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Sydney Metro – ground characterisation and TBM selection for the Sydney Harbour crossing

The Sydney Harbour crossing is a key element of Sydney Metro City & Southwest, which includes 15.5 km of twin tube running tunnels extending from Chatswood at the north through to Sydenham, south of the Central Buisness District (CBD). One of the key features is the 1 % length of the alignment that passes under Sydney Harbour. The rest of the alignment is through rock, but the harbour crossing is designed to pass through harbour sediments and mixed face conditions undersea. An in depth study and analysis was required to confirm the feasibility of the safe construction of this short length of the tunnel in sub-aqueous, soft ground conditions. It was necessary to carry out detailed, targeted investigation of the ground to enable the selection of an appropriate tunnelling technique for constructing the tunnels.

1 Introduction

Sydney Metro is Australia's biggest public transport project. Stage 2 of the program, the Sydney Metro City & Southwest project, will extend metro rail from the Northwest Sydney, under Sydney Harbour, through new underground CBD stations and beyond to the Southwest. A critical element of this project is tunnelling beneath Sydney Harbour.

The Sydney Metro City & Southwest will consist of two 15.5 km rail tunnels running from Chatswood to Sydenham. At the commencement of the Scoping Design phase for Sydney Metro City & Southwest, it was anticipated that the tunnels would be driven through rock using tunnel boring machines. A critical element of this project is the Sydney Harbour crossing, between Blues Point, on the North Shore and Walsh Bay at the north of the Sydney CBD (Figure 1).

Extensive site investigation finally revealed the existence of a deeply incised palaeovalley within the Hawkesbury Sandstone bedrock, infilled with dominantly marine soils. This required the designers to consider crossing under the harbour through mixed face conditions and soils in the undersea stretch.

This paper describes the geotechnical characterisation of the harbour crossing focusing on TBM selection and risk assessment for the tunnelling method under the iconic landmark that is Sydney Harbour.

A detailed study of the tunnelling methodology was necessary at the Reference Design stage in order to confirm feasibility, assess costs and determine inputs for the Planning Approval process.

2 Geotechnical characterisation of the harbour crossing

Limited geotechnical information existed about the harbour prior to commencement of the concept design. As such, detailed geophysical and geotechnical investigations to facili-

Fig. 1. Location plans: City section of Sydney Metro tunnel alignment & harbour crossing alignment between Barangaroo North and Blues Point.

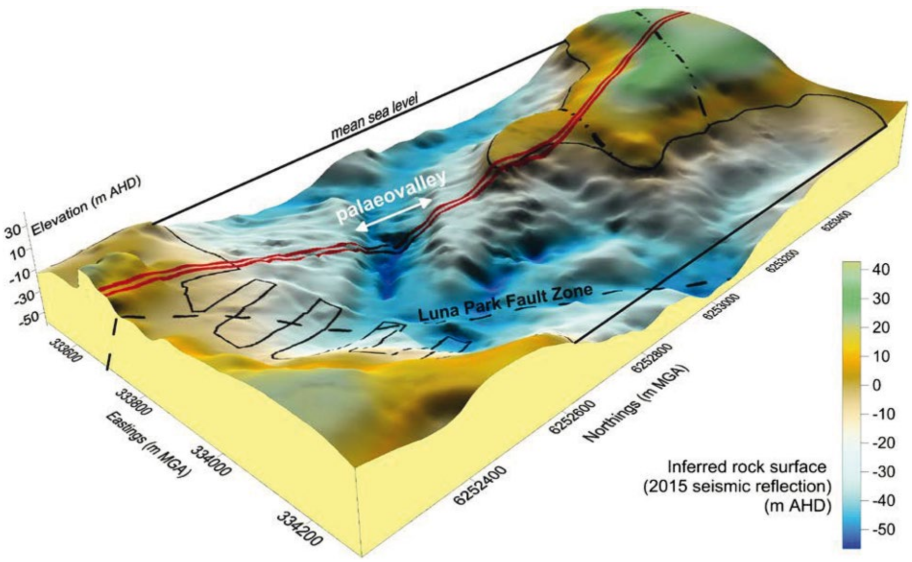

Fig. 2. Palaeogeographical rock surface from Stage 2 Seismic Reflection Survey (projected alignment in red) [1]

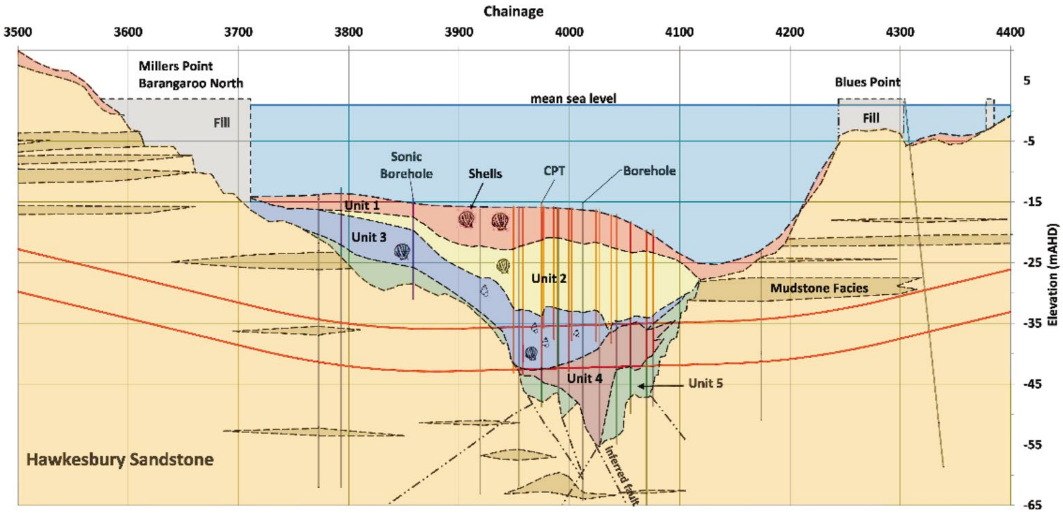

Fig. 3. Interpretative geological long section of the conditions along the proposed harbour crossing [2]

tate early planning and design work were undertaken on behalf of Transport for New South Wales (TfNSW). Staged site investigations were conducted concurrently with the concept design phases, which enabled their adjustment as the geological interpretation and concept design developed. The investigations were planned to characterise both the soil and rock formations below the harbour floor, to enable their classification into geotechnical units. The interpretation of these units was considered to be critical to design development and the identification of the geotechnical risks associated with tunnelling below the harbour [1].

2.1 General characterisation

Geophysical surveys prior to any geotechnical intrusive investigation identified the presence of a deeper palaeovalley than previously identified by *Lean* (Figure 2). This was followed by detailed geotechnical investigations to assess and correlate depth of rock with the geophysical surveys. The investigations defined a deeply incised palaeovalley, infilled by dominantly marine sediments and assisted in the definition of the sediments. The main characteristics of the palaeovalley are:

- Northwest to southeast axis orientation,
- Maximum width of approximately 160 m,
- Maximum depth of around 55 m below sea level,
- Deepest infill thickness of 38 m.

2.2 Geotechnical units

Figure 3 presents the interpreted longitudinal section along the running tunnel alignment. Soils encountered during the site investigation have been divided into five geotechnical units, which are described below. The grain size distributions are plotted in Figure 4. Units 1 and 2 are located above the tunnel crown. Units 3 to 5, as well as the sandstone bedrock will be variably encountered on the tunnel face [1].

Unit 1 forms the present seafloor to a depth of 11 m. This loose/soft layer consists of clayey silt (50 %) interbedded with fine to medium silty sand (50 %) with shells (Figure 4a). Unit 2 consists of medium dense to dense, medium grained sand (70 %) that is relatively clean and well sorted (Figure 4b).

Unit 3 consists of a firm to very stiff clay and silty clay (80 %) with some interbeds of sandy fines and shells (Fig-

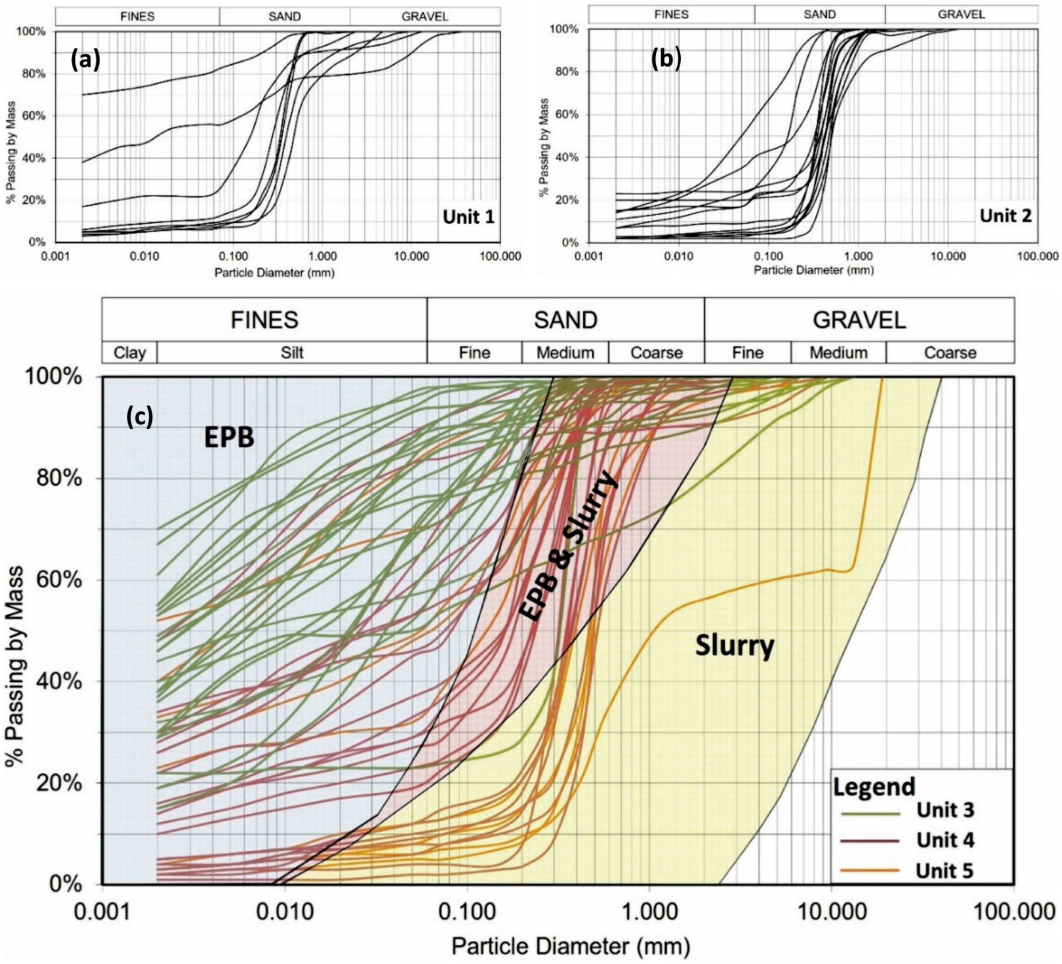

Fig. 4. Particle size distributions of the harbour sediments Unit 1 and Unit 2 with the particle size distribution plot combined at the tunnel level for Units 3, 4 and 5 for closed face TBMs (after [3]).

ure 4c). Unit 4 consists of silty sand (70 %) with interbeds of silty clay (20 %) and includes sub-rounded gravels, charcoal layers and wood fragments (Figure 4c). From the CPT data, the sand is interpreted to be typically dense to very dense interbedded with stiff to very stiff clay. Unit 5 is interpreted as colluvium. This layer is composed of cohesive "dirty" sands (70 %) interbedded with fines (30 %) and with sub-rounded to angular cobbles and boulders of sandstone, charcoal and wood fragments (Figure 4c). CPT and laboratory classification results indicate the soil component to be similar to Unit 4. The occasional residual soils are incorporated in Unit 5 material.

2.3 Bandwidth of geotechnical parameters

A compilation of the relevant geotechnical parameters to be encountered at the tunnel face can be found in Table 1. The Atterberg limits (Figure 5) tend to show that Unit 3 materials generally have medium to high plasticity. Some low plasticity values were recorded, but these are likely to be due to some sandy layers within the unit. Units 4 and 5 were grouped due to their similarity and the limited data associated with each unit. These units are dominantly low in plasticity with some medium scatter.

Based on the values highlighted in Figure 5 the potential for clogging is analyzed according to [4]. Figure 6 and Figure 7 show the ranges of the liquid and plastic limit. Only a small part of the ground of Unit 3 has high clogging potential and even less for Unit 4.

3 Selection of vertical alignment

Based on an evolving understanding of the rock level below the harbour, the design team needed to re-evaluate the alignment design concept through the harbour. It became apparent that an alignment that remained in rock in order to enable the use of an open face type of TBM would drive deeper station depths both sides of the harbour, with unacceptable impacts on the Metro Product and Customer outcomes. Furthermore, it was expected that even a comparatively deep alignment through rock would encounter highly fractured fault zones below the palaeovalley with possible hydraulic connectivity to the harbour, potentially necessitating closed face TBM technology regardless.

Therefore a tunnel alignment that passed through the soils and through the respective rock/soil transitions was assessed. The tunnelling method and risks that arise compared to excavation in full face rock were eventually classified as feasible and manageable. Additionally, the tunnel alignment was adjusted to be aligned roughly perpendicular to the main axis of the palaeovalley. This allows the minimisation of the distance excavated in mixed face conditions of rock and soils.

Table 1. Range for main geotechnical parameters for the material to be crossed

Rock	**Rock**		
Weathering grade	Fresh		
UCS [MPa]	19.7 – 39.9		
RQD [%]	90		
RMR [–]	71 – 78		
Acting water pressure tunnel crown [bar]	3.6		
CAI [–]	1.5 – 4 (avg. 3)		
Soil	**Unit 3**	**Unit 4**	**Unit 5**
Fines in % (< 0,06mm)	94 (avg. 61)	< 45	< 10
Dry density [t/m^3]	1.25 – 1.28	1.2 – 1.43	1.2 – 1.8
Saturated unit weight [t/m^3]	1.54 – 1.92	(2.06 – 2.31)	(2.22)
Pore content	0.28 – 0.64	0.33 – 0.92	0.4 – 0.7
Cohesion [kPa]	3 – 23.2 (avg. 13.3)	20.9	
Friction angle [°]	17.2 – 23.3	27.7	
Earth pressure coefficient at rest [K_0]	0.6 – 0.95	0.64	
Permeability [cm^2]	$2.1 \cdot 10^{-8}$ – $2.2 \cdot 10^{-7}$		
Acting water pressure tunnel crown [bar]	3.4 – 4	4.2	3.4 – 4.2
Liquid limit [%]	46 – 70 (avg. 57)	22 – 46 (avg. 36)	
Plastic limit [%]	22 – 29 (avg. 26)	13 – 27 (avg. 21)	
Water content [%]	39 – 56	32.3 – 44.4	
Consistency index	0.0 – 0.4		

During the assessment of the tunnelling strategy, the adoption of an immersed tunnel (IMT) lying on the sea bed was assessed, as it offered the shallowest rail alignment option. However, this option was finally discarded since it became apparent that factors other than tunnel grade were dictating station depths. Additionally, the results of contamination testing revealed the presence of raised levels of mercury within the upper marine sediments. These would be disturbed by the dredging works associated with an IMT approach.

4 Major concerns and risks

The following concerns and risks were assessed in detail during the the feasibility study of the shield tunnelling option for the harbour crossing:

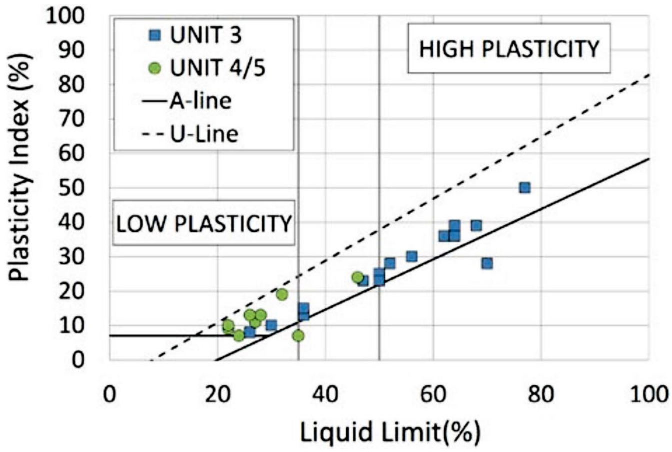

Fig. 5. Atterberg limits of Units 3 to 5.

- Unstable ground conditions, both at the transitions and in the central soft soil sections,
- Handling mixed face conditions at the rock/soil transitions,
- Realisation of hyperbaric interventions under high hydrostatic water pressures,
- Low cover of rock and low cover to the sea bed, specially close to the northern transition zone,
- Difficult access from the surface (off-shore) if any ground improvement treatments are required,
- Higher loads on the segmental lining compared to the rock stretches.

Table 2 summarises the concerns and risks that the abovementioned aspects pose for shield tunnelling together with the available mitigation options.

5 Selection and application of the tunnel boring machine

The pressurized shield technologies available to handle the expected conditions are discussed next, together with the assessment on their suitability for the harbour crossing. The estimated excavation diameter at the tender stage is around 7 m.

5.1 Slurry shield

Slurry shield technology provides face support by a pressurised fluid. Muck conveyance takes place hydraulically (Figure 8) with a separation treatment plant is installed at the surface. Stones, small boulders or rock blocks that could eventually block the hydraulic circuit must be crushed down to small sizes by means of the installation of a stone crusher in the working chamber.

Tables 3 and 4 present the selection criteria and the main application field of a slurry shield machine. The DAUB recommendations [5] rate the applicability of slurry shields based on key features of the expected ground conditions.

5.2 EPB shield

The face is supported by the excavated muck, which is conditioned and compressed in the excavation chamber to apply the confinement pressure that supports the tun-

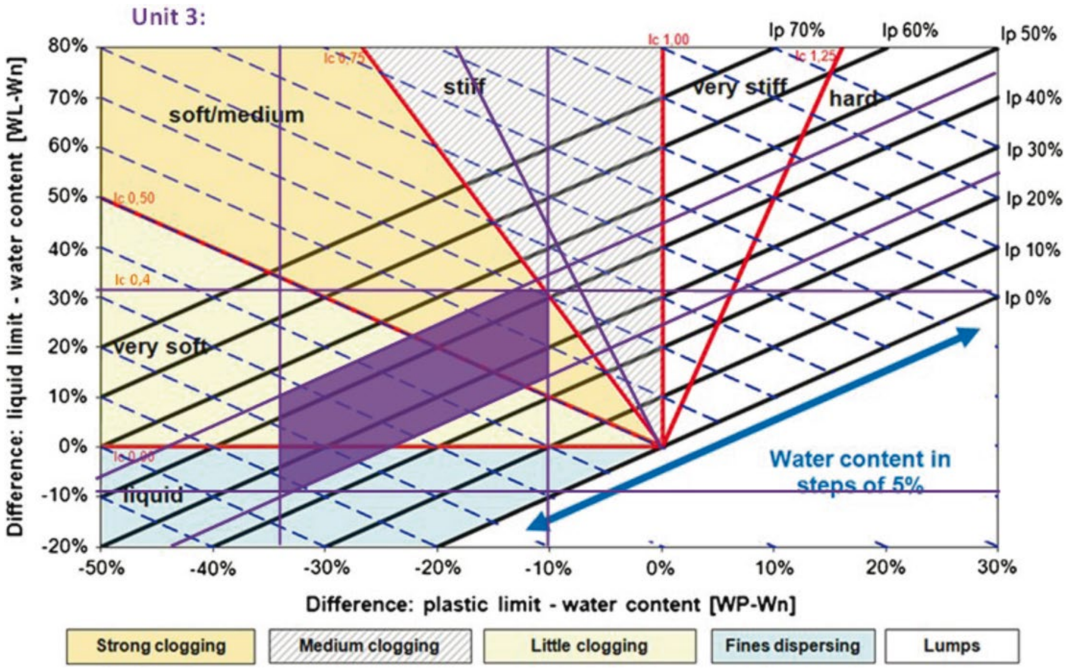

Fig. 6. Clogging potential of soil Unit 3

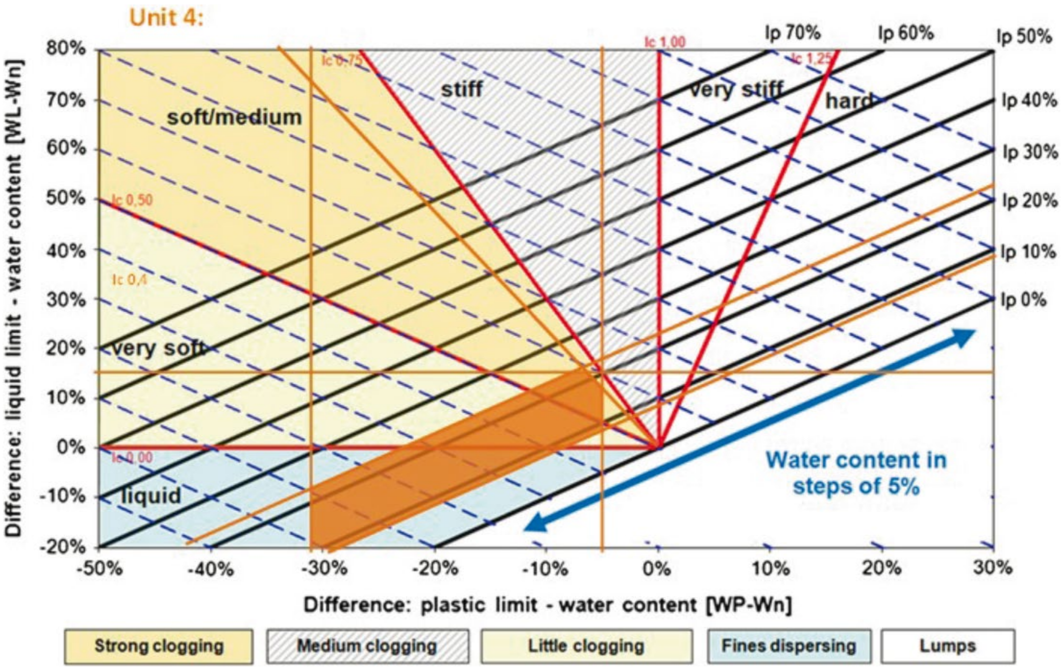

Fig. 7. Clogging potential of soil Unit 4

nel face. The muck is extracted from the excavation chamber by means of a screw conveyor turned at a controlled speed to maintain the required confinement pressure in the excavation chamber.

Tables 5 and 6 rate the applicability of EPB shields according to DAUB recommendations [5]. In particular the expected high confinement pressures put the EPB technology in disavantage compared to slurry shield technology.

5.3 Convertible shield

Convertible TBM technology would allow working in open mode with a belt conveyor installed to the central excavation chamber. This provides high performance rates when excavating in sound rock conditions, compared to EPB and slurry technologies. Convertible TBMs have the capability of changing to pressurized mode for the stretch to be excavated in soils. However, the gain in performance in the short rock stretches would not be balanced by the time needed to convert from open to closed mode and later from closed to open mode for the excavation of the soil stretch. Additionally, two muck conveyance systems would have to be installed in the tunnel, belt conveyor for the excavation in rock and hydraulic conveyance for the excavation in soils. Also due to geometrical restrictions, convertible shields generally require diameters greater than approximately 6.5 m.

Table 2. Summary of concerns and risks

Category	Concern/Risk	Mitigation options
Unstable mixed face and soft soil conditions and high hydrostatic water pressures	Full face soft soil tunnelling with high face support pressure. Estimated support pressure at crown around 4.2 bar.	Use of pressurised shield technology capable of handling this magnitude of pressures if soft cohesive and granular soils. Raising vertical alignment will allow to reduce pressures. However, face stability and blow-out assessment required
	Tunnelling in heterogeneous mixed face conditions leading to difficulties in face support control with high face support pressure	Use of pressurised shield technology that allows to safely handle transition zones. Raising vertical alignment will allow to reduce pressures. However, face stability and blow-out assessment required. Execution of ground treatments at the transition zones in order to minimise risk of face unstabilities.
	Hyperbaric interventions with high compressed air pressures in full face soft soil	State of the art shield technology is prepared to assure safe conditions for preparation and execution of hyperbaric conditions. Face stability and blow-out pressure analysis required.
	Hyperbaric interventions with high compressed air pressures in the transitions	Due to presence of heterogeneous material (sand, gravel, cobbles, boulders) in the transition (Unit 5), the feasibility of hyperbaric interventions with no ground treatment must be assessed. Otherwise ground treatment options to be evaluated. Face stability and blow-out pressure analysis required.
	Working procedure with high hyperbaric pressure	Depending on compressed air working regulations, hyperbaric intervention with mixed gases might be required. TBM equipment to be adjusted accordingly.
	Thickness and reinforcement of the segmental lining design for the soft soil stretch	Segmental lining thickness and reinforcement to be reviewed for soft soil conditions (poor bedding) with low cover (low axial compression of the ring).
Mixed face conditions in the transitions	Mixed face conditions in abrasive hard rock leading to high tool wear	Adequate tool equipment and shield operation to minimise wear and damages. Plan tool inspection and replacement in hyperbaric conditions prior and after the two transition zones. If high tool wear occurs, then additional intervention along the transitions might be necessary. Abrasiveness and strength of the Hawksberry Sandstone at harbour crossing to be further evaluated.
Low cover of rock and low cover of sediments to the sea bed	Minimum cover to sea bed	Definition Design establishes 1.5 × D (11 m). Operating with pressurised shield tunnelling technology minimum cover to sea bed could potentially be reduced. However, face stability and blow-out pressure analysis required.
	Minimum cover of sandstone	Definition Design establishes that TBM stays with at least 1 m of rock cover. Operating with pressurised shield tunnelling technology minimum rock cover 1 m is feasible as long as the minimum cover to sea bed is granted.
No access from the surface	Very difficult to carry out corrective measures if difficulties occur in the shield tunnelling process	Selection of appropriate shield technology Foresee ground treatments if there are doubts on the capacity of shield tunnelling technology to handle the expectable ground conditions regarding excavation and advance as well as hyperbaric interventions.

5.4 Hybrid shield

The combination of typical EPB shield screw conveyor muck extraction from the chamber with fluid muck transport is succesfully taking shape in shield tunnelling with the hybrid EPB technology [6] [7] [8] [9]. Behind the screw conveyor, a pressurised slurryfier box is installed. With this system, safe operation with high pressures is feasible with no risk of pressure losses. From the slurrifier box, the muck is then transported hydraulically. To handle the muck from this point, several options come into question:

- Pumping muck to shaft for separation treatment at the surface plant,
- Pumping directly to muck cars or belt conveyor at the TBM gantry if consistency allows it (e.g.soft silts and clays),
- Small separation plant at the gantry to allow transport of the solid part by belt conveyor or muck cars to the tunnel portal. The liquid part can be pumped using smaller pumps than those used in slurry shield technology. Shield performance is reduced in the stretch excavated in soils due to the limited capacity of the small

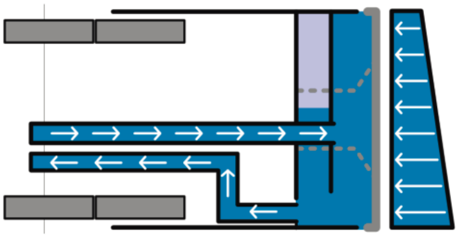

Fig. 8. Scheme of a slurry shield TBM

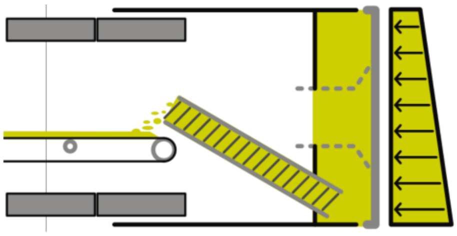

Fig. 9. Scheme of an EPB TBM

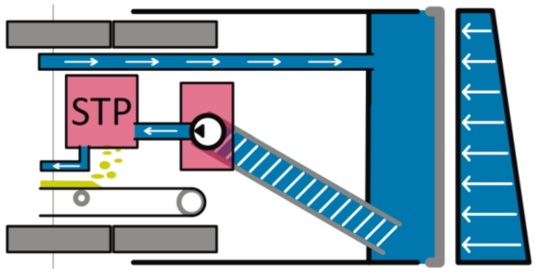

Fig. 10. Scheme of a hybrid TBM with separation plant at the gantry

separartion plant. However, with this option no separation treatment plant is required at the surface, providing considerable space saving for jobsite installations.

5.5 Comparison and suitability assessment of the TBM technologies

Table 7 presents a comparative suitability assessment of the available shield technologies that came into question for the harbour crossing. Slurry shield technology was ranked in first position since it is a long- proven technology to manage high face support pressures. It also represents the option offering a higher guarantee of success for crossing transition zones and potential boulders. The main advantage of hybrid EPB shield technology, ranked in second position, lies in the fact that no spoil separation is needed in the rock section, where muck conveyance can take place conventionally by belt or muck cars.

6 High pressure compressed air works

The major risks and concerns listed in Section 4 can be overcome with the appropriate selection of a TBM as discussed in Section 5. Regarding the realisation of hyperbaric interventions, particular considerations apply under the high water pressures expected, which will require interventions to be carried out at compressed air pressures between approximately 3.5 and 5 bar.

Work in compressed air at pressures above historical statutory limits, which in many countries are between 3 and 4 bar (gauge), can involve the use of breathing mixtures other than compressed natural air or the use of saturation techniques.

There are two options for diving works under high pressure [10]:

– Non-saturation exposure ("non-sat" exposure): A short duration exposure comprising a compression, a working period under pressure, immediately followed by a de-

Table 3. Selection criteria and main application field of slurry shields in soft soil according to [5]

Feinkornanteil (< 0,06 mm) DIN 18196 Fine grain fraction (< 0,06 mm)	< 5 %	5 – 15 %	15 – 40 %	> 40 %	
	+	+	+	O	
Durchlässigkeit k nach DIN 18130 [m/s] Permeability k [m/s]	sehr stark durchlässig very highly permeable > 10^{-2}	stark durchlässig strongly permeable 10^{-2} – 10^{-4}	durchlässig permeable 10^{-4} – 10^{-6}	schwach durchlässig slightly permeable < 10^{-6}	
		O	+	O	
Konsistenz (Ic) nach DIN 18122 Consistency (Ic)	breiig pasty 0 – 0,5	weich soft 0,5 – 0,75	steif stiff 0,75 – 1,0	halbfest semi-solid 1,0 – 1,25	fest hard 1,25 – 1,5
	– O	O	O	O	O
Lagerungsdichte nach DIN 18126 Storage density	dicht dense	mitteldicht fairly dense	locker loose		
	+	+	O		
Stützdruck [bar] Supporting pressure [bar]	0	0 – 1	1 – 2	2 – 3	3 – 4
	O	+	+	+	+
Quellverhalten Swelling behaviour	kein none	gering little	mittel fair	hoch high	
	+	+	O	–	
Abrasivität LCPC-Index ABR [g/t] Abrasiveness LCPC-index ABR [g/t]	sehr schwach abrasiv very low abrasive 0 – 500	schwach abrasiv low abrasive 500 – 1000	mittel abrasiv medium abrasive 1000 – 1500	stark abrasiv high abrasive 1500 – 2000	sehr stark abrasiv very high abrasive > 2000
	+	+	+	O	O
Brechbarkeit LCPC-Index BR [%] Breakability LCPC-index BR [%]	sehr schwach very low 0 – 25	schwach low 25 – 50	mittel medium 50 – 75	stark high 75 – 100	sehr stark very high > 100
	O	+	+	+	O

Unit 3 Unit 4 Unit 5

+ Haupteinsatzbereich / Main field of application
O Einsatz möglich / Application possible
– Einsatz kritisch / Application critical

Table 4. Selection criteria and main application field of slurry shields in hard rock according to [5]

Gesteinsfestigkeit [MPa] Rock compressive strength [MPa]	0 – 5 o 5 – 25 o	25 – 50 o	50 – 100 o	100 – 250 o	> 250 o
Bohrkern- Gebirgsqualität [RQD] Core sample - rock quality designation [RQD]	sehr gering very poor 0 – 25 o	gering poor 25 – 50 o	mittel fair 50 – 75 o	gut good 75 – 90 o	ausgezeichnet excellent 90 – 100 o
Rock Mass Ratio [RMR] Rock Mass Ratio [RMR]	sehr schlecht very poor < 20 o	schlecht poor 21 – 40 o	mäßig fair 41 – 60 o	gut good 61 – 80 o	sehr gut very good 81 – 100 o
Wasserzufluss je 10 m Tunnel [l/min] Waterinflow per 10 m tunnel [l/min]	0 o	0 – 10 o	10 – 25 o	25 – 125 o	> 125 o
Abrasivität (CAI) Abrasiveness (CAI)	kaum abrasiv not very abrasive 0,3 – 0,5 +	schwach abrasiv slightly abrasive 0,5 – 1 +	abrasiv abrasive 1 – 2 o	stark abrasiv very abrasive 2 – 4 o	extrem abrasiv extremely abrasive 4 – 6 o
Quellverhalten Swelling behaviour	kein none +	gering poor +	mittel fair o	hoch high –	
Stützdruck [bar] Supporting pressure [bar]	0 o	0 – 1 +	1 – 2 +	2 – 3 +	3 – 4 +

Rock

+ Haupteinsatzbereich / Main field of application
o Einsatz möglich / Application possible
– Einsatz kritisch / Application critical

Table 5. Selection criteria and main application field of EPB TBM in soft soil according to [5]

Feinkornanteil (< 0,06 mm) DIN 18196 Fine grain fraction (< 0,06 mm)	< 5 % –	5 – 15 % o	15 – 40 % o +	> 40 % +	
Durchlässigkeit k nach DIN 18130 [m/s] Permeability k [m/s]	sehr stark durchlässig very highly permeable $> 10^{-2}$	stark durchlässig strongly permeable $10^{-2} – 10^{-4}$	durchlässig permeable $10^{-4} – 10^{-6}$ o	schwach durchlässig slightly permeable $< 10^{-6}$ +	
Konsistenz (Ic) nach DIN 18122 Consistency (Ic)	breiig pasty 0 – 0,5 o	weich soft 0,5 – 0,75 +	steif stiff 0,75 – 1,0 +	halbfest semi-solid 1,0 – 1,25 o	fest hard 1,25 – 1,5 o
Lagerungsdichte nach DIN 18126 Storage density	dicht dense +	mitteldicht fairly dense +	locker loose +		
Stützdruck [bar] Supporting pressure [bar]	0 +	0 – 1 +	1 – 2 +	2 – 3 o	3 – 4 –
Quellverhalten Swelling behaviour	kein none +	gering little +	mittel fair o	hoch high –	
Abrasivität LCPC-Index ABR [g/t] Abrasiveness LCPC-index ABR [g/t]	sehr schwach abrasiv very low abrasive 0 – 500 +	schwach abrasiv low abrasive 500 – 1000 +	mittel abrasiv medium abrasive 1000 – 1500 o	stark abrasiv high abrasive 1500 – 2000 o	sehr stark abrasiv very high abrasive > 2000 –
Brechbarkeit LCPC-Index BR [%] Breakability LCPC-index BR [%]	sehr schwach very low 0 – 25 +	schwach low 25 – 50 +	mittel medium 50 – 75 o	stark high 75 – 100 o	sehr stark very high > 100 –

Unit 3 Unit 4 Unit 5

+ Haupteinsatzbereich / Main field of application
o Einsatz möglich / Application possible
– Einsatz kritisch / Application critical

compression. It does not involve any storage time in a habitat (equivalent to a "bounce dive" in diving).

- Saturation exposure ("sat" exposure): A long duration exposure during which the exposed person lives at a storage pressure and can make transfers under pressure to and from the working chamber.

According to the ITA guidelines [10], the following statements are relevant for the planning of the harbour crossing:

- High-pressure, non-sat exposures only permit short working periods e.g. for planned routine inspection work, because of the relatively lengthy decompression required from such pressures.
- Routine non-sat exposures at high-pressure only permit short working periods (typically 45 minutes at 6 bar). Such exposures typically only enable inspection and limited maintenance to be undertaken. Where significant working periods are required for major maintenance, saturation working should be undertaken. When the exposure pressure exceeds 6 bar, the useful working period available with non-sat exposures but still adhering to the 2 hour decompression limit becomes impractically short and saturation exposure should be considered. For safety reasons, saturation exposure should always be undertaken at pressures of 7 bar and over.

The maximum working time depends on the pressure and local guidelines. Mixed gas diving offers several options to increase the working time and reduce the decompression

Table 6. Selection criteria and main application field of EPB TBM in hard rock according to [5]

Gesteinsfestigkeit [MPa] Rock compressive strength [MPa]	0 – 5	5 – 25	25 – 50	50 – 100	100 – 250	> 250
	o	o	o	–	–	–
Bohrkern- Gebirgsqualität [RQD] Core sample - rock quality designation [RQD]	sehr gering very poor 0 – 25		gering poor 25 – 50	mittel fair 50 – 75	gut good 75 – 90	ausgezeichnet excellent 90 – 100
	+		o	o	–	–
Rock Mass Ratio [RMR] Rock Mass Ratio [RMR]	sehr schlecht very poor < 20		schlecht poor 21 – 40	mäßig fair 41 – 60	gut good 61 – 80	sehr gut very good 81 – 100
	+		o	o	–	–
Wasserzufluss je 10 m Tunnel [l/min] Waterinflow per 10 m tunnel [l/min]	0		0 – 10	10 – 25	25 – 125	> 125
	o		o	o	o	o
Abrasivität (CAI) Abrasiveness (CAI)	kaum abrasiv not very abrasive 0,3 – 0,5		schwach abrasiv slightly abrasive 0,5 – 1	abrasiv abrasive 1 – 2	stark abrasiv very abrasive 2 – 4	extrem abrasiv extremely abrasive 4 – 6
	+		+	o	o	–
Quellverhalten Swelling behaviour	kein none		gering poor	mittel fair	hoch high	
	+		+	o	–	
Stützdruck [bar] Supporting pressure [bar]	0		0 – 1	1 – 2	2 – 3	3 – 4
	o		+	o	–	–

Rock

+ Haupteinsatzbereich / Main field of application
o Einsatz möglich / Application possible
– Einsatz kritisch / Application critical

Table 7. Comparative suitability assessment of the available shield technologies

	Slurry	**EPB**	**Convertable Slurry – Open**	**Hybrid (screw-pumping circuit)**
High pressure; advance	Lower torque, thrust, wear	Higher torque, thrust, wear	Lower torque, thrust, wear	Lower torque, thrust, wear
High pressure intervention	State of the art	Bentonite pumping devices Restart more difficult	State of the art	
High pressure; muck discharge		Screw gate control critical >> 3 bar		
Open mode belt	Separation in rock possible Lower advance rate	Centre belt and large screw Impossible to realise D= 7.0 m	Difficult D = 7.0 m	Screw-belt solution
Additional time for conversion	Water pumping circuit, no pressure			
Boulders and clogging	Special design considerations	Large screw required; Pressure control critical		
High pressure compressed air works	Intermediate chamber possible	Intermediate chamber difficult to realise	Intermediate chamber difficult to realise	Intermediate chamber possible
Costs	Separation and pumping	Belt	Separation and belt Conveyor and pumping circuit Downtime for circuit Downtime for conversion	Separation and belt Conveyor and pumping circuit Downtime for conversion Muck skipps possible
Ranking	1	not an option	3	2

time. According to [10], the following gases and gas mixes should be considered when designing a breathing mixture: Oxygen, Nitrogen, Helium, Heliox, Nitrox and Trimix. Figure 11 gives an indication of the ranges of application of pressurization measures according to [11].

7 Conclusion

The assessment described in this paper determined that a slurry shield was an appropriate methodology for the harbour crossing. This informed the planning for the tender process to ensure that sufficient land was acquired, including a site for the separation plant and a site for an

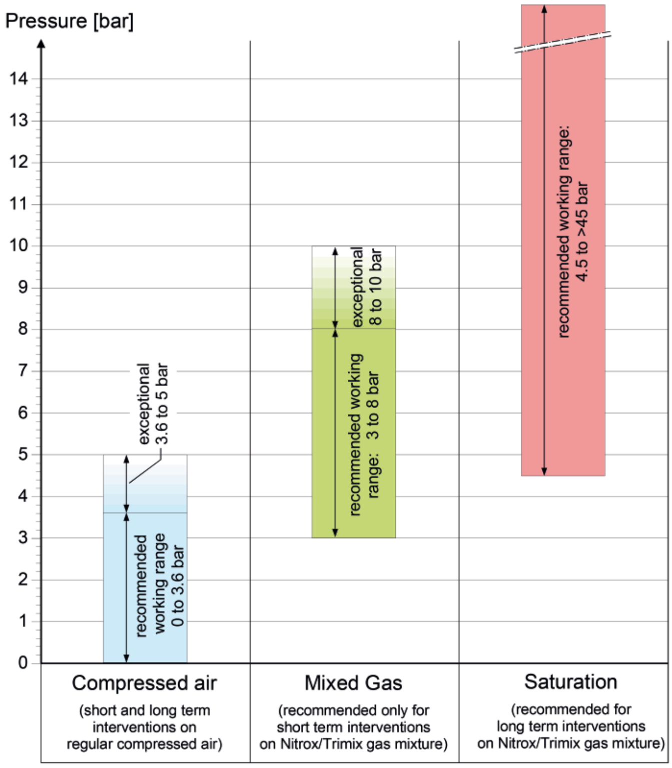

Fig. 11. Recommended pressure bandwidth for the application of regular compressed air, mixed gases (trimix) and saturation diving [11]

additional shaft. It also helped to describe possible construction requirements that were included in the Planning Application and Environmental Impact Statement, so that the tenderers were able to consider a wide range of options for construction.

Tenders were issued in September 2016 and both tenderering Contractor Joint Ventures offered a slurry shield solution for the construction of the under-harbour crossing.

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