictions would only allow 2 lanes of traffic. There is even a possibility for future expansion to have 3 lanes on each deck for a total of 6 lanes in a tunnel. Such a configuration at least gives the potential of the cost of such tunnels per km per lane to be on the order of ½ to ⅓ of the cost for traditional configurations. Moreover, such a tunnel can be constructed using more readily available standard size TBMs in a shorter construction time and with less disruption to the public.

A welcome breakthrough in the planning of utilities has been achieved in Ashgabat, Turkmenistan where the planners and decision makers have finally been able to implement a 30-km multi-use utility tunnel scheme. This 6 meter diameter tunnel acts to lower the groundwater table by acting as a drainage collection and transfer tunnel which collects and stores unwanted subsurface drainage water and transfers it to discharge points in the desert. The same tunnel contains electrical power lines, telephone conduits and potable water pipes in different compartments (Wallis 2007). Our industry has talked about such multi-use tunnels, so called utilidors, for decades and generally they are rejected for legal liability reasons. It is good to see such a project on such a scale being constructed in Turkmenistan.

Bold, Visionary, and Daring Concepts

There are numerous very bold concepts that have been proposed. Many appear almost outrageous and may never be built because of cost or other reasons but they have been proposed and talked about by serious planners and engineers.

A Submerged Floating Tunnel (SFT) has been proposed several times in various parts of the world but never built. Conceptually, the SFT can be a lot shorter tunnel which gives much greater flexibility in locating tunnel alignments and portals. SFTs are a perfect example of "thinking out of the box." It is so creative that one can allow your imagination to soar on these types of projects. Recently, SFTs have been identified by the Discovery Channel as one idea for a crossing of very large body of water or maybe even an ocean. Such a concept has many non-technical obstacles which may prevent such a project to get farther than the conceptual stage. However, SFT engineers have identified the major issues to address to make such a concept work from a technical standpoint (Ostlid, 2006).

All of the proposed long sub sea tunnels, such as the Gibraltar and Bering Straits tunnels, that are now in the planning stage fall into the category of bold and visionary tunnels as did the Channel Tunnel for over a century. ITA has been very active in the evaluation and promotion of sub sea tunnels, especially the Gibraltar Tunnel, and has summarized some of the projects now in the planning stage (ITA 2008). The author believes that technology will be eventually developed to make the tunnels currently in the planning stage feasible as well.

The Swiss Metro is a bold and visionary concept developed for a very high speed transportation network in Switzerland with possible extensions to other parts of Europe. Maglev trains would be propelled at very high speed through tunnels in a partial vacuum. A lesser-known but comparable scheme for North America, the American Metro, has been suggested for consideration by a railroad dispatcher and railroad buff, Swartzwelter (2003). A network of tunnels between major cities would be constructed for very high speed (1000 km/hour) transfer of people and goods.

These and other very bold, visionary, and daring projects, possibly even the use of underground space on the moon, are part of the forward vision of our industry. Many may never get past the "What If" idea stage. It is, however, important for our industry to stretch wherever it is appropriate. In a relative sense, this may be similar to previous bold and visionary thinking by our forefathers which resulted in the Thames Tunnel, the alpine tunnels, and the Channel and Seikan sub sea tunnels.

PLANNING IMPACT FROM ISSUES AND EVENTS OUTSIDE OUR INDUSTRY

There are many issues and events outside of our industry that will have a significant impact on our planning for tunnels. Some of these issues we do not even know about yet but one of these is the price and availability of oil. There have been numerous claims over the past decades that the world would run out of oil, or cost so much that other fuels will be necessary. This has not happened yet but may happen, if nothing else, because of greatly increased demand for oil by developing countries. So there is a much greater chance that the world will need substitute technology or fuels, possibly to include hydrogen fuel cells or a hybrid. These developments will give planners new challenges and new opportunities.

The fuel cell is a concept that was invented in 1839 but did not gain any real practical use until used by NASA for space travel. The concept is being worked on by many countries including the USA; there are several local and regional agencies which have fuel cell or hybrid technology as a test. One of the major factors for planners is that when hydrogen is the fuel, the only emission is water. If vehicles were to be powered by hydrogen, or a high level hybrid, adverse emissions are drastically reduced or nearly eliminated. Planners and designers would have to modify their approach to tunnel ventilation during normal service use while still providing essential fire and life safety services. Such a concept would possibly drastically reduce tunnel operational costs and possibly even capital cost.

Hybrids are fast gaining popularity both in additional research and in practical applications by forward thinking and visionary travellers. Some use different fuels which may impact tunnel ventilation systems in various ways. Some, however charge large electric batteries which, when used to propel vehicles through tunnels would drastically reduce ventilation demands especially in long tunnels.

It may be preposterous to think that the internal combustion engine may be replaced or metamorphosed into something better, but stranger things have happened even within the author's lifetime such as the development of television, jet engines, space travel, computers, air conditioning, cell phones, etc. The author is not predicting such a transformation in transportation may take place but our industry should think on what effect it would have on the design of the ventilation system and the operation of the tunnels if it were to take place.

Another concept that may affect future tunnel planning is related to propulsion technology such as MagLev or other future propulsion breakthrough we don't even know about yet. There are Maglev systems in operation now but not in tunnels although the author understands that a maglev test track in Japan goes through a short section of tunnel. Much more development, and reduction in cost, will be necessary to make Maglev, or any other new propulsion system, worth considering for tunnels. However, there are some promising aspects if the concept becomes viable. For instance, the system is capable of being faster and it is environmentally friendly. Moreover, it can negotiate tighter curves and steeper grades both of which may allow tunnels to be shorter and therefore less costly. Whether such a concept will be technically feasible or cost effective is yet to be seen, but consideration of such a concept for bold and daring planning of future tunnels may not be unreasonable.

VISIONARY USE OF UNDERGROUND SPACE

New ideas for improved and greater use of underground space are constantly being proposed. Now, thousands of years after the use of caves for refuge, there are very interesting proposals for the use of underground space, especially from Japan. These include multi-modal complexes with offices, living quarters, public meeting areas, sports arenas, recreation, schools, research facilities, etc. all connected to the rest of the city at multi-modal stations.

There are abundant locations where products (such oil, gas and even wine) are already being stored in bulk storage caverns. There are wine cellars created for storage and entertainment. In Kansas City in the United States, there are existing mined openings with over 450,000 square meters of space that is leased to various users for storage, office space, etc. New technology, concepts, and designs to provide as much sunlight to underground facilities as possible are being developed (Bennett 2008). Major underground space facilities require creative vision but can be planned boldly just like any other underground project.

Beneficial use of underground space is not just for the developed countries. Hand-dug underground cellars and bins have been used for centuries to safely store food and other goods. This may still be one of the best and least expensive ways to improve the quality of life in the developing countries. Underground spaces, properly designed, can be built with local labor and limited outside resources to provide good and safe environment for storage of water, food and other products and equipment. If designed and constructed properly they are earthquake resistant and energy efficient. As part of the work ITA is doing as an NGO with the United Nations, ITA has proposed that the development of mined or earth sheltered construction and underground space be included as part of the effort to create sustainable rural communities, especially in areas with extreme climates.

CONCLUSIONS

As the growth of cities, particularly the megacities, continues, they will all need abundant infrastructure and the demand for the Underground will be enormous. In fact, even if a fraction of the needed infrastructure is funded, the capacity of our industry will be challenged. We would be challenged to build the required infrastructure fast enough. There simply may not be enough planners, designers, and contractors to do the work.

Tunnels and underground space play a dominant role in our standard of living and in the preservation of the environment. Moreover, they are increasingly recognized as being environmentally and socially friendly and energy efficient. Underground Space is Good for Sustainability and is an Ally in the fight against Global Warming.

In past years, planners did not have the luxury of the many tools and techniques that exist today. We should be very proud of our forefathers who had great vision and whose ideas were not achieved in their lifetime. Technology development was so slow from about 1850 to 1950 that their ideas did not materialize until technology made their schemes feasible. Now (2008), technology is keeping up with our ideas and vision which can be implemented relatively quickly. Accordingly, planners should be aggressive and bold in their plans for tunnels and underground space.

During the lifetime of the project you are planning today, new technology and/or environmentally driven concepts will develop that may significantly affect your project.

The principles discussed for traditional tunnels also apply to the more noble use of underground space for living, working, and storage. Nor are they confined to application only to developed countries. ITA has recommended that the development of earth sheltered construction and underground space be included as part of the effort to create sustainable rural communities, especially in areas with extreme climates.

Owners and planners should use risk management principles from the very first time a tunnel solution is considered and carry out systematic risk management evaluations throughout planning, design and construction. These same principles should be used to systematically develop and implement value engineering and new opportunities, especially those thinking out of the box. This is particularly true for long tunnels that have abundant uncertainties. Our industry can not afford to wait for decision makers to become aware of the sustainable development benefits of the Underground. Instead we must be pro-active and let the world know that sustainability is not possible without infrastructure and that, often, the best form of infrastructure involves the underground.

Owners should develop ways to account for a financial credit resulting from environmental advantages especially for long transportation tunnels that accrue enormous environmental benefits to society. These environmental cost advantages should be incorporated into cost ranges that take into account the long service life of the tunnels by making the decision on Life Cycle Cost and Benefit concepts, not initial capital cost. It should always be remembered that tunnels are an investment, not a cost.

There are numerous bold and visionary projects already completed or under consideration. There are even daring projects that may not get built but which stretch our imagination of what is possible with underground space. The tunnel and underground industry is very creative and our ability to innovate has been proven many times. Owners and planners should have faith in the tunnel and underground industry. The industry will be up to any challenge so planners can plan boldly with vision.

REFERENCES

Bennett, David J., 2008. *"Beyond Sustainability: The Case for Environmental Architecture,"* http://djbarchitects.home.att.net/sustainablebase.htm, 16 pp, Accessed January 14, 2008.

ITA, 2007. Underground Space, an Unexpected Solution to Promote Sustainable Development. Joint UN-ITA Workshop conducted at the United Nations, December 14, 2007, In Press at ITA WebSite: www.ita-aites.org.

ITA, 2008. Challenging Tunnel Projects Worldwide, ITA WebSite: www.ita-aites.org, Accessed January 14, 2008.

Ostlid, Havard, 2006. Tunnels Between Continents? Possible or Not Possible? Proceedings of ITA Training Workshop, Seoul, Korea, ITA WebSite: www-ita-aites.org.

Parker, H. W., 1976. Field-Oriented Investigation of Conventional and Experimental Shotcrete for Tunnels, Thesis submitted to the University of Illinois at Urbana-Champaign, Illinois, in 1976 in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering, 628 p.

Parker, Harvey W., 1999. The Development of Hard and Soft Ground Tunnels, Proceedings, Tenth Australian Tunnelling Conference, Keynote Addresses and Asia-Pacific Forum Volume, The Australasian Institute of Mining and Metallurgy Publication Series 1a/99, Victoria, Australia, 1999, pages 25–31.

Parker, Harvey W., 2001. Early Developments of Shotcrete and Steel Fiber Shotcrete, *Proceedings,* Eighth Engineering Foundation Conference on Shotcrete, Campo do Jordo, Brazil, 1999, United Engineering Foundation Press, ASCE, 2001, pp 240–258.

Parker, H.W., 2004. Underground Space: Good for Sustainable Development, and Vice Versa," *Proceedings,* ITA-AITES World Tunnel Congress, Singapore, May 2004.

Parker, H.W. and Semple, R.M. 1972. Development and Large-Scale Testing of Innovative Tunnel Support Systems, *Proceedings*, North American Rapid Excavation and Tunneling Conference, American Institute of Mining, Metallurgical and Petroleum Engineers, Chicago, Illinois, 1972, p. 469–497.

Parker, Harvey W. and Reilly, John, 2008. Risk and Life Cycle Costs and Benefits for Underground Projects, *Proceedings,* North American Tunneling Conference, San Francisco, SME, Denver (In Press).

Reilly, J.J. 2006. Cost Estimating, Probable Cost, Risk Identification and Risk Management for Infrastructure Projects. *Proceedings American Public Transportation (APTA) Conference,* June 2006.

Reilly, J.J. and Parker, H.W. 2007. Benefits and Life-Cycle Costs of Underground Projects. *Proceedings, AITES-ITA World Tunnel Congress, Prague*..Vol. 1: 679–684.

Stack, B., 1982. *Handbook of Mining and Tunnelling Machinery,* John Wiley and Sons: Chichester, 742 pp.

Swartzwelter, Brad, 2003. *Faster than Jets*, Alder Press, Kingston, WA, USA, 188 pp.

Wallis, Shani, 2007. Personal Communication.

Probable Cost Estimating and Risk Management

John Reilly
John Reilly Associates International, Framingham, Massachusetts

ABSTRACT: Costs of complex/underground projects have been consistently underestimated and delivery on time and on budget has been problematic. This has been attributed, to inadequate cost estimates and unidentified and/or insufficiently managed risk. Use of probabilistic cost estimates like the Washington State Department of Transportation's CEVP® process (developed by the author and others) has produced more realistic cost estimates, explicitly identified and quantified risk (as input to risk management plans) and early awareness of key project issues. This paper updates previous work (NAT 2004), adds implementation detail for probalistic cost estimating as used by WSDOT, FHWA and other agencies and will address key issues in risk management, as related to probalistic cost estimates.

INTRODUCTION

Good project management requires, among other key elements, good cost and schedule estimates, as well as a process to identify and deal with uncertainty and management of risk. These elements are the focus of this paper.

THE COST ESTIMATION PROBLEM

Even when a project is well planned and managed, in a significant number of cases project conditions change and problems arise. Of these, political changes seem to have the most significant effect (Salvucci 2003). These changes and problems have resulted in significant undesirable consequences which include cost and schedule over-runs, resource competition between projects, negative media attention and, consequently, public mistrust.

Thus we find that the public is skeptical of our ability, as a profession, to accurately estimate the final costs of large, complex public projects and is also skeptical of our ability to manage these projects to established budgets. Questions they have asked include:

- "Why do costs seem to always go up?"
- "Why can't the public be told exactly what a project will cost?" and,
- "Why can't projects be delivered at the cost you told us in the beginning?"

Our inability to answer these questions consistently is a consequence of many factors—including inadequate cost estimating procedures and our prior inability to correct these poor estimating practices (Flyvbjerg et al. 2002). Additionally, the effects of poor project management and poor communication with the public has further added to the problem—resulting in unfortunate results, including negative votes for proposed transportation funding.

Many government agencies, including the Federal Highway Administration (FHWA) and some State Departments of Transportation have recognized this problem and in response are now requiring risk-based cost and schedule estimating, as well as formal risk management plans (FTA, 2003; FTA 2004, FHWA 2006).

Examples of Poor Cost Information and Estimation

One international survey (Reilly and Thompson, 2000) found that specific, relevant cost information was usually unobtainable. Little objective history could be found, including findings that would support recommendations for improvement. Because of the difficulty in obtaining hard data, firm conclusions could not be reliably drawn but the following findings were reported by the owners:

- There are significant cost and schedule overruns suggestive of poor management in at least 30%, and possibly more than 50%, of the projects.
- It appears that the factors that most directly influence success or failure are (a) expertise and policies of the owner and (b) procurement procedures.
- The professional teams engaged in projects were judged, by the owners, to be competent leading to the conclusion that problems in poorly performing projects may lie primarily with the ability of the owner to effectively lead and manage the project process.
- Risk mitigation was not well-understood or applied, even in elemental ways. This was considered to be a promising area for development,

in particular as it related to cost over-runs and unforeseen events.
- Reported cost and performance data—especially for "good" results—should be treated very cautiously.
- Consistent, complete and relevant data are very hard to get and almost impossible to validate after project completion.
- Conclusions based on reported cost data, unless the conclusions are grossly evident (e.g., meta-findings), should also be treated with caution.

Other studies confirm the problem (Flyvbjerg et al. 2002). Flyvbjerg surveyed 258 projects spanning 70 years and found that the problem of accurate cost forecasts has been chronic for that time period. Key findings were:

- 9 out of 10 transportation projects underestimated costs with an average overrun of +28%

- Road projects averaged +20% higher than estimated
- Tunnel and Bridge averaged +34% higher
- Rail projects averaged +45% higher than estimated

Specific examples include several of the FTA Demonstration projects such as Tren Urbano in Puerto Rico—$1,285 million over initial budget (+133%), the Silver Line Transitway Project in Boston—$286 million over budget (+90%), the London Jubilee Line Transit Project—2 years late and £1.4 billion over budget (+67%), the Channel Tunnel Rail Project—£3.7 billion (+80%) over budget, Denmark's Great Belt Link rail and road link (+54%), the 2003 Woodrow Wilson bridge tender in Virginia 72% over estimate and, Boston's Central Artery Project—many billions over the initially published cost numbers (which were extremely unrealistic) and years late.

Note: the cost percentage number in parentheses in the above paragraph indicates the final cost of the project divided by the budget which was communicated at time of decision to proceed. This important because it is the "number" that the public tends to remember and the media reports. However, it does not include new scope and other changes, which might be quite legitimate. It does include poor initial cost estimates and/or poor estimation of risk and other factors—including poor management, the effects of external events and political changes or transitions (Salvucci, 2003).

Of major concern is that, as an industry, we have not corrected the "chronic cost underestimation" of such projects—if we had done so, there would have been a uniform number of results equally over budget as under budget. This problem has existed for over 70 years, as shown by Flyvbjerg, whose conclusion is that the problem is both an inability to estimate accurately, a bias to estimate on the optimistic side and political misrepresentation.

The Influence of Variables

The final, definitive cost and schedule of a project cannot be predicted accurately because the project can, and will, be affected by a number of variables. These variables include nature (e.g., ground conditions, weather), technology (e.g., design, methods, equipment, materials) and human (e.g., labor, public, politics, regulatory agencies, funding/insurance/bonding agencies, market conditions). These variables cause uncertainty in cost and schedule through variations in those project conditions assumed for the estimates (e.g., average unit rates, progress rates, and escalation rates) and through uncertain impacts from unplanned events (deviations from those assumptions).

Early Information and Uncertainties

Early in project development when project estimates are initially developed, information on these variables is typically limited, but a process for identifying and managing potential problems should be developed at this time, when the problems are easier to resolve, if identified.

If these uncertainties are not explicitly included in the estimating process, and if inevitable estimating biases are not corrected, project cost and schedule estimates are likely to be inaccurate, consensus will be difficult to achieve, and it will not be possible to answer critical questions such as: "Which project alternative is best?"; "What scope is actually affordable or will actually be built?"; "Is the current estimate high or low relative to what the actual cost and schedule will ultimately turn out to be, and by how much?"; "What should the funding/budget and milestone dates be for this project?"; "How can the project cost and schedule best be controlled?

POTENTIAL SOLUTIONS

A variety of approaches have been developed to attempt to provide better cost and schedule estimates. These various approaches generally differ in the following areas:

- Traditional contingency-based deterministic (single value) approaches vs. probabilistic approaches—either combined uncertainty or itemized uncertainty, e.g., individual risks;
- Separate and unlinked cost and schedule models vs. integrated cost and schedule models;
- Varying levels of detail and approximation; and

- Input assessment methods (e.g., cost data base vs. project-specific judgment of technical experts).

The author, clients and colleagues (WSDOT 2007, Roberds and McGrath, 2005; Grasso, 2002;) believe that a flexible (depth and breadth of detail and degree of approximation), probabilistic, risk-based approach using an integrated cost and schedule model is the most appropriate way to quantify uncertainties for complex projects and to guide risk management in order to better define and control costs and schedules.

Example of One Approach

Such an approach forms the basis of the Washington State Department of Transportation's (WSDOT) Cost Estimate Validation Process (WSDOT, 2007) which is used on all WSDOT projects over $25 million has been used on a number of Federal Highway Administration and State Department of Transportation programs and other Agency projects (e.g., Alaska Railroad, Toronto Waterfront Revitalization). The approach has also been used to quantify uncertainty in programmatic measures such as program expenditure and cash flow and for programs consisting of a large number of individual projects, each of which are uncertain but often related to some degree. Specifics of the development of this approach follow.

WSDOT'S COST ESTIMATE VALIDATION PROCESS—CEVP

In January 2002, the Washington State Secretary of Transportation was questioned by a State Senator about the poor reliability and history of increases of cost estimates for a large project. WSDOT managers and key consultants—"the core team" (Reilly et al., 2002)—were asked to develop a better cost estimation process. As part of defining "the problem," a review of relevant data led to the following findings:

1. There is a general failure to adequately recognize that an estimate of a future cost or schedule involves substantial uncertainty (risk),
2. Uncertainty must be included in cost estimating,
3. Cost estimates, must be validated by qualified professionals, including experienced construction personnel who understand "real-world" bidding and construction,
4. Large projects often experience large scope and schedule "changes" which affect the final cost. Provision for this must be made in the cost estimates and management must deal competently with these changes.

WSDOT decided to act on these findings by:

1. Developing an improved cost estimating methodology,
2. Incorporating cost validation, risk identification and management,
3. Openly and reliably communicating "ranges of probable cost" to public, media and political decision makers.

WSDOT's strategy was to deal openly with the process of public infrastructure cost estimating so that the public would better understand, and be better informed, as project manages and elected officials make critical project funding decisions. The challenge was to develop a valid procedure to do this. WSDOT decided to open the "black box" of estimating and present a candid assessment of the range of potential project costs, including acknowledgment of the uncertainty of eventual project scope, the inevitable consequence of cost escalation due to inflation, and other major risks.

The WSDOT Process

The WSDOT team developed a specific management-cost-risk assessment tool which was called the "Cost Estimate Validation Process" or CEVP® . The draft procedure included:

1. A cost validation process adapted from the Boston Metrowest Water Supply Tunnel project,
2. Inclusion of the impacts of risk and opportunity events derived from procedures previously developed for infrastructure tunnel projects (Einstein 1974; Anderson, Reilly and Isaksson 1999; Grasso et al. 2002),
3. Use of independent subject matter experts, particularly those who have been responsible for construction of these projects in a hard-money bid environment.

The basic approach requires a peer-level review, or "due diligence" analysis, of the scope, schedule and cost estimate for a project and then incorporation of uncertainty (uncertainty includes both risk and opportunity) to produce ranges of probable cost and schedule. Specific objectives of the method are to evaluate the quality and completeness of the "base costs" together with the inclusion of inherent uncertainty (risk and opportunity) in the estimate. Risk mitigation can also be included.

WSDOT launched the CEVP® program with a major commitment of its personnel, including functional and project staff, staff from project partners, members of the consultant teams already working on

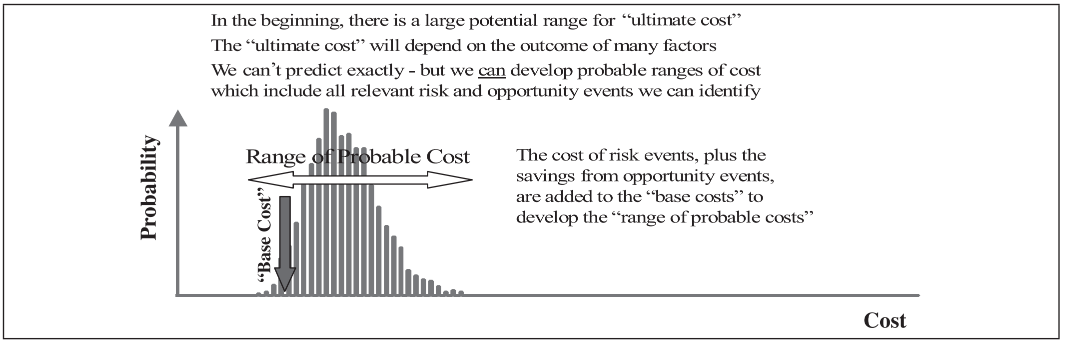


Figure 1. Future costs are a "range of probable cost"

some of the larger projects and, the core CEVP development team. To this were added external specialized consultants including a group of very senior engineering, construction and cost estimating specialists drawn from around the country (see "Acknowledgments" at the end of this paper). Figure 1 shows base cost and the range of probable cost histogram.

Key Concepts

As the CEVP methodology emerged, several key principles were identified. Among these were:

1. Avoid single number estimates. Recognize that at any point in the development of a project, from initial conceptualization through the end of construction, an estimate will require selecting a representative value to characterize many factors that are inherently variable. These variable factors will include issues that have been identified and quantified (the known/knowns), those that have been identified but not yet quantified (the known/unknowns) and those that have not yet been identified (the unknown/unknowns). Some factors will be controllable by design or by the owner, some will not. But all of these contributing factors are fundamentally uncertain and need to be treated as such.
2. Use a collaborative assessment environment that combines high levels of critical external peer review expertise, particularly in construction and estimating construction in a bidding environment, with appropriate roles and responsibilities for the Project Team. Project Teams and owners are (and should be expected to be) biased. They are generally too optimistic about the project and want to see it advanced, funded and built. Balance this bias with independent subject matter experts, peers and others with valued experience that is based on experiences separate from the specific project.
3. Acknowledge that both cost uncertainty and schedule uncertainty are major contributors to problems with project estimating, and incorporate both in the evaluation methodology. WSDOT foresaw the clear advantage, in fact the necessity, to integrate the effects of cost and schedule uncertainty. CEVP® was developed:
   – To incorporate quantified uncertainty for both risk and opportunity factors,
   – To identify these factors using an aggregated-component approach that separated components whose cost and/or duration could be considered separately and,
   – To integrate cost and schedule using appropriate analytical methods.
4. Be practical and use common sense notions of risk descriptions and quantification. The CEVP® method was to be completely rigorous and treat uncertainty in ways that acknowledged correlation, independence and other probability principles. However, the sources of information and definition of uncertainty were likely to encompass a range which might extend from highly quantified issues to those where subjective opinion from the contributors was all that would be available. This range of uncertainty data needed to be captured objectively.
5. Produce project output that could be understood by the ultimate audience, the public. This led, ultimately, to a focused approach that presented the concepts of cost ranges, probability, risk and opportunity and risk management to the public, media and political decision makers in June of 2002. The public, media and political decision makers accepted these concepts surprisingly quickly and without major comments.

CEVP®—PROCESS AND RESULTS

CEVP® develops a probabilistic cost and schedule model to define the probable ranges of cost and

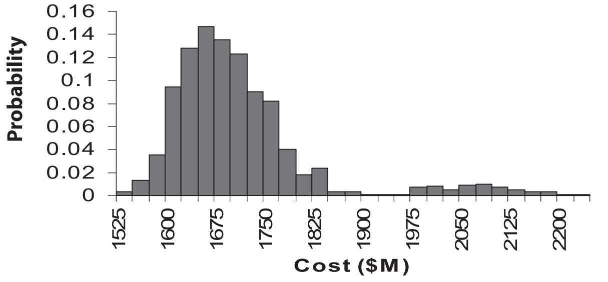


Figure 2. Model results—probability vs. probable cost

schedule required to complete each project. The results of the assessment are expressed as a probable distribution of cost and schedule values for the project as shown in Figures 1 and 2. The CEVP process (Reilly and Brown, 2004):

1. Critically examines the Project estimate to validate all cost and quantity components using independent external professionals.
2. Removes all "contingency" and allowances for unknowns, then
3. Replaces the contingency and other approximating allowances with individually identified and explicitly quantified uncertainty events (risks and opportunities).
4. Builds a model of the project—normally in an Excel spreadsheet using a flow-chart of key planning, design, permitting and construction activities. Included are quantification of cost and critical path schedules. The model assigns the quantified uncertainty events to activities with the associated probabilities and impacts.
5. Runs a simulation to produce the projected "range of probable cost and schedule" and reports the results.

CEVP® Workshop Elements

Key elements of the CEVP® workshop are

1. Develop a model of significant project elements reflected in a "flow chart,"
2. Cost validation—determination of "base cost" and,
3. Risk elicitation—defining the probability and impacts of risk events.

The fourth element is the subsequent communication of results to the public, media and political decision-makers. The basic CEVP® process has been described previously in several papers (Reilly and Brown 2004, Reilly 2005) so the following text will describe the flow chart, cost validation and risk elicitation.

The Project Flow Chart

The Project Team provides a detailed description of the expected project plan, with the major activities and their associated costs and durations. From this information, the team develops a project flow chart that represents the sequence of major activities to be performed in the project. Major decision points (e.g., funding decisions) and project milestones, as described by the Project Team, are explicitly represented in the flow chart. The base costs and durations, as well as any related major uncertainties or correlations for each activity are entered on the flow chart using values as confirmed or defined by the base cost review team.

Cost Validation

The cost part of the workshop is led by a manager with program delivery experience, supplemented by team members with both design and real-world construction experience. The use of personnel with experience in contractor's methods is necessary to bring that perspective into the cost review for a well-shaped determination of "base cost"—the cost if "all goes as planned and assumed" without contingency. The process consists of the following:

1. The project team first briefs the CEVP® specialists on the detailed scope of the project and identifies cost and schedule risks that that have been included in the project estimate.
2. The CEVP® cost specialists discuss the cost estimate with the project team, reviewing what the estimate represents and the basis of its development. They discuss what metric has been used to calibrate the estimate and what contingencies have been included in the estimate.
3. A review of the scope of the project is completed with the project team on an element by element basis to assure that all elements and phases of the project have been accounted for.
4. The estimate is reviewed to assure that items such as: right of way, mobilization, permitting,

mitigation, temporary facilities and utilities, construction phasing requirements, seasonal constraints, cuts/fills, hazardous material issues, archaeological issues, storage and disposal of material, haul distances, compaction and testing, protection of work, testing of mechanical and electrical systems, occupancy permits, demobilization, etc. have been recognized and addressed—from a cost standpoint.

5. The schedule for the project is also reviewed—Is it realistic? Does it consider adequate time for mobilization? Set-up of temporary facilities and utilities? Construction permitting? Construction phasing? Dealing with differing site conditions? Traffic or operational issues? Seasonal constraints? Site access limitations? Testing of piping? Electrical and signals? SCADA systems?, etc.
6. Unit prices and production rates that have been assumed for the major items of work are reviewed, asking if the production numbers (the basis of the units costs) are reasonable and if there are any risks that those unit prices may not have taken into account—such as high ground water or the presence of organic material.
7. The contingency that is included in each unit price—or the entire estimate—is identified and removed from the cost estimate. This is done in order to develop the "base cost" of the project (the contingency is subsequently replaced by the probable cost of risk and opportunity events).
8. During the discussions, and upon completion of the above review, items of work that may be missing, over- or under-estimated are identified and recorded. Estimates for missing items are developed and recommendations for adjustments are made. Finally, an agreed "base cost" is determined. This becomes the base to which the cost of potential risk and opportunity events are added by the cost/schedule uncertainty model.

Risk Identification and Quantification

The risk identification and quantification is led by an experienced risk elicitator/analyst who is familiar with uncertainty theory, de-biasing techniques and the structure of a subsequent cost and risk model. Other workshop participants include representatives from the project team who have familiarity with the plans, strategies, assumptions and constraints on the project, plus the Subject Matter Experts (SME's) who bring an independent perspective on important areas of project uncertainty.

The identification and quantification of uncertainties requires a balance of project knowledge, risk analysis expertise, cost estimating expertise, and objectivity. Project knowledge and the independent expertise of SME's are essential to identify the uncertainties. Risk analysis expertise is required to capture balanced information on risk and model uncertainties. The goal of the risk workshop is to identify, quantify and model the uncertainty in project cost and schedule. The risk identification process—preparation and workshop—includes the following activities:

1. Introduction to the participants of principles of uncertainty (risk and opportunity) assessment
2. A preliminary list of risks and opportunities, generated by the project team
3. Workshop identification of potential risks and opportunities. This is done in an open brainstorming process that typically begins with a prior list of potential uncertainties from the project team, lists from similar projects and other sources. In the workshop, it is necessary to provide a critical environment that allows for this initial information to be combined with other suggested risks. As a practical matter, the team should identify a screening criteria to help produce a prioritized list of significant cost and schedule risks.
4. Characterization of potential risks and opportunities. This process combines subjective and objective information to identify the consequences to the project if each of the risks were to occur. Typically there are varying opinions on the range of consequences, such as increased cost or schedule delay. The risk elicitator is responsible for guiding the group to an appropriate agreement regarding the consequences of the risks—i.e., probability of occurrence and impact. Independence and correlation among risks is also defined, positively or negatively or conditionally.

The risk and opportunity events that are the output of the workshop should be defined to be independent as far as possible. When this is not possible, the dependencies among events must be defined and accounted for. In addition, each risk or opportunity event must be allocated to the project activities that are affected by it or, if a given event affects multiple project activities, significant correlations among occurrences need to be addressed. Significant uncertainties and correlations among event impacts also need to be defined. This information is incorporated in the cost and schedule to produce the model results.

Risk elicitation in the workshop is an iterative process that combines subjective and objective information. Uncertainty characterizations and probabilities are defined simultaneously to provide reasonable, practical descriptions of uncertainty.

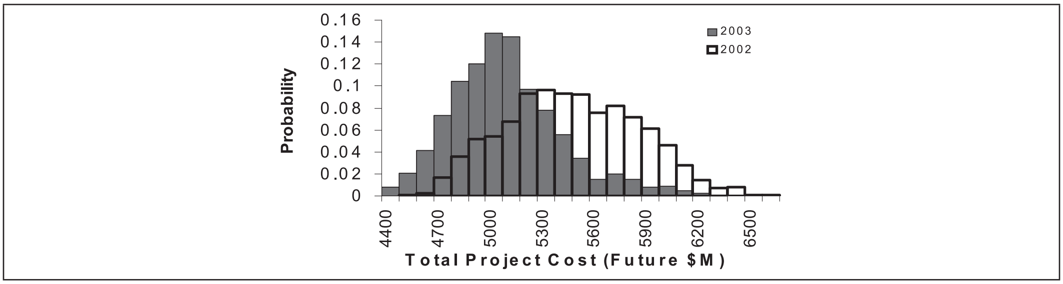


Figure 3. Improvement in probable cost for successive CEVP® workshops

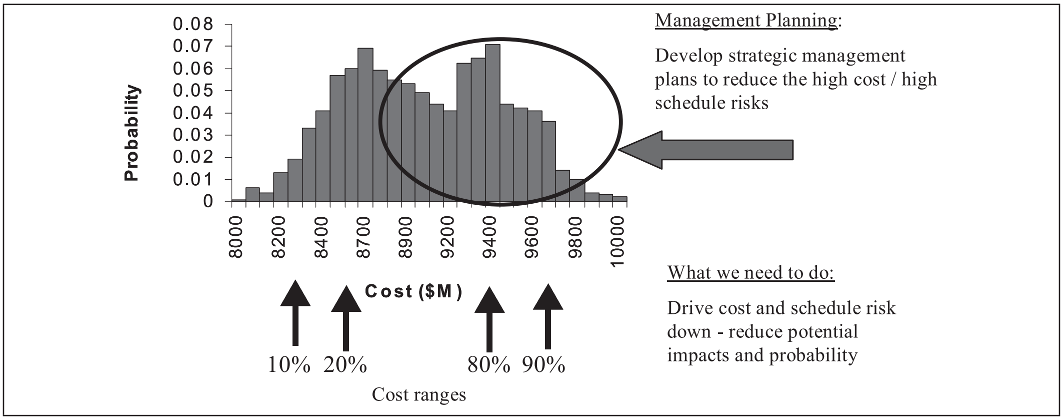


Figure 4. General risk management approach after CEVP®

Completion of the CEVP® process

The "range of probable cost and schedule" is determined by combining base costs determined from the cost validation with the risks identified in the risk workshop in a Monte-Carlo model which:

1. Integrates base costs with risks and opportunities (uncertainties) in a probalistic model
2. Reports the results as a "range of probable cost and schedule"

Results of the model analysis are presented as cost and schedule probability distributions, usually in a graphical form (Figures 2, 3) with supporting tabulations of characteristic statistics. First order descriptions and models are sufficiently accurate and are used for most projects. These distributions can describe a variety of situations of interest including:

1. Current dollar (time of assessment) cost and year of expenditure cost ($YOE)
2. Fully funded or partially funded scenarios
3. Comparative design options
4. Probable date of completion for the project
5. Probable schedule to meet project milestones

The specific form of the reported results can vary depending upon need and the results can be used for a number of applications, including:

1. Project assessment/management re-direction
2. Risk management plans
3. Data input to value engineering workshops
4. Integrated management of multiple projects
5. Better internal and external communications
6. Financial management options and alternatives

CEVP® is iterative in nature and represents a "snapshot in time" for that project and under the conditions know at that point. Changes to optimize cost or reduce risk can be verified in a reassessment of the project and model update. An example for a complex project in Seattle comparing 2003 results to 2002 shows a reduction in both probable cost and range of uncertainty by management of scope and risk (Figure 3).

RISK MANAGEMENT

Early, strategic risk management is one of the most important tools for managing cost and schedule. Referring to London's Jubilee Line Transit Project with a cost overrun of +67% the Secretary of State's

Agent (oversight consultant) stated: "Time and cost overruns could have been minimized with a more established strategy at the very beginning of the project" (Arup, 2000).

But, how to determine the "more established strategy at the very beginning of the project"?

A key output from the CEVP® assessment is a ranked listing of the risk and opportunity events contributing to the uncertainty in a particular estimate. The ranked risk table presents the most important risk issues, along with a measure of their contribution to the total uncertainty in the estimate. The variety of risks, including technical risks, policy risks, environmental risks, construction risks, etc. can be treated in a consistent way using this data.

One of the not-so-incidental benefits of CEVP® is that it provides an explicit quantification of potential risk and opportunity events that could impact the project's cost and schedule. From this quantified risk profile, risk management plans can be developed earlier in the project life-cycle. Risk management procedures are well understood and many references are available (Einstein et al., 1974; Roberds and McGrath 2005; Grasso et al. 2002; Isaksson, 2002).

CURRENT DEVELOPMENTS

CEVP® is proving to be a useful process for estimating and communicating ranges of probable costs and schedules, as well as explicitly identifying and quantifying risks for large, complex projects early in the planning and design phases. This produces better information that the public and elected officials and can be used to make more informed decisions, while allowing engineers to better manage these projects.

WSDOT has internalized the CEVP® process and uses it, and a simpler, cheaper "Cost Risk Assessment" process, for many of its projects. The U.S. Federal Transit Administration (FTA) and the Federal Highway Administration (FHWA) have each investigated CEVP and similar processes and have run demonstration projects. They have concluded that a probalistic cost-risk process, such as CEVP® or an alternative, should be used for most large, complex transportation projects.

As of this writing further demonstration projects and educational seminars are underway and several government Agencies are beginning to require the process in their upcoming projects (e.g., Florida, Toronto Waterfront) and international enquiries following presentations of the CEVP process have shown interest in its application.

FINDINGS

1. WSDOT recognized the value that cost validation and risk assessment yields in the determination of the "range of probable cost" including explicit potential risk events.
2. WSDOT found that the CEVP® results allowed a more intuitive communication with the public which better related to "…what people already know."
3. WSDOT found that CEVP® focuses early attention on the significant cost and schedule risks for a project and increases the project team's awareness of risk.
4. Use of experienced external subject matter experts, who have constructed similar projects, is good value and gives an independent check on key assumptions.
5. Because risks are explicitly defined, a risk management plan can be quantified earlier. This allows significant management and control of cost and schedule earlier in a project and allows a more explicit communication of cost and schedule (and changes thereto) with the public and key political decision makers.
6. WSDOT recognized that CEVP® is not a "magic bullet" or a "quick fix." WSDOT therefore committed to improve its cost estimating process by implementing the CEVP® program on a state-wide, long-term basis and training staff in the technique.
7. Presentation of CEVP® to the industry, including FHWA representatives, resulted in a review, assessment and recommended use of probalistic cost estimating processes by that and related agencies.

RECOMMENDATIONS

1. Owners of complex infrastructure and underground projects should consider using a probalistic cost–risk type process for cost estimates and risk identification.
2. Periodic updates to the model should be used to assist with, and explain rationally, project changes. They can, additionally, evaluate and compare alternatives.
3. The process should be used to assist owners in determining a more realistic "range of probable cost" which can enable better communication about, and management of, these projects.
4. This is only possible if the owner truly wants to know the realistic "range of probable costs," is prepared to communicate this to the public and decision makers and then will manage the projects to the subsequently established budgets.
5. It is recognized that significant concerns have been raised that, if we tell the public the more realistic probable costs, which tend to be greater than other estimates, those projects may not be funded and authorized. Such concerns imply that

we cannot trust the public with the real cost information. If true, such a position has moral implications that the profession needs to address.

6. A risk management plan should be developed and implemented using the explicit, quantified definition of potential risk events.

ACKNOWLEDGMENTS

This paper follows previous papers and presentations by the author and colleagues describing the CEVP® process. References can be found on the WSDOT website at http://www.wsdot.wa.gov/projects/projectmgmt/riskassessment.

Material from Michael McBride (formerly with MWRA Boston); Dwight Sangrey, Bill Roberds and Travis McGrath of Golder Associates (see references following) was used in this paper. The author is grateful for this input.

REFERENCES

Arup, 2000, “The Jubilee Line Extension, End-of-Commission Report by the Secretary of State’s Agent” UK Department of the Environment, Transport and Regions, July.

Einstein, H.H. and Vick, S.G. 1974, ‘Geological model for a tunnel cost model’ Proc Rapid Excavation and Tunneling Conf, 2nd, II:1701–1720.

Flyvbjerg, B., Holm, M.S., and Buhl, S. 2002, “Underestimating Costs in Public Works Projects: Error or Lie?” Journal of the American Planning Association, Summer, 2002. Vol. 68, Issue 3; pg. 279–296.

FHWA, 2006, “Guide to Risk Assessment and Allocation for Highway Construction Management,” Report FHWA-PL-06-032.

FTA, 2003, Operating Guidance Memorandum No. 22, “Risk Assessment Procedures, Requirements and Report Formats for PMO Contractor Deliverables and Services,” US DOT, November 10th.

FTA, 2004, “Risk Assessment Methodologies and Procedures,” Project No. DC-03-5649, Work Order No. 6, May.

Grasso, P., Mahtab, M., Kalamaras, G. and Einstein, H. 2002, ‘On the Development of a Risk Management Plan for Tunnelling,’ Proc. AITES-ITA Downunder 2002, World Tunnel Congress, Sydney, March.

Isaksson, T., 2002, ‘Model for estimation of time and cost, based on risk evaluation applied to tunnel projects,’ Doctoral Thesis, Division of Soil and Rock Mechanics, Royal Institute of Technology, Stockholm.

Lockhart, C. and W. Roberds, 1996, “Worth the Risk?” in ASCE Civil Engineering, April 1996.

Reilly, J.J., Isaksson, T. and Anderson, J., 1998, ‘Tunnel Project Procurement and Processes—Fundamental Issues of Concern’ Conference on “Reducing Risk in Tunnel Design and Construction,” Basel, December.

Reilly, J.J. and Thompson, 2001, ‘International survey, 1400 projects,’ confidential report.

Reilly, J.J., 2001, ‘Managing the Costs of Complex, Underground and Infrastructure Projects,’ American Underground Construction Conference, Regional Conference, Seattle, March.

Reilly, J.J., 2002, w. McBride, M., Dye, D. and Mansfield, C.—Guideline Procedure. ‘Cost Estimate Validation Process (CEVP)’ Washington State Department of Transportation, January.

Reilly, J.J., 2004, w. Brown, J. “Management and Control of Cost and Risk for Tunneling and Infrastructure Projects” Proceedings, World Tunneling Conference, International Tunneling Association, Singapore, May.

Reilly, J.J., McBride, M., Sangrey, D., MacDonald, D. and Brown, J., 2004, “The development of CEVP—WSDOT’s Cost-Risk Estimating Process” Proceedings, Boston Society of Civil Engineers, Fall/Winter ed.

Reilly, J.J., 2005, “Cost Estimating and Risk Management for Underground Projects,” Proc. International Tunneling Conference in Istanbul, May, Balkema.

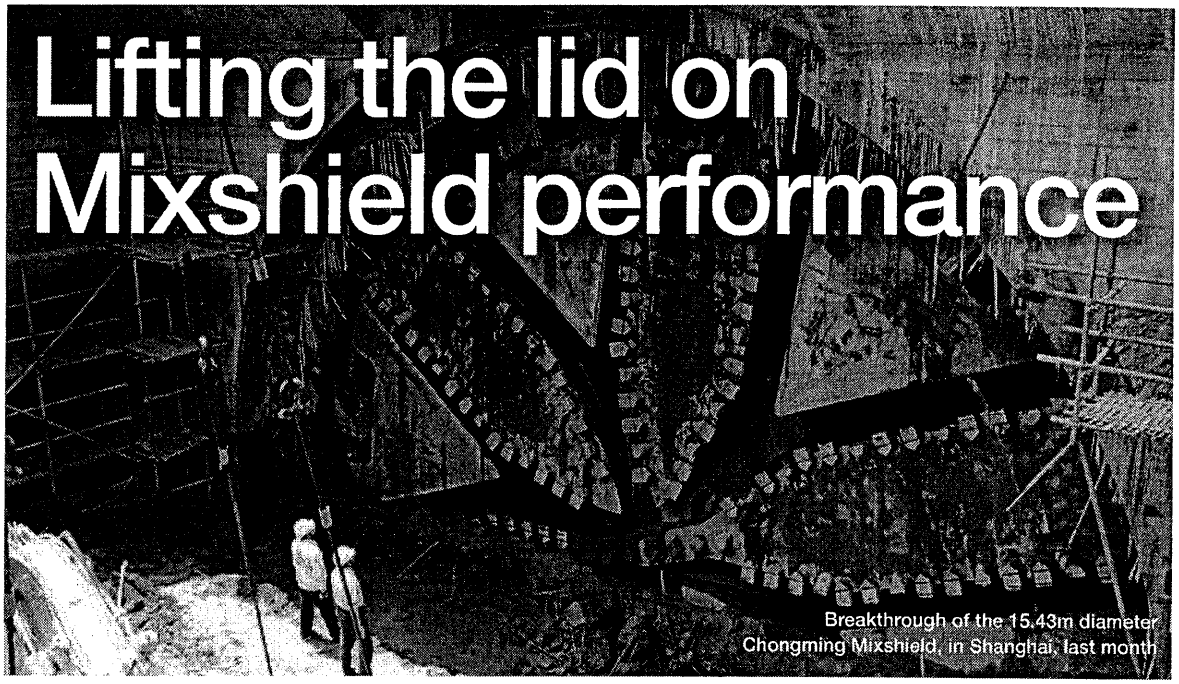
Reilly, J.J., 2006, “Risk Identification, Risk Mitigation and Cost Estimation,” Tunnelling and Trenchless Construction, April 2006.

Roberds, W. and McGrath, T., 2005, “Quantitative Cost and Schedule Risk Assessment and Risk Management for Large Infrastructure Projects,” Project Management Institute October.

Salvucci, F.P., 2003, “The ‘Big Dig’ of Boston, Massachusetts: Lessons to Learn,” Tunnels and Tunnelling, North America, May and Proc. International Tunnelling Association Conference, Amsterdam, April.

WSDOT, 2007, Guidelines for CEVP® and Cost Risk Assessment, Oct 31 2005, updated 2007 http://www.wsdot.wa.gov/projects/projectmgmt/riskassessment.

Lifting the lid on Mixshield performance



Breakthrough of the 15.43m diameter Chongming Mixshield, in Shanghai, last month

There remains much potential for the future development of Mixshields, particularly in terms of increased diameters and higher face support pressures. In part two of their article, Werner Burger and Gerhard Wehrmeyer, of Herrenknecht AG, look at two particularly influential projects and their impact on future Mixshield technology

A glance at the development of Mixshields over the past two decades (figure 8) shows an impressive increase in tunnel diameters. What's more, from a TBM technology and manufacturing point of view, there is no obvious technical limit on further increases.

Diameter increases are closely connected to the planned purpose of a tunnel. Two and three lane road tunnels have now been constructed with diameters of 11.2m (A86 Road Tunnel, Paris) and 14.2m (Lefortovo Tunnel, Moscow), and a three-lane road tunnel is currently being built in China with a diameter of more than 15m (Chongming, Shanghai).

With these diameter increases, multi-purpose or combined-use tunnels such as road/water storage (SMART, Kuala Lumpur) or road/subway (Silberwald, Moscow) are also becoming more widespread. The ability to excavate very large diameters also creates additional potential for new usage concepts, like subway station platform tunnels.

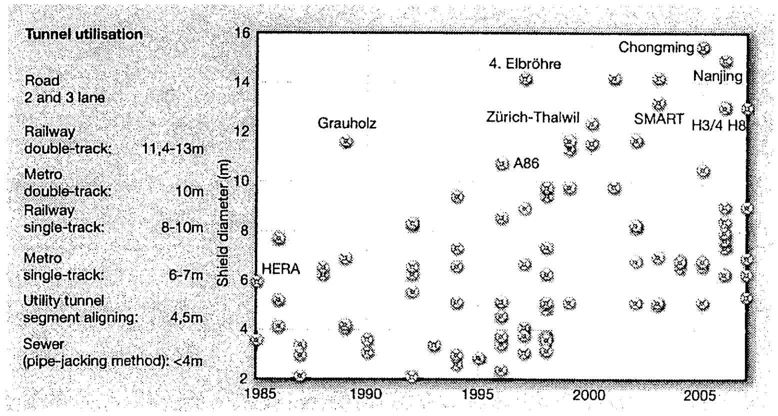
Twin-track rail tunnels with diameters of 11.4m-12.6m already exist, and the increasing speed of trains and higher demands of operational safety (emergency rescue/escape concepts) will create further need for larger tunnel and machine diameters.

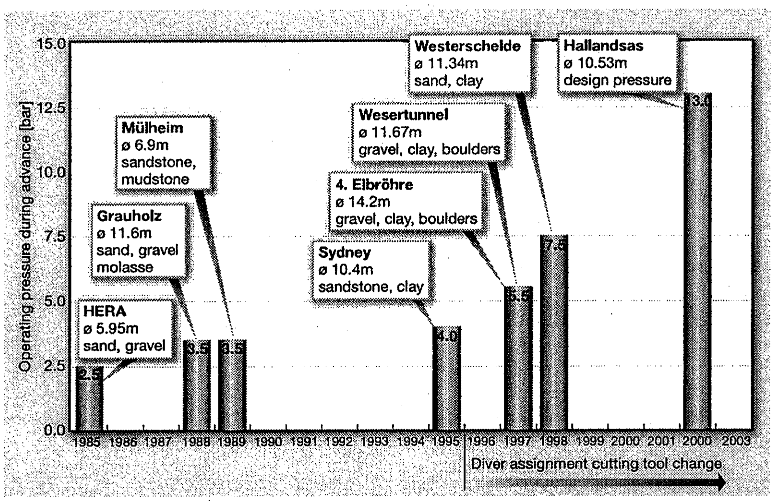
Increasing performance demands, combined with experience from past projects, has also contributed to a continued increase in Mixshield operating pressures (see figure 9). Compared with EPB machines, the Mixshield's use of a closed slurry circuit as the mucking system enables higher face pressures to be effectively dealt with. Controlling a large pressure drop in a continuous mucking system is also easier with a slurry circuit than with a screw conveyor, especially in heterogeneous or highly permeable ground conditions.

A significant increase in face pressure affects all components of the shield that are exposed to the surrounding soil or groundwater. In particular, it affects:

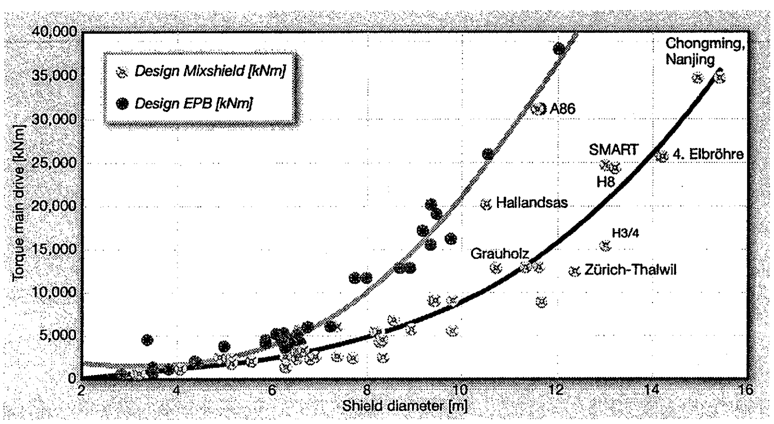
- Shield structure
- Tail seal systems
- Main bearing seal systems
- Articulation seals
- Shield thrust system
- Slurry circuit
- Equipment (and procedures) for face access

Below: Fig 8 - Diameter development of Herrenknecht Mixshields





Above: Fig 9 - Operating pressure of Herrenknecht Mixshields



Above: Fig 10 - Torque comparison of cutterhead drives (Mixshield vs EPB-shield)

While it is possible to accomplish the required shield thrust by changing the number or diameter of the thrust cylinders, far more sophisticated technical solutions are required for seal systems. This is especially true of the main bearing seal system, which is one of the most sensitive design elements in high-pressure applications. For support pressures beyond 4 bar, pre-stressed cascade systems are used with the individual cascade chamber pressures automatically following the face pressure.

These systems can handle pressures far beyond 10 bar for an extended period of time in dynamic mode without the risk of overloading the individual lip seals. Long-term field experience with large diameter drive systems (bearing diameter range of 6m) with face pressures of 7 bar to 10 bar already exist and full scale workshop and commissioning test programmes with pressures of 15 bar have been performed successfully. In emergencies or extended stoppages (long-term static mode), additional inflatable seals are included.

While it is now possible to address high-pressure operations by using appropriately designed equipment, the key questions relate more to the potential and the limitations for chamber access under hyperbaric conditions.

Technical solutions to reduce the need for man access to the excavation chamber are available and currently include:

- Accessible cutterheads for atmospheric cutter tool change (larger machines only)
- Remotely activated standby cutter tools
- Load detection and wear sensor systems

However, these technical features will not totally eliminate the need for a "Plan B" for manual intervention to cover unforeseen conditions or worst-case scenarios.

Based on the system of excavation and face support, a Mixshield requires lower cutterhead torque compared with an EPB shield (figure 10), as the cutterhead is only excavating the ground at the tunnel face into the suspension-filled excavation chamber. The excavated soil sinks towards the submerged wall opening in the invert due to gravity, assisted by the flow direction of the circulated slurry, and is carried to the suction pipe after clearing the rock crusher and suction grille.

An EPB shield requires a comparatively high torque at the cutterhead because, in addition to the soil excavation, the cutterhead itself acts as a mixing tool inside the excavation chamber, which is completely filled with muck.

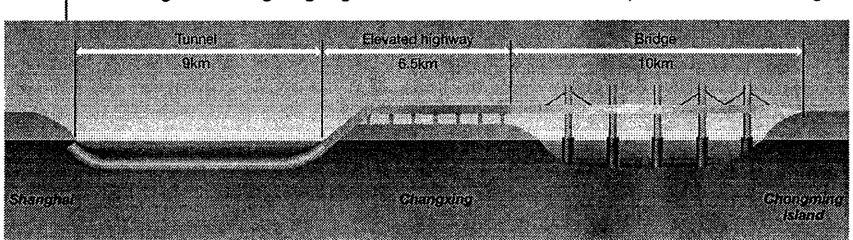
Therefore by adopting high torque EPB drive systems that have been developed for large diameter machines, such as that used on the M30 project, in Madrid (with 125,000kNm), there is huge potential for the development of larger diameter Mixshield machines.

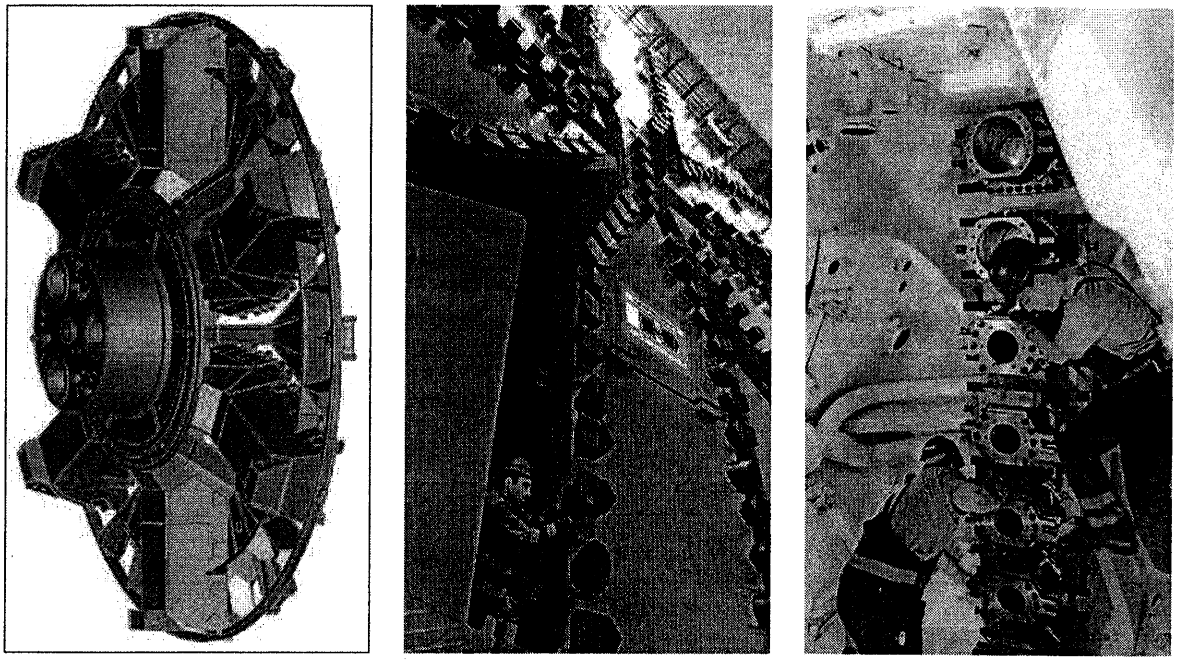
Examples of projects

The following presentation of the Chongming and A86 tunnel projects demonstrates the efficiency of current Mixshields and the value of development.

Mixshield used as a shield with slurry supported face – Chongming, China: A twin tube road tunnel is currently being built beneath the Yangtze River in the city of Shanghai, comprising two 7160m-long bores with three lanes each. The tunnel, along with a new bridge, will link the islands of Changxing and Chongming to the freeway system and city. The geology of the tunnel is defined by its position in the river delta, consisting of soft clay deposits and thin sand layers. The tunnel has an outside diameter of 15m. The pre-cast concrete ring consists of 9+1 segments with a length of 2m. The segments are 640mm thick and weigh up to 16.7 tons. The basic concept of the two Mixshield machines for the project is based on experiences from the Mixshield used at

Below: Fig 11 - Chongming alignment





Above: Fig 12 - Accessible cutterhead: Design (left); front view (middle), view from inside (right)

the fourth Elbe Tunnel and advancements in large diameter shield developments in high water pressure conditions. With a shield diameter of 15.43m, the two machines are currently the world's largest diameter shields.

The Mixshield machines have following technical features:

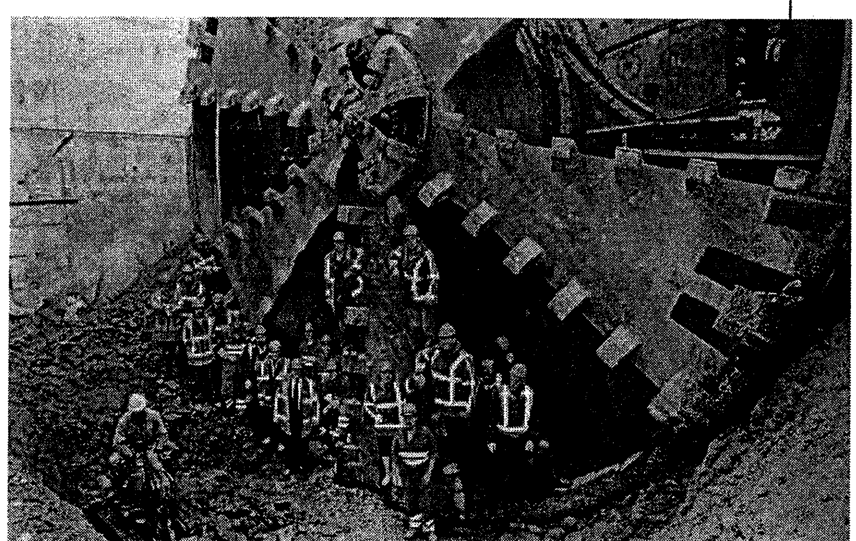
- The shields are designed for an anticipated operational pressure of 6 bar at springline level. Due to the underwater application, and nearly straight alignment, (Rmin = 4.000m), a shield articulation joint was not included
- The invert area of the Mixshield is equipped with two agitator wheels (Ø1.900mm), which assist the material flow to the grille and a 500mm diameter suction pipe. Submerged wall gate, bentonite nozzles, cutting wheel and extensive excavation chamber flushing arrangements complete the Mixshield configuration to address the soft soil conditions and potential clogging risks
- The double shell tailskin with integrated grout lines has a three-row wire brush seal and an inflatable emergency seal system. Furthermore, freezing lines are integrated into the tail shield, which, in case of emergency, can be used for ground freezing around the machine to minimise the risk of water inrush during brush seal changes or repair works
- The cutterhead is designed with six main spokes accessible under atmospheric pressure. To reduce the need for pressurised face access, one complete set of cutting tools (covering the entire face area) is exchangeable under atmospheric conditions from within the cutterhead spokes. To suit to the anticipated geology, the cutterhead was equipped with massive scrapers. Two hydraulically operated overcutters can create an overcut of 40mm in radius. The cutterhead front and outer areas, as well as the rear, are designed to be durable and wear resistant to cope with the single drives of more than 7000m (see p31).

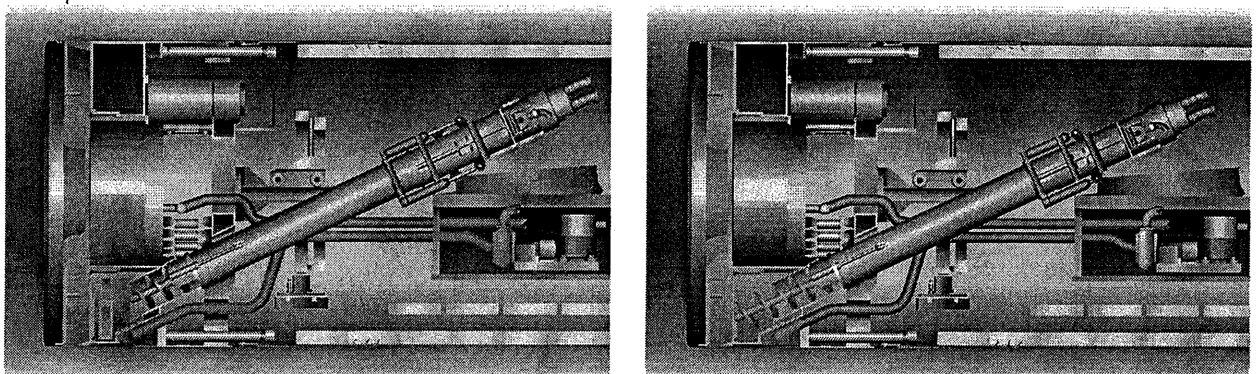
As an additional safety feature, the Mixshields are equipped with all components – such as air locks and installations – necessary for pressurised face access including saturation diving activities.

The installed cutterhead drive power is 3750kW and the bearing diameter is 7.6m. The torque of the variable frequency electrical drive is 34800kNm, the shield thrust capacity is 203000kN and the TBM system is designed for a nominal mining speed of 45mm/min.

The three-section backup system has an overall length of 118m and is divided into primary backup, bridge section and

Below: Breakthrough of the Westerschelde machine, in The Netherlands





a) Operation mode slurry

b) Operation mode EPB

Above: **Fig 13 - Machine concept of the A86 Mixshield, used in Paris, France**

secondary backup.

The primary backup, or first three-deck trailer, contains all the hydraulic power packs and electrical systems for the supply and operation of the shield, along with slurry pumps and backfill grout system. For an even distribution of the wheel loads the trailer contains an integrated support system of auxiliary rail elements (steel invert slabs) and multi-wheel sets. The prefabricated 35 ton invert elements are installed in the area under the 67m bridge section. The supply crane system is installed inside the bridge cross-section to transfer segments, grout and other consumables to the TBM. All installations and workplaces for extension of services are located in the third section, along with ancillary equipment.

The machine is supplied with segments and grout by rubber-tired transport vehicles, which travel in convoy and carry either segments only or segments and grout tanks. The segment transfer on the backup is done by segment crane and a segment feeder. The grout is supplied in transfer tanks to the first backup.

The shield structures and assemblies of the 132m-long and 2,300 ton TBMs were manufactured in Shanghai. Cutterheads and other main components such as drive assemblies and thrust cylinders were manufactured in Germany and shipped to China. After shop acceptance, the TBM was disassembled and transported to the start shaft about 6km from the workshop.

Tunnelling started for the first tube in September 2006, and in January 2007 for the second. In March 2008, the first 7160m tunnel was about 90% complete and the second about 70%. Constant weekly performances of 90-120m are now being achieved by each TBM. Both drives are scheduled to finish in 2008 (the first TBM in May, and second in September), almost a year ahead of the project schedule.

Mixshield used in differing operational modes – A86 tunnel: To close the gap in the A86 orbital motorway, a 10.1km-long, two-deck road tunnel for cars has been built to the West of Paris. A second tunnel for trucks is planned for construction at a later stage. Two levels, with three lanes each, require an outer diameter of 11.565m. The tunnel crosses the entire spectrum of geological formations under Paris: Marl, clay, limestone, chalk and sand as well as three different groundwater levels. For optimum adaptation to the geological conditions, the machine had to operate in different modes:

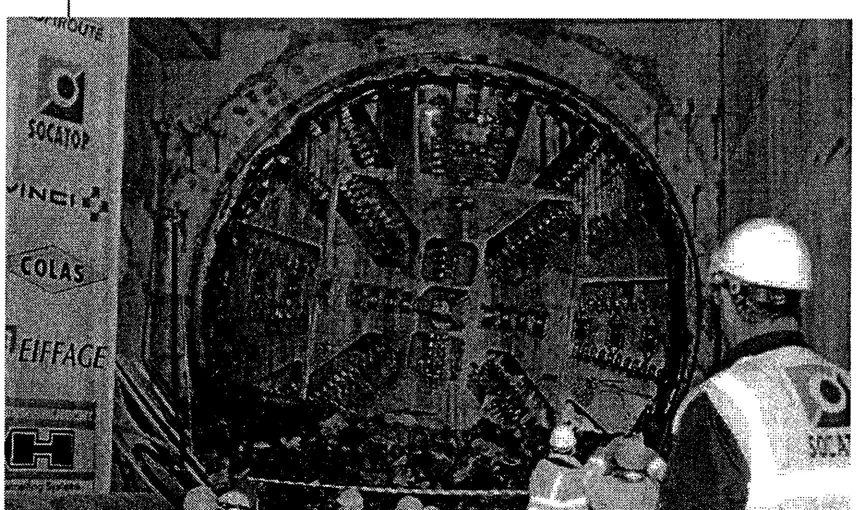
- As slurry shield with slurry supported face (slurry operation - see figure 13a)
- As earth pressure balance (EPB) shield with face support provided by conditioned muck (see figure 13b)
- In Semi-EPB, or compressed air, mode
- In open mode (muck discharge via screw conveyor, non pressurised excavation chamber)

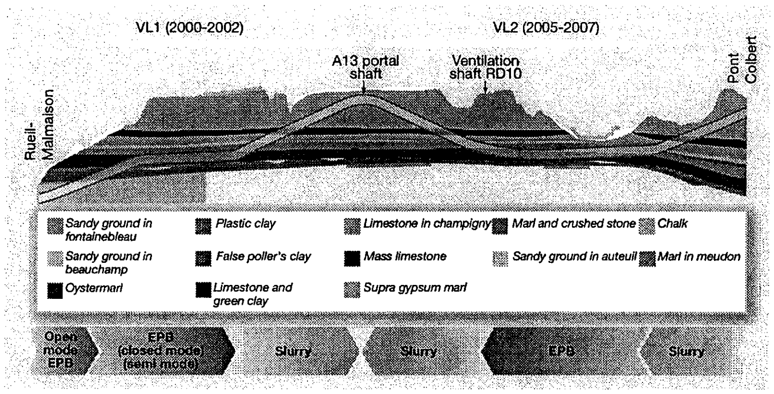
The change between different operational modes is carried out within the tunnel. Shield and backup are equipped with the full range of equipment for each mode. For slurry mode, this included a full slurry circuit with submerged wall/pressure wall installation and also a rock crusher. For EPB mode, components such as screw conveyor and TBM conveyor were installed.

The cutterhead is designed for use in all modes of operation without the need for modification. The cutterhead concept is a closed wheel type with a full set of mixed tool equipment including 17" backloading disc cutters and ripper tools for two directions of rotation.

In slurry mode, the excavation chamber and the lower part of the pressure chamber are filled with bentonite slurry; the upper part of the pressure chamber contains the air bubble, and the entire area is pressurised. In EPB mode only, the excavation chamber is pressurised so the submerged wall becomes a pressure bulkhead. The pressure chamber is then at atmospheric pressure and can be used as a working chamber, only pressurised during

Below: **The A86 machine breaks through**





Above: Fig 14 - A86 Tunnel alignment

face access. To change from EPB to slurry mode, the entire screw casing is moved back, thus clearing the submerged wall opening in the invert and the suction grille below. After this, a specially designed jaw crusher moves from parked position to operational mode.

Some of the slurry mode installations, such as the air bubble pressure regulation system or the bentonite circulation systems, can also be used in EPB mode when required. Having the two systems permanently available provides potential synergy.

Apart from the ability to change modes of operation, the TBM also has the following technical key features:

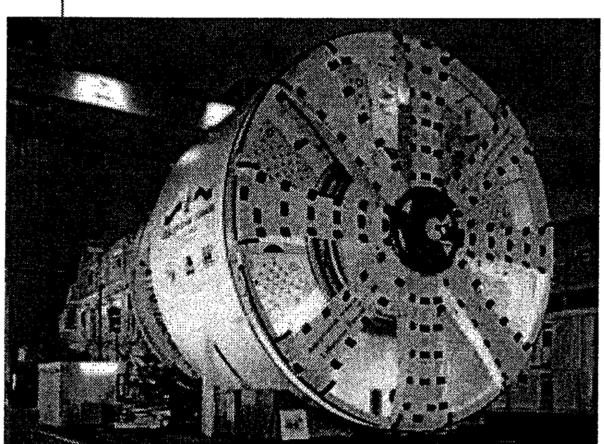
- To cater for EPB mode, installed cutterhead power is 4000kW and the available cutterhead torque is 35000kN/m. Shield thrust is 150000kN, and the designed advance speed is 80mm/min
- The slurry circuit with 1900m³/h flow volume is designed for a mining speed of 50mm/min in slurry mode. The tunnel is runs uphill and the largest difference in height between portal and TBM is 160m. This configuration needed to be addressed in the design of the slurry circuit as, under some conditions, the friction losses in the discharge line are less than the geometrical height between TBM and treatment plant
- A specially designed camera system for the excavation chamber was installed for the first time and successfully tested in semi EPB/compressed air or open mode
- Due to the steep tunnel gradient of 4.5% rubber tired vehicles were used for segment and grout transport. At the tunnel portal a semi-automatic loading station for the vehicles was installed loading one complete multi stack truckload at the same time, which together with a quick unloading system in the gantry reduced the turnaround cycles

The pre-cast invert slab elements for the final lower road deck were installed 200m behind the trailing gear, concurrent to the advance of the TBM. In November 2000, the machine started excavating the VL1 tunnel (figure 14) in open mode EPB configuration. The first 150m in an incomplete starting configuration through chalk containing a high amount of flint was excavated in two-shift operation, quickly reaching mining speeds of 80mm/min. After having installed the TBM and portal systems in their final configuration, the operation was changed to three shifts.

Following a fire in the rear section of the tunnel in 2002, mining activities were halted for three months. By October 2002, the TBM was operated in open mode, closed mode EPB with face pressures of 1-2 bar and semi EPB mode. The semi EPB mode proved to be the most appropriate method for excavating the stable but water bearing material, using the compressed air to control the water and achieving dry excavated material.

With the ground conditions changing into Fontainebleau sand, the machine was changed in-tunnel to slurry mode and operated in that mode for one year achieving mining speeds of 50mm/min. The breakthrough of the first tunnel was in October 2003. The TBM was disassembled, transported and reassembled at the Pont Colbert starting portal for the VL2 tunnel.

For the VL2 tunnel the TBM began excavation in slurry mode. Immediately, around 10m after the portal, a major six-lane motorway had to be passed beneath with shallow cover. Launch and passing under the freeway was completed after just nine days with no problems. After 1.2km in slurry mode, the TBM was changed back to EPB mode, and after passing an escape and ventilation shaft at the deepest point of the VL2 tunnel the TBM mode was changed back to slurry again. The machine arrived at the portal in August 2007.



Left: **The 14.2m diameter Lefortovo Mixshield, before it was shipped to Moscow, Russia**

Conclusion

Initiated by the requirements of numerous large scale projects around the world, the development of Mixshield technology has taken major steps forward, as illustrated in this and the previous article (*T&TI*, May p35). Numerous additional features are also currently on the drawing board or being used for the first time. These include:

- Advanced wear detection systems for cutting tools and structure
- Positive ground support of the tunnel wall along the shield skin
- Advanced ground improvement scenarios for closed mode from within the machine
- Total integration of the whole package of above ground and underground measurement, process and alignment control data for a controlled boring process (CBP)
- Approaching diameters of 18m to 20m
- Fully variable, multi-mode concepts (EPB/HD slurry/LD slurry)

The ability to handle high water pressures, the potential for crusher installation, low power requirements, high accuracy of face pressure and settlement control, and favourable face configurations, are just some of the current advantages of Mixshield technology. The combination of these advantages along with the ability to change modes of operation, brings the concept close to combining the best of both worlds. Nevertheless, there is also still huge potential for future development of the technology, that will see even greater tunnelling challenges conquered. T&T