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HH – Fast Förbindelse

Review of the project with regards on the TBM specific parts and challenges

1. Introduction

The project is in a very early phase and aims to connect Helsingborg (Sweden) to Helsingør (Denmark). The objective of this report is to assess the feasibility of the TBM tunnels stated in the documents elaborated from other teams in the past couple of years.

The study bases on a railway tunnel, two single track tunnels, ~7 km long in the north, and two tubes for the road tunnels with two lanes each, ~12 km long, further south.

General overview with both alignments

2. Validation project layout and tunnel geometry

For the validation the available information was used and the experience from previous tunnels done with similar requirements around the world. See list of references In Appendix 1.

2.1. Reference projects rail tunnel

- Malmö City Tunnel, Sweden
- Channel Tunnel, England-France
- Follobanen, Oslo-Ski
- Hallandsas, Sweden
- Leipzig City Tunnel, Germany
- Liefkenshoek Tunnel, Belgium
- Botlekspoortunnel, The Netherlands

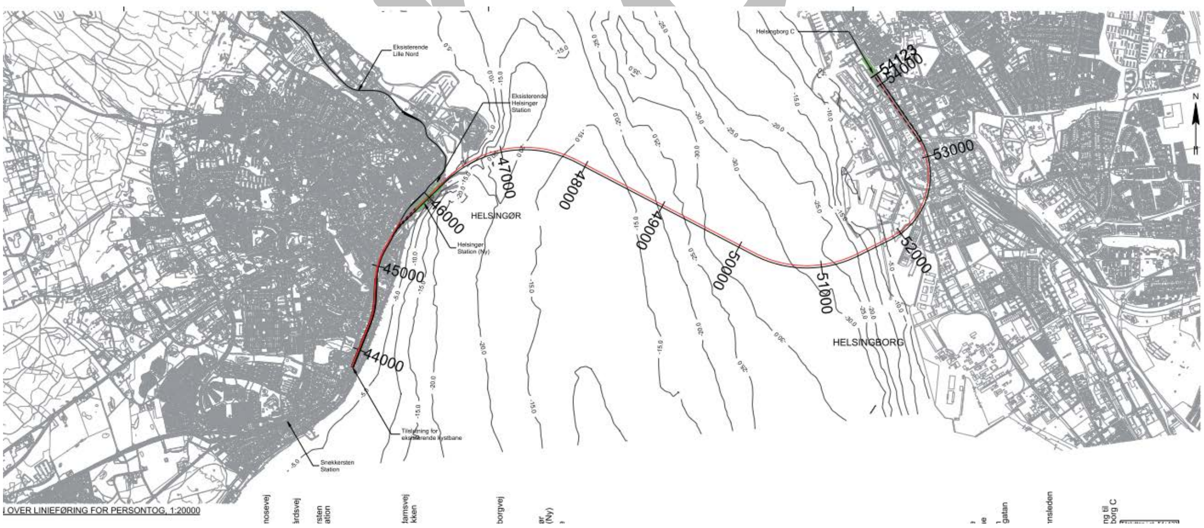
2.2. Reference projects road tunnel

- Bosphorous Highway Tunnel, Turkey
- Waterview Tunnel, New Zealand
- Port Said Road Tunnels, Egypt
- Tunnel Tuen Mun – Chek Lap Kok, Hong Kong
- A86 – Socatop, Paris
- Elbtunnel, Hamburg
- Miami Port Tunnel, USA
- SMART Tunnel, Kuala Lumpur
- Shantou Su Ai project, China
- Alaskan Way, USA
- Changjiam Under River Tunnel, China
- Westerschelde, Holland

2.3. Rail Tunnels

Overview

The bored tunnel is starting on the Danish side in the harbour of Helsingør (@ Chainage 46.300), crosses the sea and connects to Helsingborg retrieval shaft (@ Chainage 53.300). This results in a bored tunnel length of app. 7km (x2).

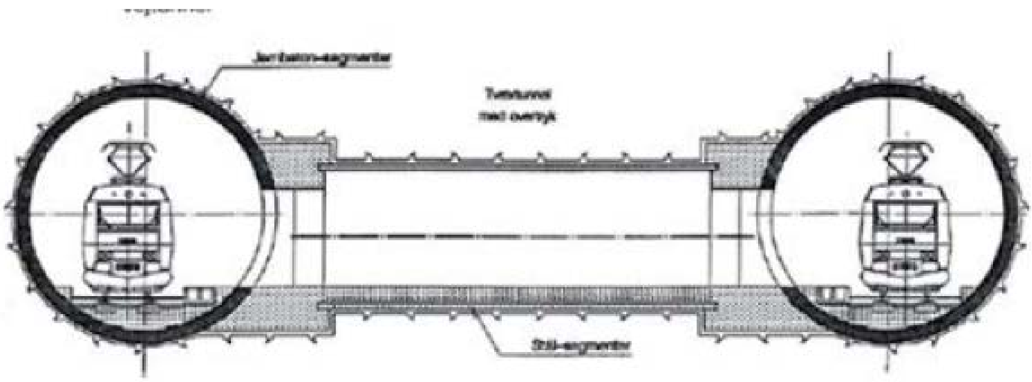


Overview alignment rail tunnels

Cross Section

The cross section of the rail tunnels was taken from Malmö City Tunnel. It consists of two parallel tunnels linked by cross passages. The suggested inner diameter is 7,9 m which is also in the same range than the references (Leipzig City Tunnel, Channel Tunnel, etc.).

This is considered to be sufficient, up to a design speed of 160 km/h. If higher speed is considered, detailed investigations are recommended. The reason is the free area that remains, when the train is in the tunnel. At high speeds there is a lot of aerodynamic friction in the tunnel that consumes a lot of the traction energy. This can easily limit the maximum possible speed in the tunnel, when the cross section is too small.



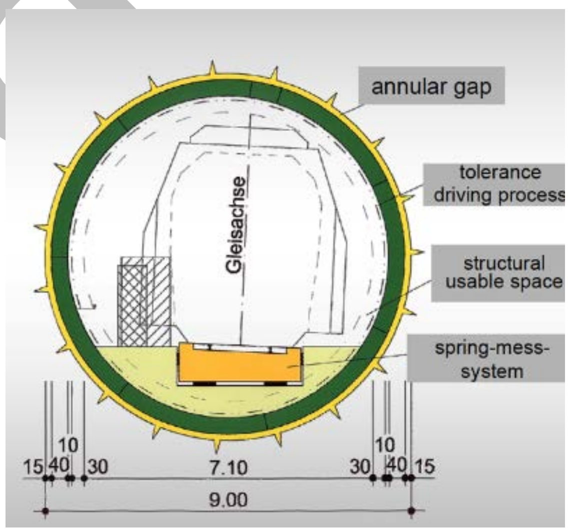
Cross section Malmö City tunnel

Due to high water pressure, we suggest a segmental lining of 40 cm, which is more than Malmö City Tunnel (35 cm), but less than Channel Tunnel (45 cm).

The minimal horizontal radius is approximately 800 m (not sure as the plan is very difficult to read). This leads to a conicity of the shield and an annular gap of max 15 cm and a outer diameter of the TBM of 9.0 m. This is similar to the cross section of Leipzig City Tunnel.

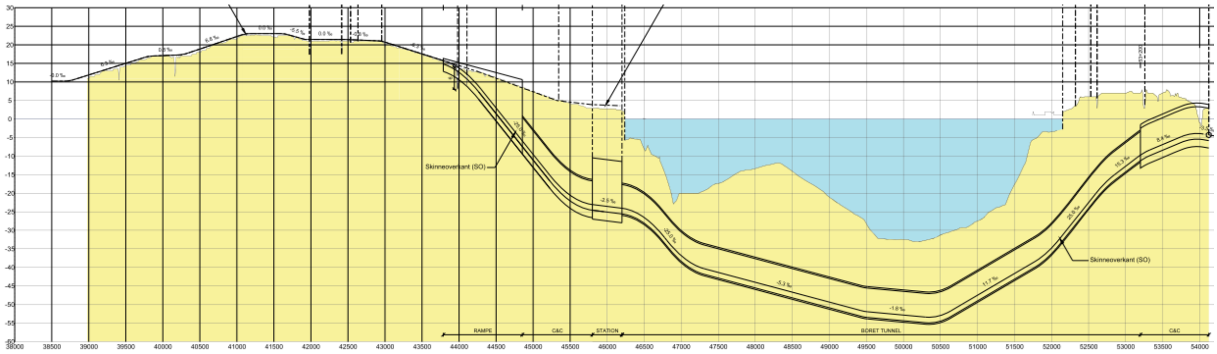
Inner diameter	7.9 m
Segmental lining	40 cm
Outer diameter	8.7 m
Annular gap	15 cm
Outer diameter	9.0 m

Calculation of TBM diameter



Cross section Leipzig City Tunnel

Longitudinal Profile



Longitudinal profile rail tunnel

The tunnel passes roughly 50 m below water level @chainage 50.250 (measured at tunnel crown). As far as the picture above allow to see, the min. coverage is 5 m @chainage 46.590 with 23 m water pressure on top. This results in ca. 0.5 x D, which should be pointed out to be critical under these circumstances.

The max. slope is app. 2,5%, but needs to be verified as the quality of the picture above is limited.

Slope

For different reasons the level of the stations on both sides are potentially not finally fixed yet. This can have an impact on the slope of the tunnel. Depending on the final considerations the slope can be steeper or less steep. The TBM itself does not limit the steepness of the slope in a traffic tunnel. The design components of the railway track are more delicate and will be guiding this issue. In St Petersburg an EPB TBM made a tunnel with a 30° slope.

More delicate is the logistic to supply the TBM. With a slurry TBM the mucking is not the problem, because this is done with the slurry circuit - no limit when it comes to the slope. For the EBP TBM most likely a conveyor belt will be used. The horizontal radius should be limited to min. 500 m. The slope is usually not critical for the conveyor belt solution - though the conveyor belt itself must be designed by an experienced supplier, as the availability must be high to insure the targeted production rates and there are many details that needs to be considered.

For the rest of the transports such as lining segments, grout for the annular gap and other supply goods there are generally two options: rail or MSV's (Multi Service Vehicles). For a rail driven solution the slope should be limited to 2%. The tendency though goes towards MSV's. In the meantime, MSV trains have been developed and successfully operated for example at the Brenner Base tunnel. For this logistic system the slope again is not the limiting factor.

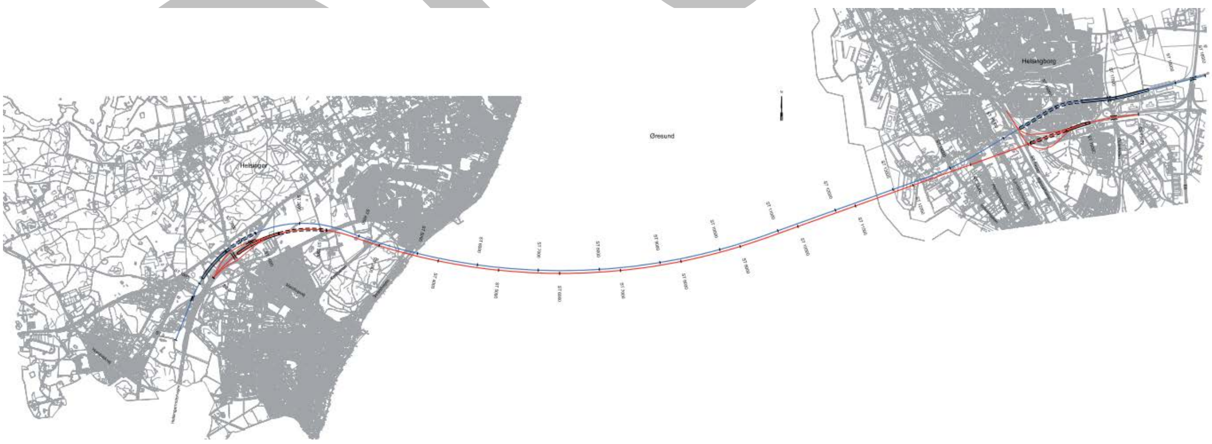
Multi Service Vehicles (MSV)

With these considerations, the TBM and its logistic will most probably not be limiting the choice of the level of the stations or more generally the slope of the tunnel.

2.4. Road Tunnels

Overview

The bored tunnel is starting on the Danish side in the harbour of Helsingør (@ Chainage 2.200), crosses the sea and connects to Helsingborg retrieval shaft (@ Chainage 14.000). This results in a total length of app. 11,8 km (x2).

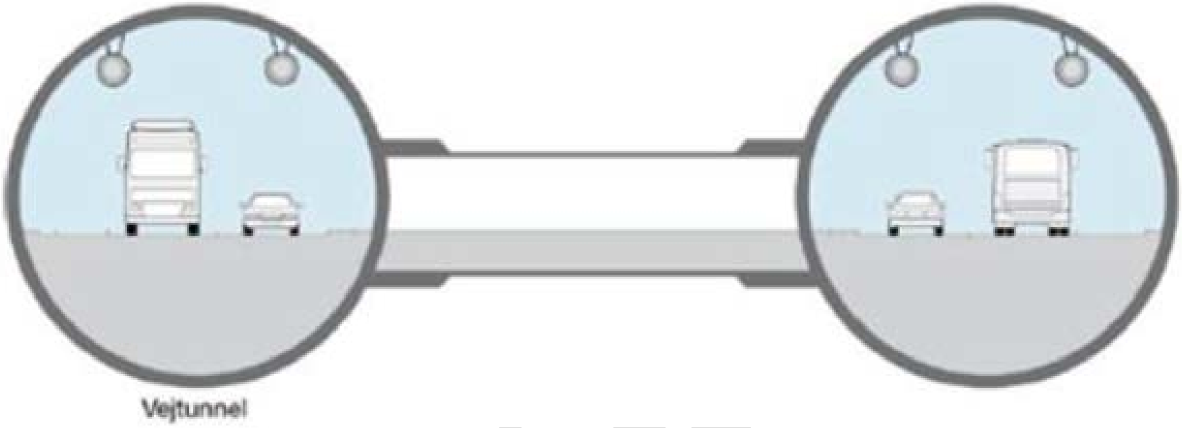


Overview alignment road tunnels

The road tunnel is the red line on picture below.

Cross Section

The cross section of the road tunnels is based on a 13-m inner diameter with a full concrete slab. Based on the experience of other projects and the references in appendix 1 we consider to re-evaluate the size and optimise the use of the space in the cross section. Two potential options are mentioned below. This is mostly motivated on the fact, that the size of the TBM necessary to gain a 13-m inner diameter goes towards the upper limit of feasibility in combination with the geology predicted and the crossing of the sea.

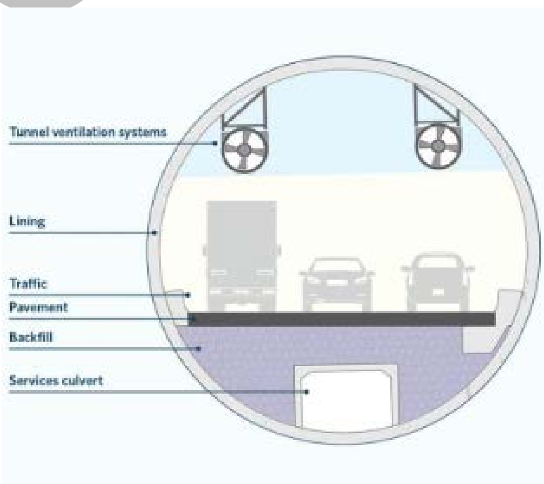


Cross section road tunnel

Due to high water pressure, the size of the tunnel and the given geological conditions, we suggest a segmental lining of at 60 cm and a conicity of 20 cm. This results in a bored diameter of 14,6 m. This is similar to the cross section of the Waterview tunnel in Auckland

Inner diameter	13 m
Segmental lining	60 cm
Outer diameter	14.2 m
Annular gap	20 cm
Outer diameter	14.6 m

Calculation of TBM diameter



Example Waterview tunnel Auckland

Potential optimizations:

The cross section of the road tunnel showed above is not very detailed, but the use of the space can potentially be optimized. As we couldn't find the basic requirements, the following questions need to be answered:

- What kind of traffic passes through the tunnel, only cars or trucks as well?
- How large do the lanes need to be, same size for both or can the left ones be reduced in combination with the obligation for trucks to stay on the right lane?
- Does the tunnel really need an emergency lane? If yes, which size?
- What kind of space is further needed for a walkway, or similar?
- How does the drift and maintenance concept work? Where are all the cable installations? Where are the tubes for water and drainage?
- Is there a reason, why the invert is filled up with concrete?

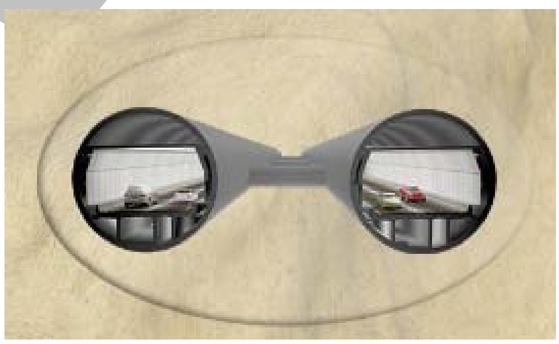
We suggest to evaluate the following options:

Option "Service Space Elements":

Use of prefabricated service space elements underneath the road deck. This is very important for drift and maintenance, as most cable systems and the water and drainage tubes can be installed there, and thus maintained without entering the tunnel itself. This enables to significantly limit the disturbance of the traffic flow due to maintenance works as it is even possible to do most of the maintenance works at daytime and get away from work during night shifts.

As a further benefit the amount of concrete to fill up the space not needed under the road deck can be reduced significantly.

As an example of recent project with a similar concept the Waterview Project in Auckland or TM-CLK project in Hong Kong can be considered (Appendix 1).

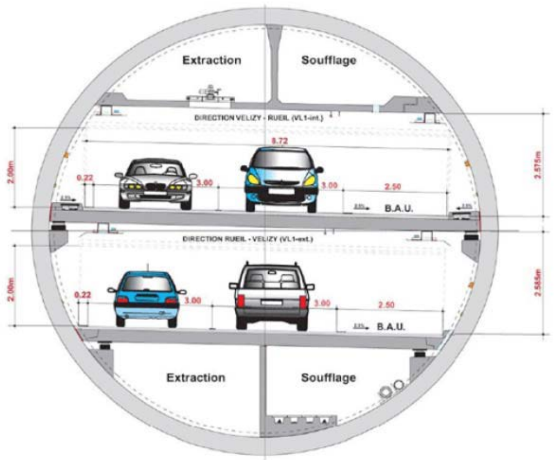


Cross section CLK project Hong Kong

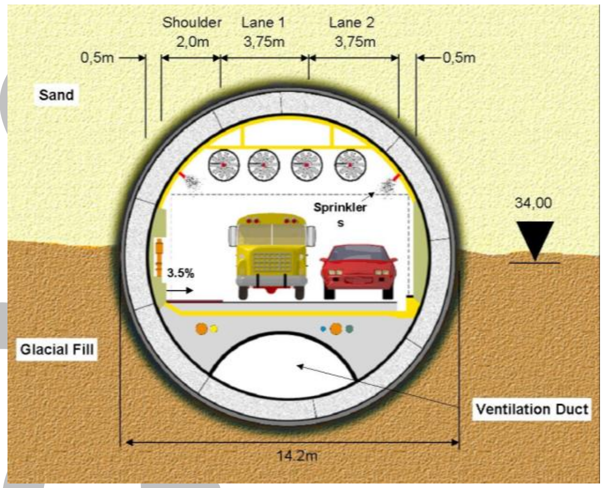
Option "Optimized lane concept":

As only 2 traffic lanes are actually planned for this project (+ a rescue lane) we see a potential optimisation in the required width of the tunnel.

- The project Socatop in Paris had two 3 m-width light traffic lanes (no trucks) and one 2,5 m-width rescue lane - in one tunnel.
- The Elbtunnel in Hamburg consists of two 3,75 m-width traffic lane and one 2 m-width rescue lane.



Cross section Sokatop tunnel Paris

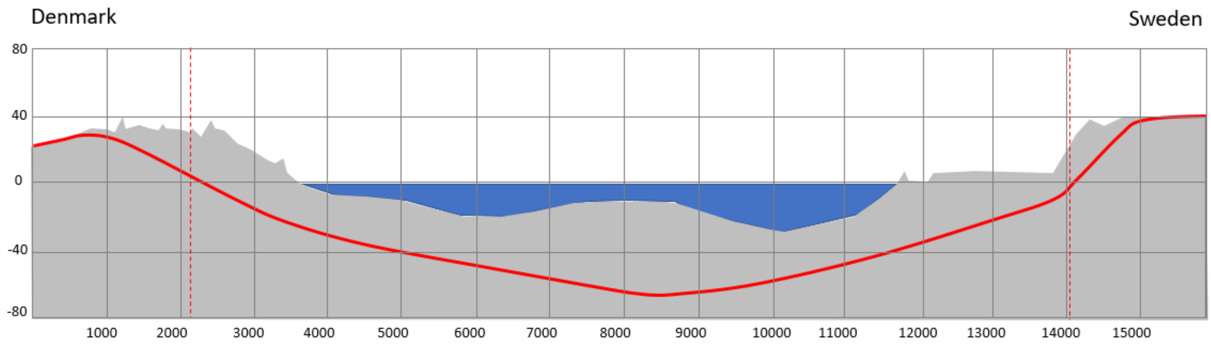


Cross section Elbe tunnel Hamburg

An optimisation would be to consider one 3 m-width light traffic lane (no trucks), one 3,75 m-width "truck" lane and one 2,5 m-width rescue lane. This would result in an inner diameter of approximately 12 m and a TBM diameter of approximately 13,6 m - one meter less than the present design. The cross section of the Elbtunnel would be a good example of an optimized cross section.

Longitudinal profile

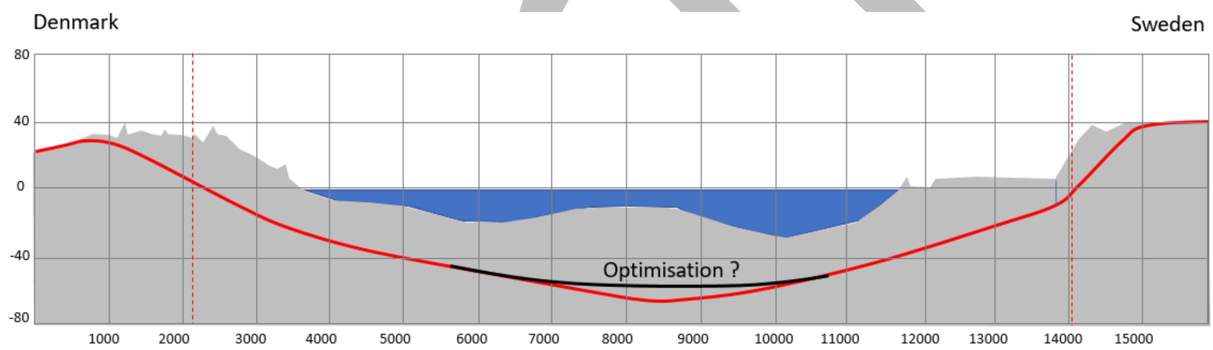
The tunnel passes roughly 65 m below water level @chainage 8.500 (measured at tunnel axis). As far as the picture above allow to see, the min. coverage under the sea is ~20 m @chainage 11.000 with ~30 m water pressure on top. The min. coverage under land is ~15 m (measured at tunnel axis) @chainage 13.800. The max. slope is app. 2,5%, but needs to be verified as the quality of the picture above is limited.



Longitudinal profile road tunnel

Option "Optimization vertical profile":

Without any further explanation, it is not obvious why the tunnel must go down that deep @chainage 8500. It seems that the standard grade from both sides have been continued until the two tunnels met at the respective chainage. There might be a possible optimisation (see picture below) to reduce the maximal depth of around 10 m. This will reduce the water pressure of around one bar, which is not a game changer, but still gives the TBM more reserves to operate.



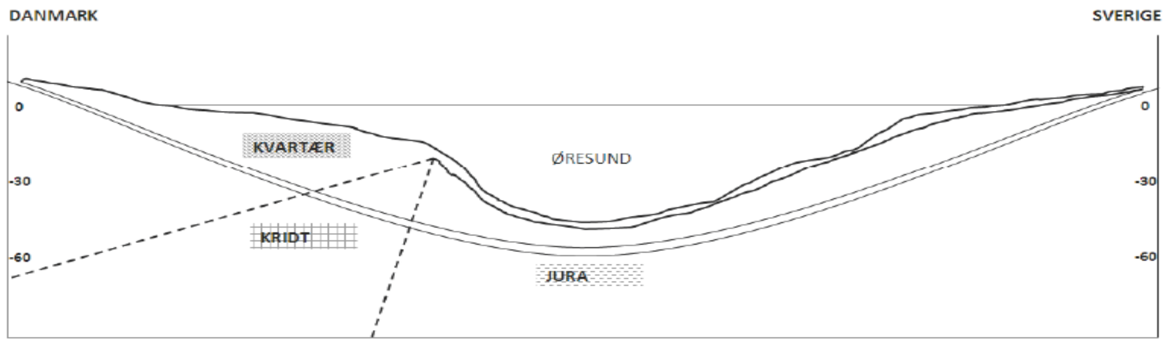
Option optimizes vertical profile road tunnel

3. Validation geology

3.1. General situation

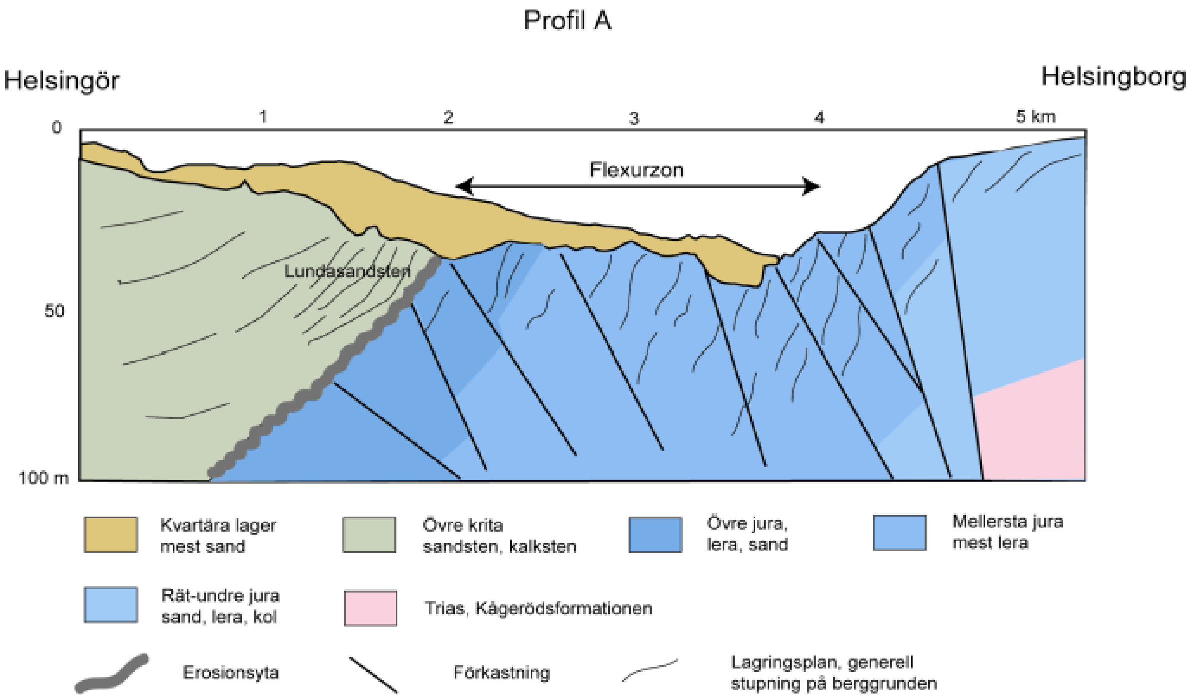
The HH connection will pass over the most significant geological structure in the whole of Southern Scandinavia, namely the so-called Tornquist zone. This marks the limit between the Baltic bedrock area in the east and northeast and the Danish sediment basin in the west.

The boundary itself has the character of a giant flexure (fold), which brings down the 135-190 million-year-old Jurassic deposits, so that they lie very superficially in the coastal area at Helsingborg and directly below approx. 20 m young (post-glacial) sea-deposited sand in the middle of the Sound and at the Danish coastline. The jurassic layers are here covered by deposits from the periods Cretaceous and Dania.



Summary of the geological situation in the Öresund

The picture above matches with the more detailed one below:

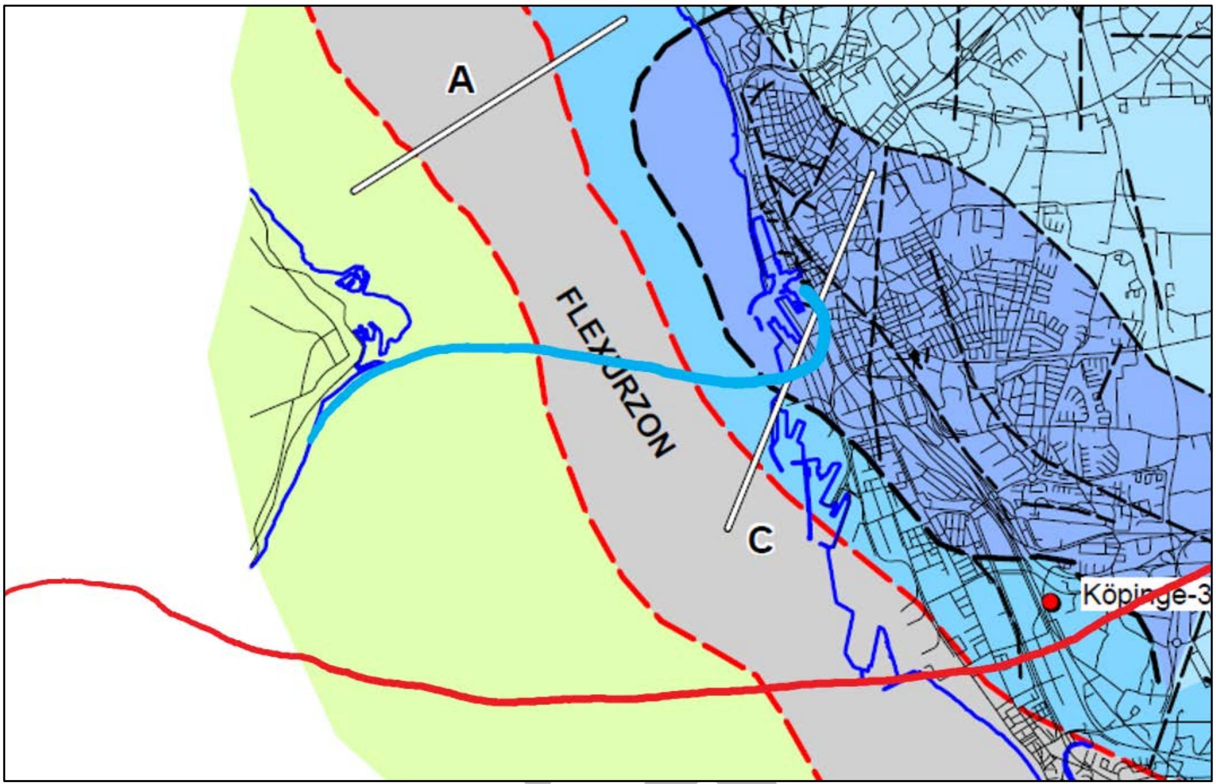


Geological prognosis in the Öresund

The section of the geological profile corresponds to a section a bit more on the north and is not precisely representative of the situation expected for the two alignments we are looking at. This of course provokes some questions, probably not necessary about the feasibility, but definitively when we talk about cost and schedule issues. We strongly recommend to ask the geologists:

- to establish a section each, best guess with the information available, in the alignment of the two tunnels.
- to elaborate a rough 3D model of the whole area with sea bed level, rock level and geology
- to put the real alignment data into that model, georeferenced to be able to really check the status of the present design.

We are fully aware of that there are just limited information around, but if we don't put that together into one common model, best guess, we cannot give recommendations to the client at the state of the art level.



Geological section in comparison with the alignments

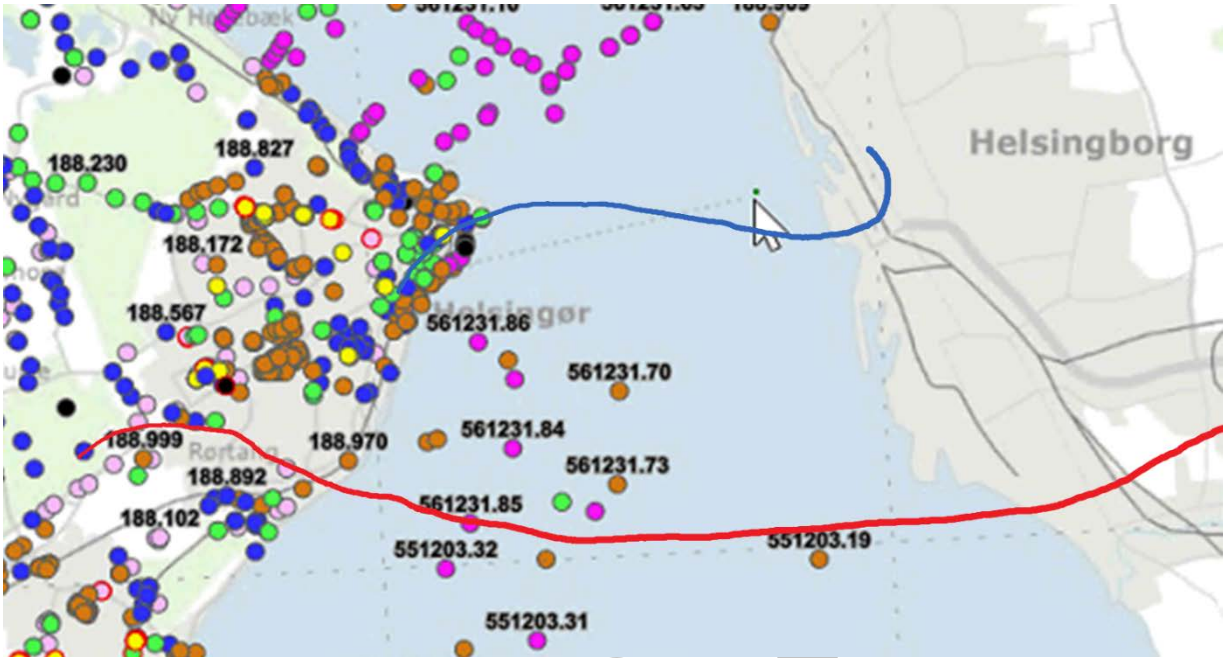
For the time being and until further information is available we base on the assumption of the previous reports, where basically the layers that will/might be encountered (from Denmark to Sweden) are:

- Quaternary: Postglacial sand deposits (3.2)
- Danish Period and Cretaceous: Limestone, upper Chalk (-)
- Jura: Sandstone, Claystone and Coal (3.5)

3.2. Additional information from Danish database

During the work with this report, we got an inside view in a Danish database with investigation performed in the sea between Denmark and Sweden the last decades. Although there are not many recent performed investigations and the ones available do not really cover the alignments to use (see picture below) the data generally confirm what was used in the previous reports.

Unfortunately, the information is only descriptive, as shown in the table below. Parameters as well as the rock surface are missing. Nevertheless, we can see, that the sands range quite deep down and the proposed alignments will have to cross them as well for the rail tunnel in the north as for the road tunnel further down south.



Overview of the investigations found in the Danish database

Again, we strongly recommend starting an investigation program along the two alignments to get more detailed information about the geology to be expected, including a detailed description of the formations that need to be crossed by the TBM's, the rock surface and even the most important parameters both for the sands and the different rock formations.

Following parameters are of paramount importance for the TBM choice and the tunnel design:

Soil	Rock
Density	Density
Water content	UCS
Cohesion	BTS
Friction	E Modulus
Atterberg limits (LL, PL, + PI, IC)	CAI
Grain Size analysis	RQD / Q / RMR
E modulus	Permeabiliyt
K0 / OCR	
Quartz content	
Permeability	

Parameters needed for the choice of the TBM

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Djup (meter under marken)	Borrplats	Geologi	Geologi (danska)	DGU-symbol
4,4	Øresund 1974	Sand – fin och mellan, välsorterad, och svag lerhalt (postglacial saltvattensand)	SAND, fint og mellem, velsorteret, svagt gytje-holdig. (postglacial saltvandssand).	postglacial saltvandssand - hs
6,3	Øresund 1974	Sand, mestadels fin, svagt silt, lerhalter (postglacial saltvattensand)	SAND, mest fint, svagt siltet, gytje-holdig, skaller. (postglacial saltvandssand).	Postglacial saltvandssand - hs
7,2	Øresund 1974	Sand, mest fin och välsorterad (sand)	SAND, mest fint, velsorteret. (sand).	sand - s
8,4	Øresund 1974	Silt, mest grov, lerhalter, sand (finsand) (postglacial saltvattensilt)	SILT, mest groft, gytje-holdig, sandet. (postglacial saltvandssilt). Note: Sandet er fint.	postglacial saltvandssilt - hi
8,6	Øresund 1974	Postglacial silt och lerhalter (postglacial saltvattensilt)	SILT, gytje-holdig, skaller. (postglacial saltvandssilt).	Postglacial saltvandssilt - hi
9,9	Øresund 1974	Sand, mestadels fin, välsorterad (postglacial saltvattensand)	SAND, mest fint, velsorteret. (postglacial saltvandssand).	postglacial saltvandssand - hs
20,2	Helsingör,FÆRGEVEJ, ROKLUBBEN, 31. juli 1975	Sand (sand)	Sand	sand - s
5	Disken, 16. september 2014	Sand, mestadels fin, (grå 2.5Y 5/1) och kalkhalter (postglacial saltvattensand)	SAND, mest fint, grå 2.5Y 5/1, kalkholdig. (postglacial saltvandssand). Note: Cardium, Macoma, Echinocardium.	postglacial saltvandssand - hs
3	Hesselø Bugt, 27. eptember 2015	Grus, kalkhalter (glacialt smältvatten grus)	GRUS, kalkholdig. (glacial smeltevandsgrus).	glacial smeltevandsgrus - dg

Example of details per investigation in the database

3.3. Quaternary: Postglacial sand deposits

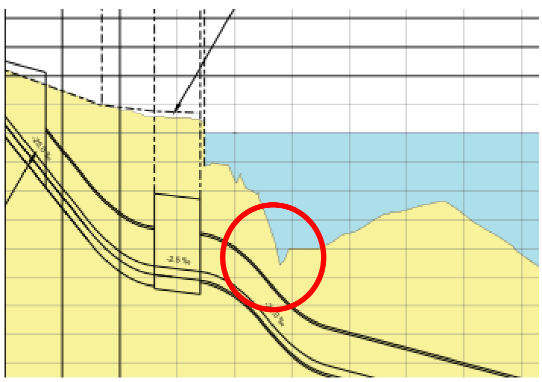
Description

While the Jurassic deposits are taken almost directly under the seabed on the Swedish part of the strait, there is a thick layer of young sand deposits on the Danish part. The layers are approx. 30 m thick on the Danish coast, while 20 m thick out in the sound. The upper part of the sand must be assumed to be mobile. While the clean, sorted sand is found up to the seabed level out in the Sound, the layer series in the coastal Danish part is covered with mud.

Analysis

No information is available concerning this sand and there are high chances that both tunnels will cross through it on the Danish side. This is highly relevant for the assessment of the feasibility of the tunnels in its present design.

Grain size analysis, permeability, E modulus are missing and will definitively be required in the next stage to make an assessment on the TBM Choice.



Low sand cover, less than one diameter

- **Rail Tunnel**: Given the very low overburden below seabed there might be a real issue and question the feasibility at acceptable risks. There are technical solutions with the TBM such as grouting or high-density Bentonite => VD TBM to avoid blowout. But in the context of crossing the sea in Sand, with less than one diameter coverage, we would definitively recommend geologically investigating the area in detail and thereafter, eventually to reassess the alignment.
- **Road Tunnel**: The diameter is larger, but the tunnel will be built deeper in those sediments. Therefore, the problem is considered to be smaller (E modulus should be higher).

As far as we could understand, the sands on the Swedish side are the same kind as the ones on the Danish side. For the further considerations we consider the parameters from the sands on the Swedish side.

Jordlager	Tunghet* γ (kN/m^3)	Hållfasthetsparametrar			Elasticitetsmodul E (MPa)
		Odränerad skjuvhållfasthet τ_{fu} (kPa)	Effektiv skjuvhållfasthet		
			c´ (kPa)	ϕ´ (°)	
Fyllning	18-22	0	0	29–32	5-10
Lermorän	20-22	100–200	0-20	31–33	30-60**
Sandsediment	18-22	0	0	37–40	30-60

Tabell 1, *Preliminära geotekniska parametrar för förekommande jordlager*
* Vattenmättad
** Lermoränen bedöms vara överkonsoliderad med ca 3 till 5* τ_{fuk}.

Parameters of the sands on the Swedish side

With the information available at present, there doesn't seem to be an impermeable layer between seabed and tunnel, so full water pressure on the tunnel needs to be considered on the Danish side.

- **Rail Tunnel**: High water pressure to be considered: ~4 bars (@crown). This is in the upper range of the standard EPB application.
- **Road Tunnel**: High water pressure to be considered: ~5 bars (@crown). This is above the application range of a standard EPB. Special features would be needed (Dickstoffpump, extra-long screw conveyor) or Hydro shield.

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3.4. Danish Period and Cretaceous: Limestone, upper Chalk (Sandstone?)

Description

Under the former seabed in the easternmost Helsingør and out to approx. 1 km from the coast, limestone from the Danish period lies directly below 25-30 m of marine, sand-dominated deposits (see above). The limestone has probably the character of hardened chalk with flint layer corresponding to the lime in which Malmö Citytunnel is led and was excavated with an EPB machine. Below the Limestone: presence of chalk with flints has to be expected.

Newer information gathered during the work with this report recommends not to look to close to the geology of Citytunnel Malmö, even if it crosses the same geology. It seems that we will rather meet a lot of sandstone, worse in Quality as the one encountered at Citytunneln Malmö, but better than the sandstone that is present in the area of the Fernmanbelt Tunnel.

We strongly recommend performing investigation to get more precise information about the geology in this part in the next design phase.

For the time being we use the parameters from the sandstone on the Swedish side.

Rock Type	Dry density (t/m^3)	Porosity (%)	Dry UCS mean (MPa)	Saturated UCS mean (MPa)	E-modulus (GPa)
Sandstone – Carboniferous	2,6	12	70	50	30
Sandstone - Triassic	2,3	25	20	10	4

Parameters Sandstone on the Swedish side

Analysis

The parameters known so far indicate that the rock is well suitable for the use of a TBM. Unfortunately, there is no information about discontinuities. This is not that bad for this phase of the project, as the face will be stabilized with either slurry or earth paste.

An important open question is the abrasivity of the rock, as this has a major impact on the cutter head wear and the effort for maintenance of the TBM generally (slurry circuit or screw conveyor).

Further the presence of flints might have an impact on the TBM design / choice, if the amount of flint is high, which is also unknown.

For the next phase we recommend to run additional ground investigations to learn more about the geology in general, the parameters of the rock near the planned tunnels, the discontinuities (joint sets) and the abrasivity.

3.5. Jura: Sandstone, Claystone and Coal

Description

To the east of the sound there are deposits from the Jurassic period directly or locally almost directly below the young sea-deposited sand.

These are hardened sandstone, siltstone and claystone with a degree of hardening varying between H.2 and H.4. The deposits grow older from west to east, and almost the entire jurassic period is represented. The westernmost lies predominantly massive sandstone from the upper Jurassic, while the layer series from middle Jurassic further east is made up of much more alternating layers of sandstone, siltstone and claystone / clay. Local coal layers are included in the layer series from the older Jurassic which lies easterly below the Sound and in the Swedish coastal area.

Sandstone, sandstone shale, iron sandstone

The sandstone is mostly fine grained. The sand fraction is dominated by quartz (85-100%). The rock is to a varying degree cemented. Usually there is a thin layer of precipitated silicon cement around the grains which creates weak bridges between the grains and which easily breaks. This cement is in the harder sandstone variants supplemented with precipitated iron carbonate, calcium carbonate and in situ formed clay minerals (kaolinite).

Fig. 7. Hård rödbrun järnkarbonatcementerad sandsten underlagrad av mörgrå mjuk tunnskiktad lera och silt som i sin tur underlagrad av lös-medelhård ljusgrå-gulvit sandsten. Nya polishuset i Helsingborg. Foto: M. Erlström 2004.

Fig. 8. Ljusgrå finkornig hård ca 0,8 m mäktig sandstensbank. Järnoxidimpregnerade sprickytor. Helsingborgsledet, Nya Polishuset i Helsingborg. Foto: M. Erlström 2004.

Examples of the Danish Period and Cretaceous: Limestone, upper Chalk

The consolidated variants exhibit a high degree of sub vertical cracking. The cracks are usually open, durable and the fracture planes relatively flat. They are partially filled with clay and precipitated iron oxides. The sandstone layers have a varying thickness. Common is a sandstone type which consists of meter thick layer packs with 5–10 cm thick layers of grey sandstone that show a high degree of “slickness”. Between those layers there are thin layers with clay that cause the rock to split up along these. Older descriptions from the area often indicate the term sandstone slate for this rock type. Deformations in the sandstone are mostly of brittle character.

The strength is variable. All variants are found, from loose to very hard but generally medium hard. Often shreds when struck (sign for low UCS, BTS). Good to excavate with TBM.

The sandstone exhibits a high permeability (through pores and fractures) and therefore at least in parts a lot of water needs to be expected.

Claystone, siltstone

The rock is dominated by clay and silt fractions and cemented to a varying degree. Most often the more cemented sections consist of more silty layers with precipitated microcrystalline siderite (iron carbonate) and calcite. Lens-shaped, locally decimetric thick very hard siderite cemented sandstone layers often appear scattered in the clay / silt-dominated sequences.

The claystone is usually layered and thin-bedded, while the clay sections show less degree of slickness. The silt units are often several meters thick, while the clays are usually thinner smaller than the meter-thick layers. Cracks that are present are usually dense and filled with clay. Watering is mostly done along the beddings plan. Deformations in clay and claystone are often of a plastic nature. Failure pattern of the clay is probably a sliding plan.

Usually medium-hard - loose. Hard thinner layers occur. The clay is usually plastic and soft. Good to excavate with TBM.

Alternation of sandstone, siltstone and claystone

Muddy sandstone shale, sandy shale clay, sandstone shale clay.

Structure: The rock is clearly geared with silt / sand and clay. When the clay content predominates, silt / sand occurs as lenticular bedding, and when silt and sand dominate, the clay occurs as irregular thin clay layers ("flask bedding"). Wave ripples are common. Thin sandstone layers (dm thick) occur frequently. Local more powerful lens-shaped sandstone lenses (<1 m thick) often occur. The sandstone lenses often cemented with iron carbonate.

Similar structure as the claystone but much clearer layered and thin layer. The layers are usually 1–5 m powerful. Feature with <1 m of strong, lenticular sandstone lenses occurs.

Most often loose and good to excavate with TBM. Medium-hard thin layers with cemented fine-grained sandstone occur. Not excluded to find very hard, meter-thick lenses with iron carbonate cemented sandstones. One must pay attention to the latter, while designing the TBM. Therefore it is very important to correctly describe this in the GBR.

Coal / Carbon

Coal is often associated with very black columnar clays. Pyrite occurs frequently. Similarly, larger wood fragments and plant material. The coal consists of massive layers that are often heavily cracked. Carbonaceous clays are layered.

Carbon occurs mostly as cm-thin layers, but fluxes up to about 0.5 m thickness and occur at 2-5 levels in the bearing series. The carbon is generally brittle and soft when clay is involved in the carbon.

The connecting clays are often soft and plastic.

In other places in the world, methane is an issue in this kind of geology. We recommend to assess this, as the presence of methane will have an impact on the design of the TBM.

Geotechnical parameters Jurassic series:

Berglager	Tunghet*	Tryck-Hållfasthet	Drag-hållfasthet	Effektiv skjuvhållfasthet		Elasticitets-modul
	γ (kN/m^3)	σ_C (MPa)	σ_T (MPa)	c´ (kPa)	ϕ´ (°)	E (GPa)
Sandsten/Sandsten i växellagring, lös	20-22	0,1-10	0-0,5	*0-20*	*29–35*	0,01-2
Sandsten/Sandsten i växellagring, medel	22-24	10-20	1-2	*20-60*	*40–45*	2-6
Sandsten/Sandsten i växellagring, hård	22-24	20->30	2-3	*60-100*	*45–50*	6->15
Lersten/Lersten i växellagring, lös	22-24	0,05-5	0-0,5	*10-50*	*30–35*	0,003-1
Lersten/Lersten i växellagring, medel	24-26	5-10	0,5-1,5	*50-100*	*35–40*	1-2
Lersten/Lersten i växellagring, hård	24-26	>10	>1,5	*>100*	*40–45*	2-3

Tabell 4, *Preliminära geotekniska parametrar för förekommande berglager*

Berglager	Tunghet	Enaxlig tryckhållfasthet	Elasticitetsmodul
	γ (kN/m^3)	σ_C (MPa)	E (GPa)
Sandsten	22 (20-25)	20 (0,3–>30)	5 (0,02-15)
Sandsten i växellagring	23 (20-25)	9 (0,1–27)	2 (0,01-15)
Lersten	24 (22-27)	3 (0,05–14)	0,4 (0,003-2)
Lersten i växellagring	24 (22-27)	4 (0,05–14)	0,4 (0,003-2)

Tabell 2, *Sammanställning av utförda laboratorieanalyser, medelvärde (min-max)*

Geotechnical parameters Jurassic series

Analysis

The Jurassic layers are well known and well described. Parameters show a soft rock (UCS up to 30 MPa and E up to 15.000MPa). The rock is known to be fractured and thus of poor to medium quality. This rock will be easily excavable.

Given the project layout (undergoing the sea) a TBM with active face support is recommended. From the geology, it seems a EPB would be suited. Attention should be paid to the high-water level/pressure and the large tunnel diameter and long TBM sections to be excavated. Maintenance might become a problem.

4. Choice of TBM / Feasibility

With the limited information available it is not possible to decide on the type of TBM. It will definitively be a TBM with a closed mode to support the front. From today's view it could be either a slurry machine or an EBP TBM or eventually even a multimode or crossover TBM. The decision will be taken in a later stage, potentially only as late as from the contractor.

The table below shows the advantages and disadvantages for both soft ground tunnelling systems, slurry-supported Shields and EPB Shields. A multimode TBM presents both the advantages of the EPB and Slurry machines but presents a higher cost and a higher technological complexity.

Criteria	Slurry-supported shield	EPB-shield
Control of support pressure	+ Support pressure control more accurate + Possibility to react very fast	- Support pressure is less accurate - Fluctuation of face support pressure
Settlement control along the shield	+ No need to inject slurry + Uniform distribution of the confining pressure in steering gap	+ Slurry has to be injected (standard in modern EPB) - Non uniform distribution of the confining pressure
High fines content	- High separation effort - Risk of clogging if non-appropriate design	+ Better for soil with high fines content
Sticky material	- Stops have to be planned to clean cutter head, etc.	+ Use of additives allows to minimise impact of sticky ground
High wear soil conditions	+ Less secondary wear, the material is surrounded by bentonite	- High secondary wear - Use of additives allows to reduce wear on cutting wheel
Coarse grained, highly permeable soil with ground water	+ Better face control face support + Less wear + Easier compressed air chamber interventions	- Face control becomes very difficult - More wear - Compressed air interventions without bentonite mud substitution not advisable
Accessibility to tunnel face under high pressures	+ Use of an accessible cutter head for access and maintenance under atmospheric conditions (for diameter >12m)	- Access difficult because face control becomes very difficult.
Accessibility to tunnel face under adverse conditions	+ Faster emptying of chamber + Compressed air application easier + Low temperature + Restart mining with full face pressure conditions	- Longer preparation time - Compressed air application more difficult - Higher temperature (friction) - Restart mining could be difficult - Necessity to plan the production and transport of big quantity of bentonite (depends which D) on the TBM
Face control during long downtime	+ Continuous uninterrupted face support	- Desegregation of foam and soil in excavation chamber - Dessication of the filter cake

Advantages and disadvantages of Slurry and EPB TBM

5. Cost estimation

Based on our experience with similar TBM projects we have performed a cost estimation. In this very early stage of the project we use only two parameters, the length of the tunnel and the number of cross passages. This is enough when we consider the level of information that is available today.

The elements that we have considered to evaluate the cost per meter tunnel are:

- Use of one TBM per tunnel
- Job site installations, incl. TBM
- Tunnelling works
- Segmental lining
- Internal structure

For the cross passages the following parameters:

- Length 20 m
- Cross section 33 m2 (road) resp. 23 m2 (rail)
- Ground freezing
- Job site installations
- Tunnelling works
- Rock support
- Membrane
- Cast in situ concrete lining
- Internal structures

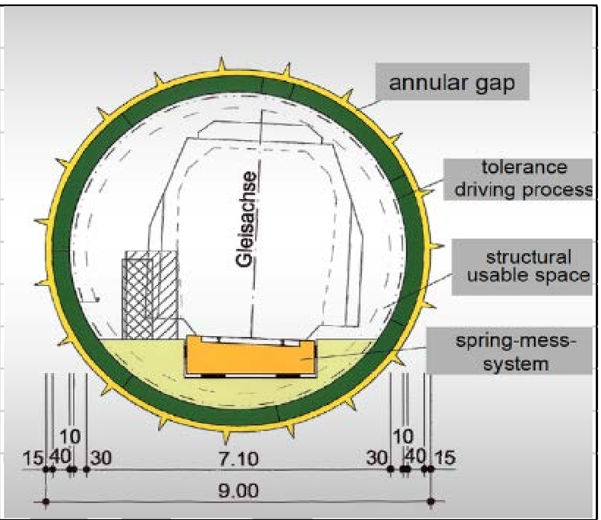
With these elements and the level of details available for this report an accuracy of +/- 30% must be accepted. The costs in showed below cover only the civil part of the tunnel, no installation, no design or client cost, no cost for financing etc.

The two **rail tunnels** with cross passages sum up to 4.5 billion SEK or **5.4 billion SEK** with an additional 20% mark-up for unforeseen.

The respective costs for the longer and much larger **road tunnel** are considerably higher. For two tunnels, including corss passages they sum up to 14 billion SEK ore **16.8 billion SEK** with an additional 20% mark-up for unforeseen.

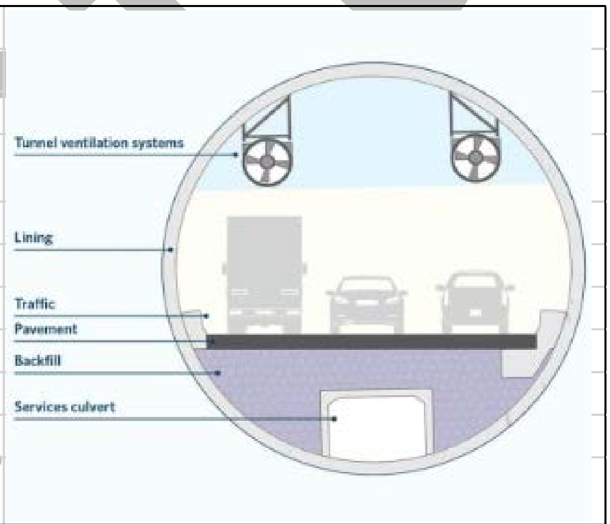
As shown in the chapters before and after there is though some room for optimization, that can be mobilized in the next stages of the project as more detailed information about the geology is available and if the client is ready to enter a discussion about alignment and size of the tunnels.

Length		7'000	m
		14'000	m
Costs	SEK	271'714	/m
	SEK	3'804'000'000	
Cross passages		250	CP/xm
		28	#
Costs	SEK	25'200'000	/#
	SEK	705'600'000	
Total Cost	**SEK**	**4'509'600'000**	



Cost estimation rail tunnel, 9.0 m

Length		11'800	m
		23'600	m
Costs	SEK	512'542	/m
	SEK	12'096'000'000	
Cross passages		250	CP/xm
		48	#
Costs	SEK	39'600'000	/#
	SEK	1'900'800'000	
Total Cost	**SEK**	**13'996'800'000**	



Cost estimation road tunnel, 13.6 m

6. Time schedule

The time schedule showed within this report is based on many assumptions and can only show a rough general estimation as there is no detailed planning available so far.

All tunnels are excavated with one TBM each. The rail tunnel will need two TBM's and so will the road tunnel. Due to the different size of the tunnels, a total of 4 TBM's will be necessary.

From our experience a delivery time of 12 months is sufficient to design and produce a TBM. During this period the contractor must prepare the launching pit and make the site ready for the reception of the TBM.

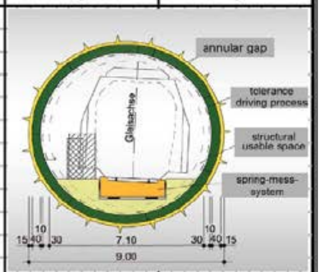
To launch two TBMs it is preferable, when this is not done simultaneously. This allows to separate many of the processes and that is the reason, why the TBM start with a difference of three months.

The excavation of the cross passages is done with ground freezing and starts in parallel with the TBM work. The last cross passage can though only be done, after the disassembly of the second TBM due to logistics reasons.

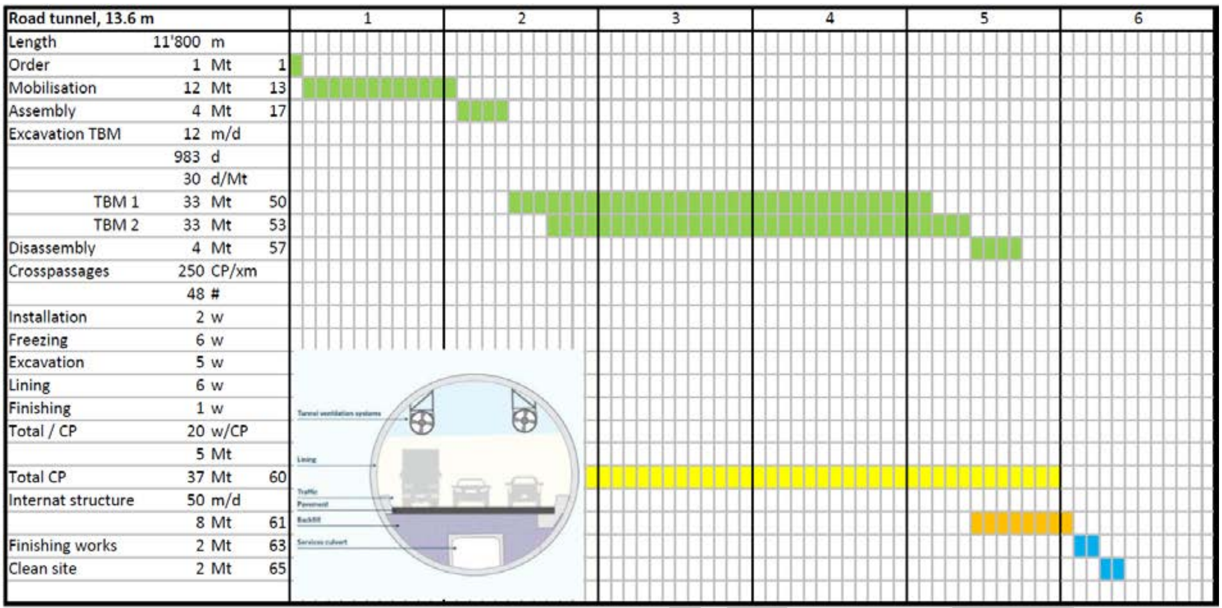
Most work of the invert, such as the cable conduct, the refill of the lower parts and a temporary concrete layer for the logistic is done in parallel with the TBM, under the back up system of the TBM. This allows an efficient logistic to supply the TBM.

The rest of the interior works is done after the break through, in parallel with the disassembly of the TBM.

Rail tunnel, 9.0 m				1	2	3	4	5	6
Length	7'000	m							
Order	1	Mt	1						
Mobilisation	12	Mt	13						
Assembly	3	Mt	16						
Excavation TBM	15	m/d							
	467	d							
	30	d/Mt							
TBM 1	16	Mt	32						
TBM 2	16	Mt	35						
Disassembly	3	Mt	38						
Crosspassages	250	CP/xm							
	28	#							
Installation	2	w							
Freezing	5	w							
Excavation	3	w							
Lining	5	w							
Finishing	1	w							
Total / CP	16	w/CP							
	4	Mt							
Total CP	19	Mt	41						
Internat structure	50	m/d							
	5	Mt	43						
Finishing works	2	Mt	45						
Clean site	2	Mt	47						



Preliminary time schedule rail tunnel



Preliminary time schedule road tunnel

7. Construction sites and logistic

The general concept is to start all TBM's form the Danish side. This means, that most of the logistic needed will be on the Danish side as well. The muck will come out on the Danish side and all supply goods for the TBM's will enter the tunnel also from the Danish side. In consequence the needed area is much larger on the Danish side than on the Swedish side.

For the early stage and within this report the following assumptions are made:

- TBM start on the Danish side
- Slurry TBM will be used, need for separation plant
- The separation plant is located on the site
- The muck is transported to a temporary port near the site by conveyor belt and loaded into a boat.
- The boat takes the muck to wherever the Danish want to create new land for development
- The segmental lining will come to the site either by train or by boat
- The storage on site is limited to the need for one week of production
- The TBM for the rail tunnel is delivered by boat to the temporary port just beside the site and the starting point of the TBM
- The TBM for the road tunnel is delivered by truck on the nearby highway.

Within these circumstances the following area is needed to smoothly organize the site:

	Danish side	Swedish side
Assembly TBM	12'000 m2	-
Paved areas	10'000 m2	5'000 m2
Separation plant	2'000 m2	-
Handling muck	5'000 m2	-
Bentonite tanks	2'000 m2	-
Segmental lining	3'000 m2	-
Workshop	1'000 m2	500 m2
Storage other materials	3'000 m2	1'000 m2
Water treatment plant	1'000 m2	500 m2
Container, parking	6'000 m2	2'000 m2
Concrete / grout storage	1'500 m2	-
Other	13'500 m2	6'000 m2
Total:	60'000 m2	15'000 m2

Space needed for the road tunnel.

	Danish side	Swedish side
Assembly TBM	8'000 m2	-
Paved areas	5'000 m2	5'000 m2
Separation plant	2'000 m2	-
Handling muck	5'000 m2	-
Bentonite tanks	2'000 m2	-
Segmental lining	2'000 m2	-
Workshop	1'000 m2	500 m2
Storage other materials	2'000 m2	1'000 m2
Water treatment plant	1'000 m2	500 m2
Container, parking	4'000 m2	2'000 m2
Concrete / grout storage	1'500 m2	-
Other	3'500 m2	3'000 m2
Total:	37'000 m2	12'000 m2

Space needed for the rail tunnel.

As a basic rule for site installation one could say "the larger, the better". If there is some space available logistic processes can be optimized and generally the work can be organized more efficiently. If less space is available, the contractor will organize himself and live with it. He will most likely find a solution for almost every size of installation area offered to him. This will of course have an influence on costs and time schedule and probably more important also on the resilience of the respective organisation. If the area has a certain size, even unpredictable events can be handled easier and better.

We have focussed very much on the Danish side, as the four TBM will start there and the need of space is much larger than on the Swedish side. A rough evaluation of the situation near the foreseen sites show that there is quite some agricultural area where the road tunnel will start and a heavily used port area where the site for the rail tunnel will be installed. As a consequence, the above-mentioned area for the road tunnel can be considered rather large and optimized for the contractor's work, whereas the size for the rail tunnel is rather minimized.

Installation area Folloline, NO

In general, one needs to understand, that the required site at the surface is not very much dependent on the size of the TBM. So, in fact both tunnels would need more or less the same size, and the differences mentioned above come more from the existing use of the areas next to the portals.

8. Recommendations

Due to the work done for this report and based on the existing documents available for us we sum up the following recommendations for further investigations respectively additional work in the next step:

Profile road tunnel:

From our point of view the profile for the road tunnel is not enough specified for an optimized evaluation of the size needed. The variation within road tunnels is much higher as in rail tunnels and the space needed should be defined in detail with the client.

- What kind of traffic passes through the tunnel, only cars or trucks as well?
- How large do the lanes need to be, same size for both or can the left ones be reduced in combination with the obligation for trucks to stay on the right lane?
- Does the tunnel really need an emergency lane? If yes, which size?
- What kind of space is further needed for a walkway, or similar?
- How does the drift and maintenance concept work? Where are all the cable installations? Where are the tubes for water and drainage?
- Is there a reason, why the invert is filled up with concrete?

Road Tunnel, Option "Service Space Elements"

Instead of filling the space under the road deck with concrete or other material it could be used as space for cables and water conducts. For this prefabricated service space elements can be used. This could be very important for drift and maintenance, as most cable systems and the water and drainage tubes can be installed there, and thus maintained without entering the tunnel itself. This enables to significantly limit the disturbance of the traffic flow due to maintenance works as it is even possible to do most of the maintenance works at daytime and get away from work during night shifts.

Road Tunnel, Option "Optimized lane concept"

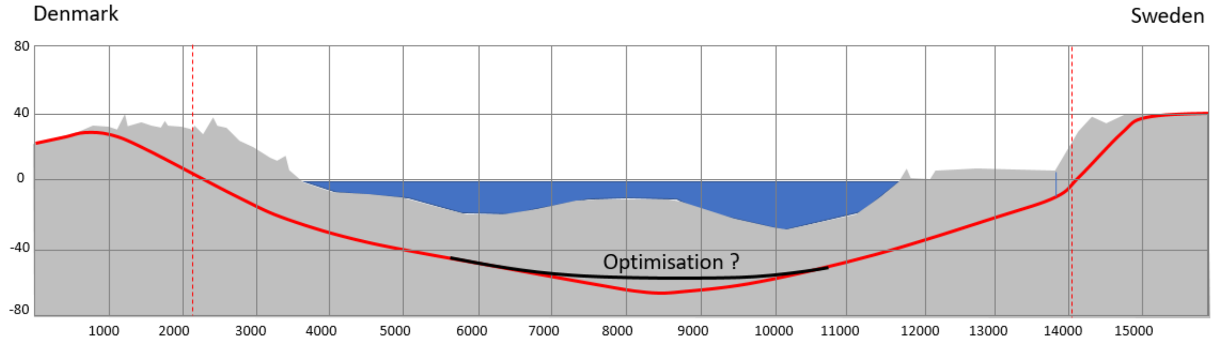
As only 2 traffic lanes are actually planned for this project (+ a rescue lane) we see a potential optimisation in the required width of the tunnel.

- The project Socatop in Paris had two 3 m-width light traffic lanes (no trucks) and one 2,5 m-width rescue lane - in one tunnel.
- The Elbtunnel in Hamburg consists of two 3,75 m-width traffic lane and one 2 m-width rescue lane.

An optimisation would be to consider one 3 m-width light traffic lane (no trucks), one 3,75 m-width "truck" lane and one 2,5 m-width rescue lane. This would result in an inner diameter of approximately 12 m and a TBM diameter of approximately 13,6 m - one meter less than the present design. The cross section of the Elbtunnel would be a good example of an optimized cross section.

Road Tunnel, Option "Optimization vertical profile"

There might be a possible optimisation (see picture below) to reduce the maximal depth of around 10 m. This will reduce the water pressure of around one bar, which is not a game changer, but still gives the TB; more reserves to operate.



Option optimizes vertical profile road tunnel

3D geological model

We strongly recommend to ask the geologists

- to establish a section each, best guess with the information available, in the alignment of the two tunnels.
- to elaborate a rough 3D model of the whole area with sea bed level, rock level and geology
- to put the real alignment data into that model, georeferenced to be able to really check the status of the present design.

Investigation program

We recommend starting an investigation program along the two alignments to get more detailed information about the geology to be expected, including a detailed description of the formations that need to be crossed by the TBM's, the rock surface and even the most important parameters both for the sands and the different rock formations.

Parameters Sans Danish side

Grain size analysis, permeability, E modulus are missing and will definitively be required in the next stage to make an assessment on the TBM Choice.

- **Rail Tunnel**: Given the very low overburden below seabed there might be a real issue and question the feasibility at acceptable risks.

Rail Tunnel, low cover Danish side

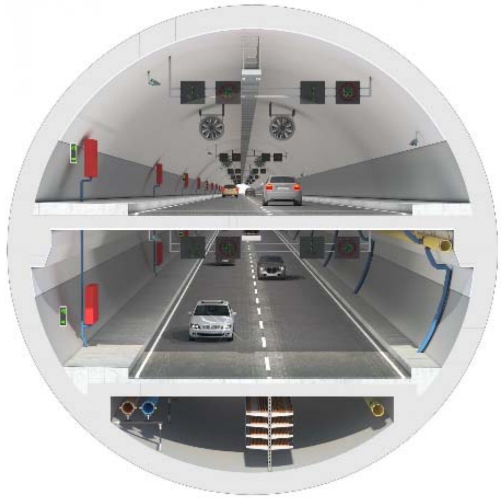
On the Danish side the cover in the sand lowers down to less than one diameter. This is very critical for the use of any TBM. There are technical solutions with the TBM such as grouting or high-density Bentonite => VD TBM to avoid blowout. But in the context of crossing the sea in Sand, with less than one diameter coverage, we would definitively recommend geologically investigating the area in detail and thereafter, eventually to reassess the alignment.

9. Appendix

9.1. List of references

Appendix one shows a list of 19 references that were considered for the present report.

1. Bosphorous Highway Tunnel / Eurasia Tunnel, Istanbul



Length:	3.340 m
Inner D:	12,00m
Bore D:	13,66m
Segmental Lining:	60cm (8+1)
Radius:	1200m
Geology:	Sandstone, claystone, volcanic rocks + active fault zone
Max W. Pressure:	9.2 bars (at crown)
TBM:	MixShield
Charachteristics:	Designed to support 12 bars Single tube with two levels 2 x 2 traffic lanes No safety/stop lane

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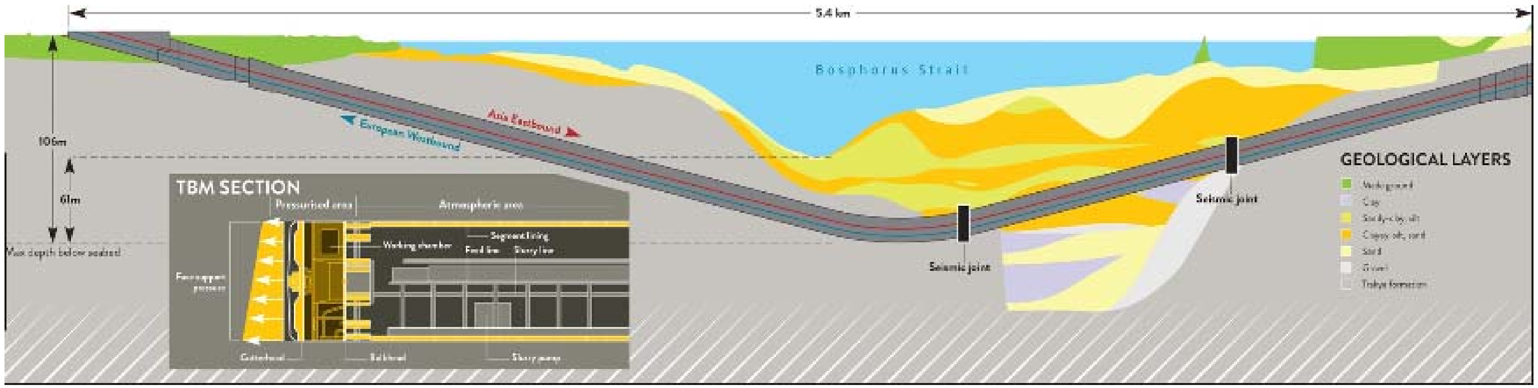
1. Bosphorous Highway Tunnel / Eurasia Tunnel, Istanbul

- Sandstone/mudstone of Trakya Formation: 67%
- Dyke inclusions of Trakya Formation: 3%
- Transition zone with rock and soil: 10%
- Sandy soils: 13%
- Clayey/Silty soils: 6%
- Coarser grained soils/cobbles: <1%



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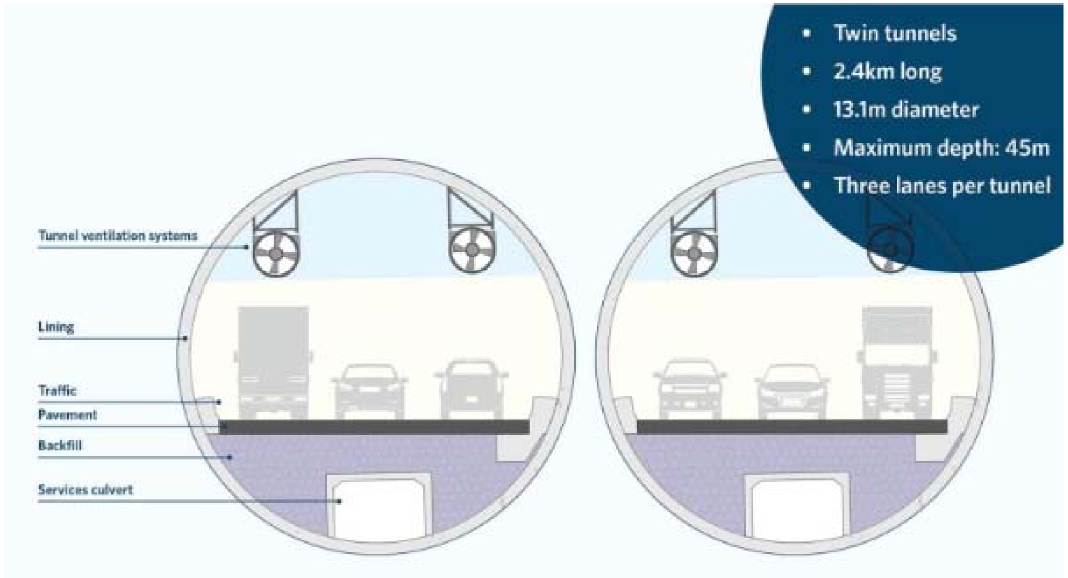
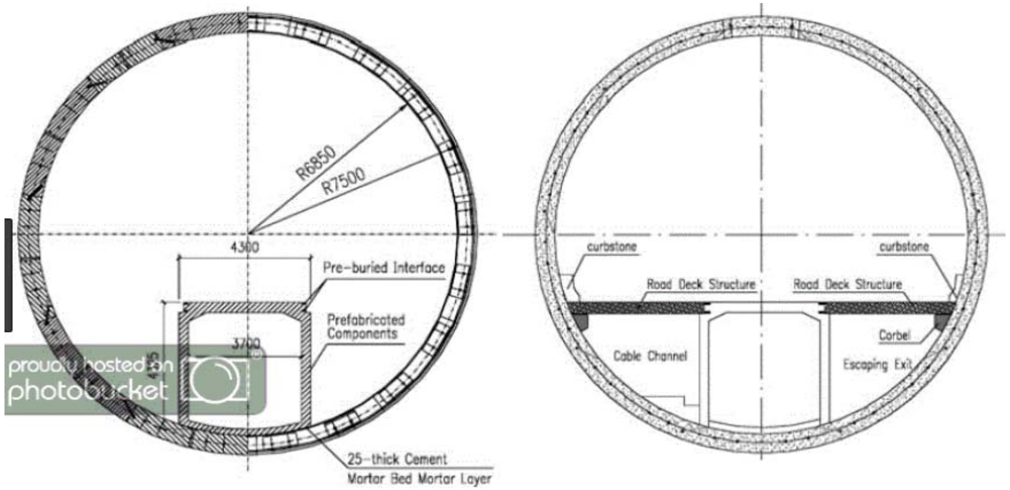
2. Waterview Tunnel Auckland

Length:	2 x 2.400 m
Inner D:	13,10m
Bore D:	14,41m
Segmental Lining:	45cm (9+1)
Radius:	500m
Geology:	Clay, Silt, Sand, Sandstone
Max Depth:	45 m
Max W. Pressure:	5.3 bars (at invert)
TBM:	EPB
Charachteristics:	3 lanes per tunnel Designed to support 5.3 bars Two tubes with 3 lanes No safety/stop lane

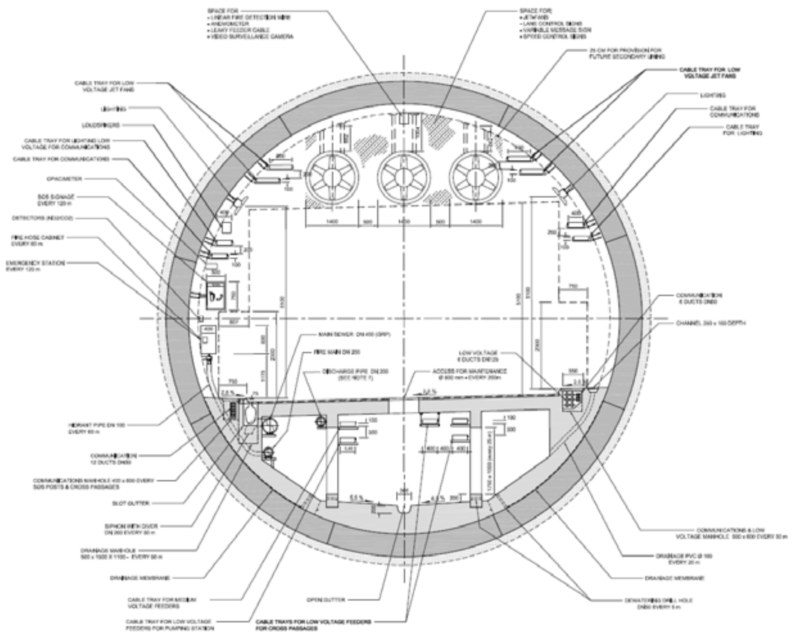




2. Waterview Tunnel, Auckland

- Very weak sandstone with interbedded laminated silstone: 76%
- Clay, Silt and sand: 7%
- Deposits from volcanic flow, comprising sand to boulder sized breccia and conglomerate: 17%

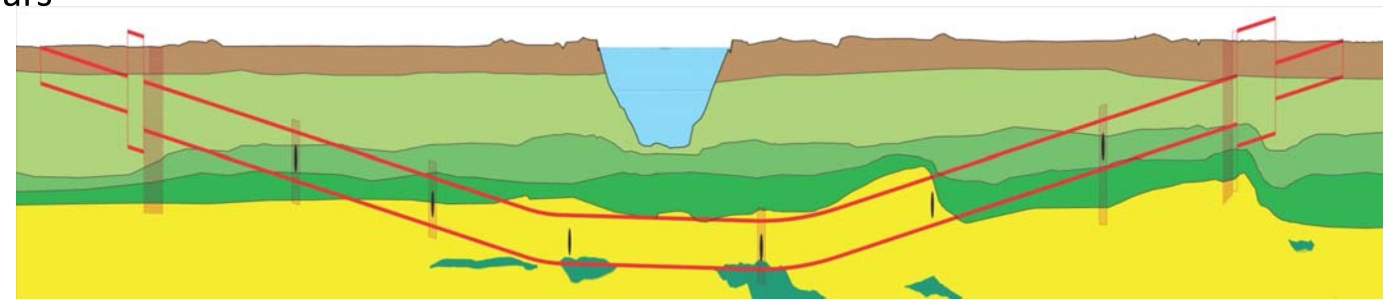
3. Port Said Road Tunnels, Egypt



Length:	2 x 2.800 m
Inner D:	11,40m
Bore D:	13,05m
Segmental Lining:	60cm
Gradient:	3,3%
Geology:	very soft to soft Clay, Sand, Silt
Max Depth:	49 m
Max W. Pressure:	5 bars (at invert)
TBM:	MixShields
Charachteristics:	2 lanes per tunnel Designed to support 6 bars Two tubes with 3 lanes No safety/stop lane

Geology

- Layer 1:
  - Clay to Silt, very soft to mainly soft
  - Clay, rarely with lenses of silt, very soft to mainly soft
  - Clay, rarely with lenses of silt, mainly firm, locally soft to stiff
  - Clay, rarely with lenses of silt, mainly firm to mainly stiff
- Layer 2: Sand, mainly fine to medium grained, occ. silty with lenses of stiff to hard clay, dense to very dense
- Layer 3: Clay, lenses in matrix of dense to vary dense sand, stiff to hard



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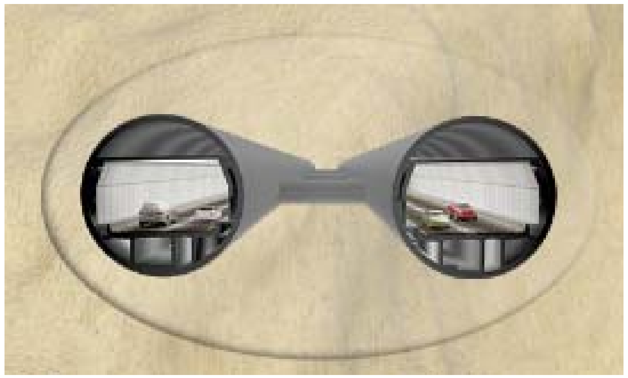
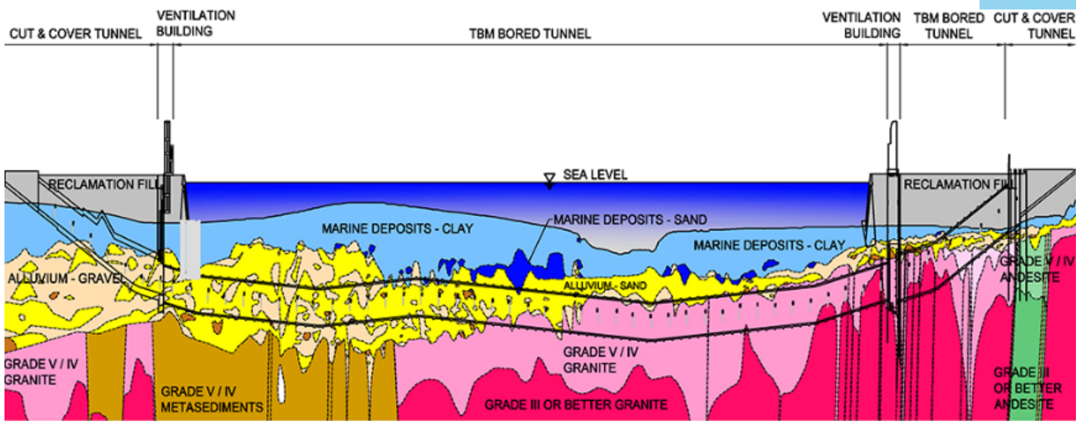
4. Tunnel Tuen Mun - Chek Lap Kok, Hong Kong

Length:	2 x 4.200 m
Inner D:	~13,00m
Bore D:	~14,5m
Segmental Lining:	60cm
Geology:	Sand, Gravel, weathered granite, Granite
Max Depth:	40 m
Max W. Pressure:	5.5 bars (at crown)
TBM:	MixShields
Charachteristics:	2 lanes per tunnel
	Designed to support 6 bars
	No safety/stop lane





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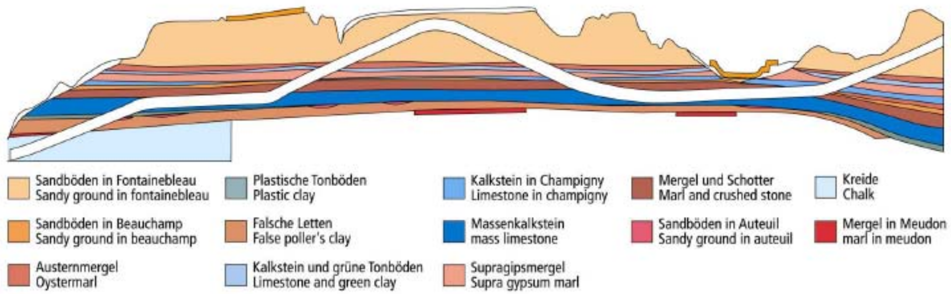
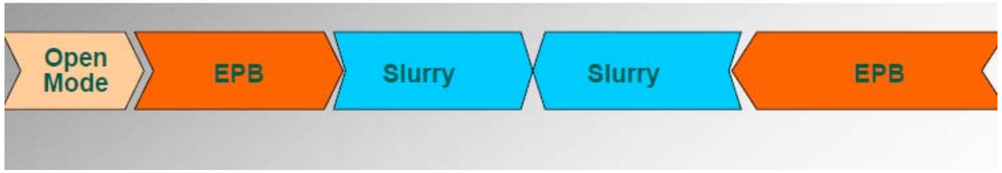
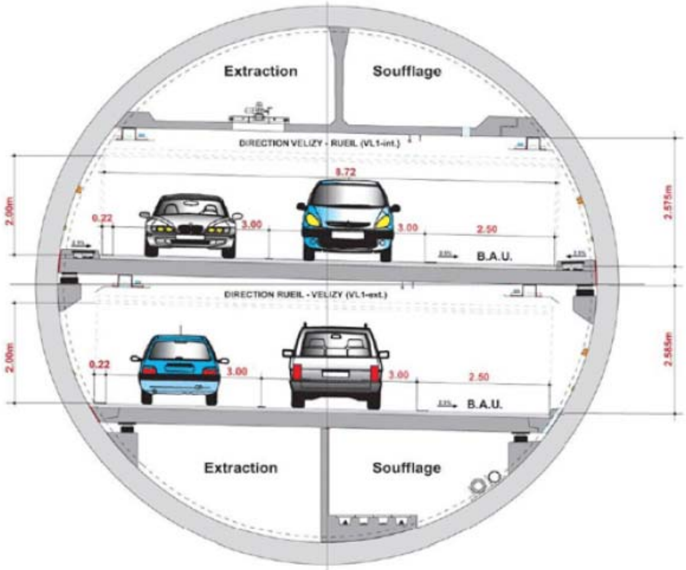
5. A 86 – SOCATOP, Paris

Length:	10.500 m
Inner D:	10,40m
Bore D:	11,58m
Segmental Lining:	40cm
Gradient:	-
Geology:	Limestone, Sand, Clay, Marl, Chalk
Max Depth:	~75m
Max W. Pressure:	-
TBM:	Convertible
Charachteristics:	Dubble Deck
	2 lanes per level + Safety lane
	Access to tunnel strictly limited to light weight vehicles (W<3,5to, H<2 m)

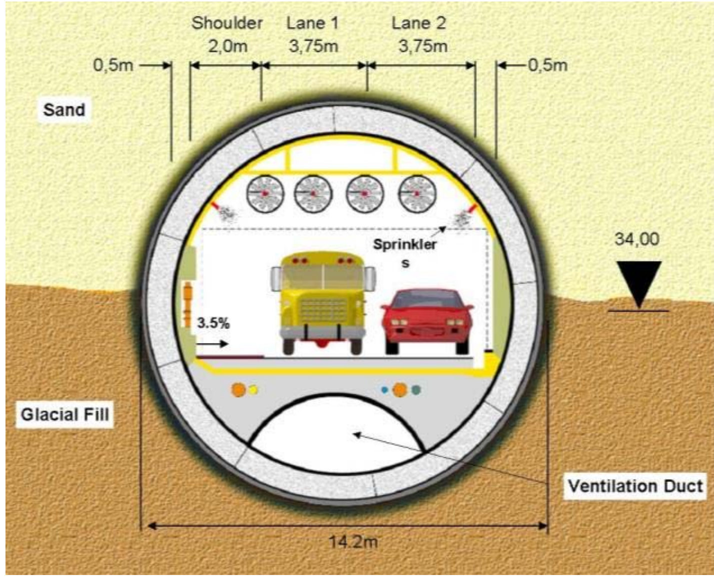


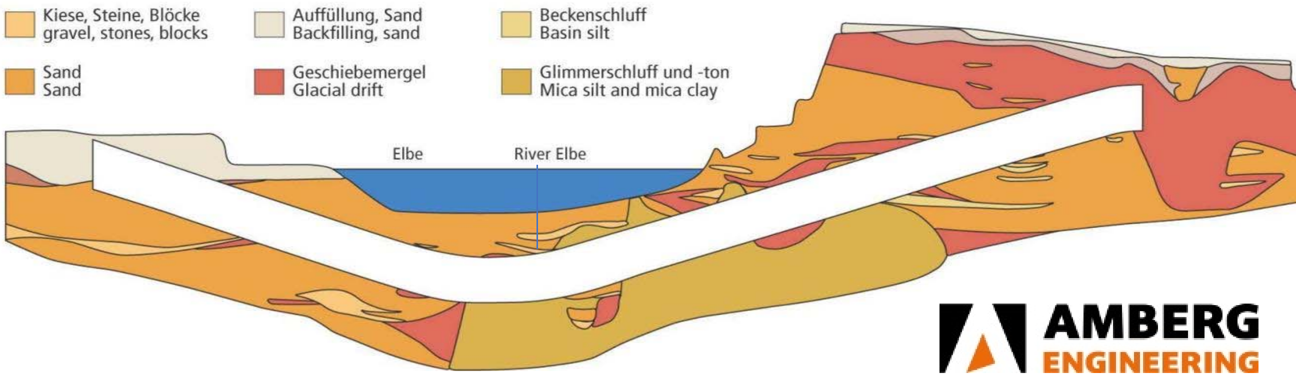




6. Elbtunnel, Hamburg

Length:	2.560 m
Inner D:	12,35m
Bore D:	14,22m
Segmental Lining:	70cm
Radius:	800m
Geology:	glacial drift, silt and gravel, sand, boulders
Max Depth:	40 m
Max W. Pressure:	3 bars (at crown)
TBM:	MixShield
Charachteristics:	2 lanes per tunnel Designed to support 4,5 bar Two tubes with 2 lanes with safety/stop lane





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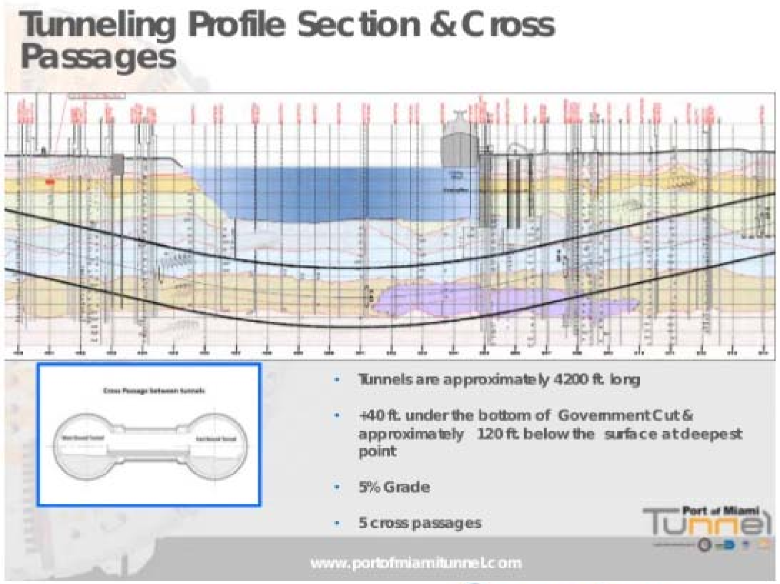
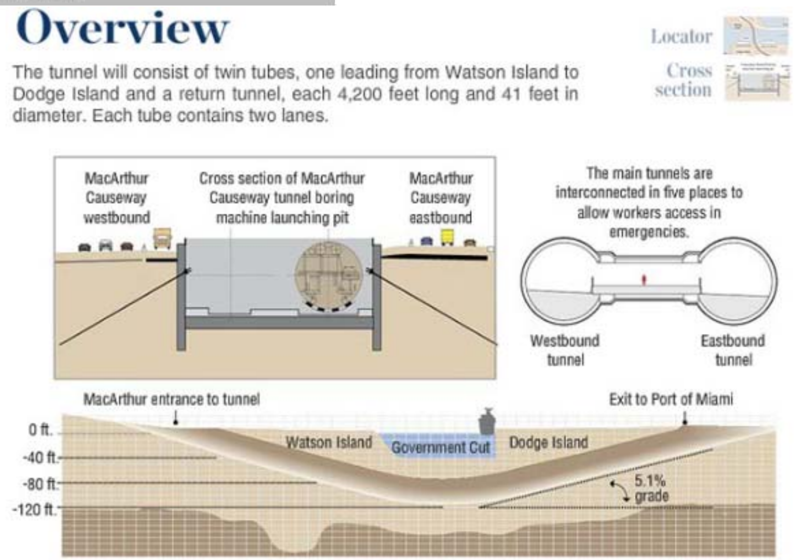
7. Miami Port Tunnel, Miami

Length: 2.338 m
Inner D: 11,30m
Bore D: 12,86m
Segmental Lining: 60cm
Curve: 250m
Gradient: 5,1%

Geology: Silty Sand, Weak Limestone
Max Depth: 36m
Max W. Pressure: 2.0 bars (at crown)
TBM: EPB
Charachteristics: 2 lanes per tunnel
Designed to support 4 bars
Two tubes with 3 lanes
with safety/stop lane





8. SMART TUNNEL, Kuala Lumpur

Length:	5.400 m
Inner D:	11,83m
Bore D:	13,21m
Segmental Lining:	55cm
Curve:	250m
Gradient:	3%
Geology:	70% karstic limestone and sections in compact and fresh marble, 30% quaternary alluvial deposits (silty, gravely sand) and mine tailings
Max Depth:	-
Max W. Pressure:	-
TBM:	Mixshield
Charachteristics:	Dubble deck tunnel 2 lanes per level (no safety lane) Designed to support 3 bars

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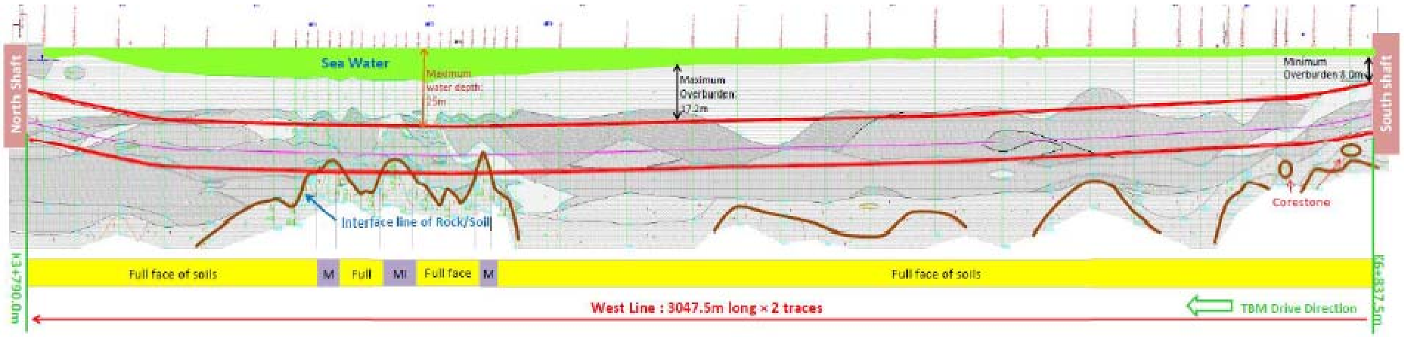
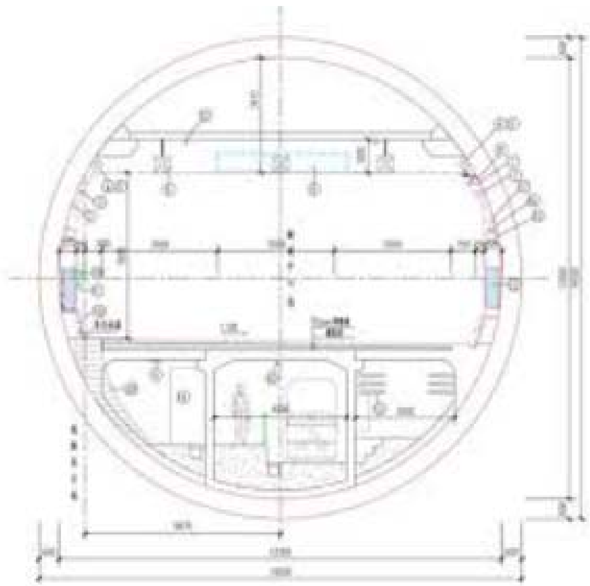
9. Shantou Su Ai Project, China



Length: 3.050 m
Inner D: 13,3m
Bore D: 14,90m
Segmental Lining: 60cm

Geology: Sandy and clayey soils, section of very hard granite (UCS up to 200MPa)

Max Depth: 17.2m (crown)
Max W. Pressure: 2.5 bars (at crown)
TBM: Mixshield
Charachteristics: Dubble deck tunnel
3 lanes per tunnel level (no safety lane)
Designed to support 4 bars
Accessible CW



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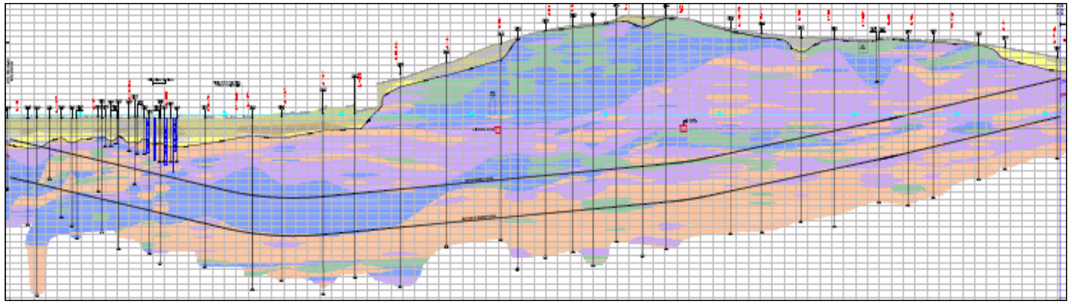
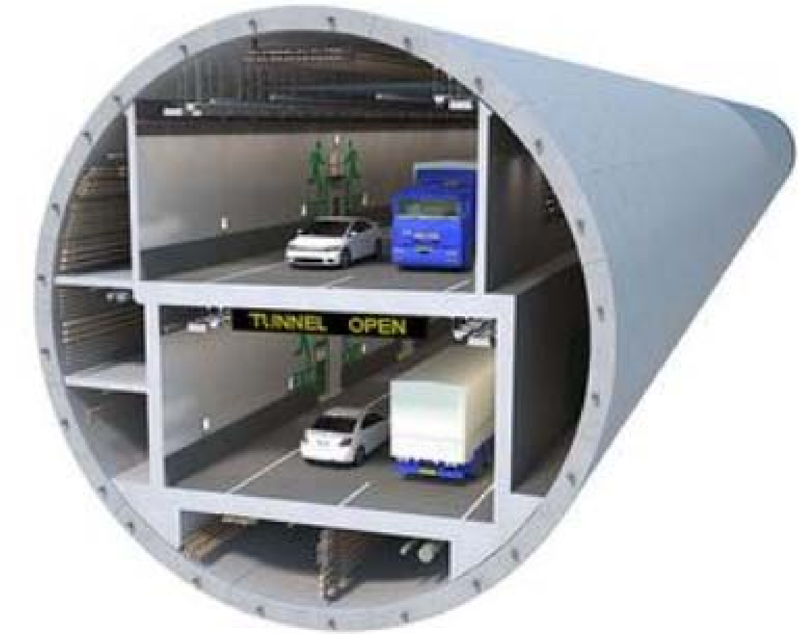


10. Alaskan Way, Seattle

Length:	2.830 m
Inner D:	~15,70m
Bore D:	17,48m
Segmental Lining:	~70cm
Geology:	65% Cohesionless sands and gravels 35% Cohesive material
Max Depth:	66m (crown)
Max W. Pressure:	3,6 bars (at crown)
TBM:	EPB
Charachteristics:	Double deck tunnel 2 lanes per tunnel level (+ safety lane)



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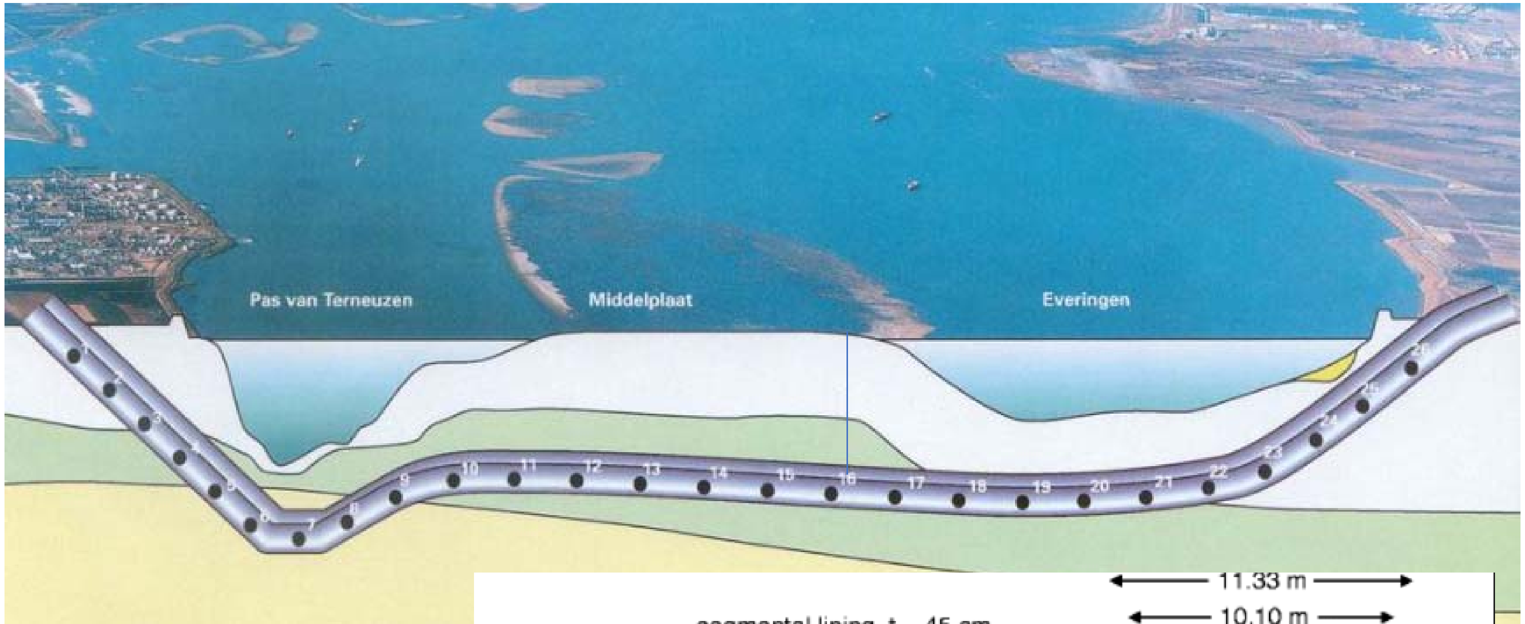
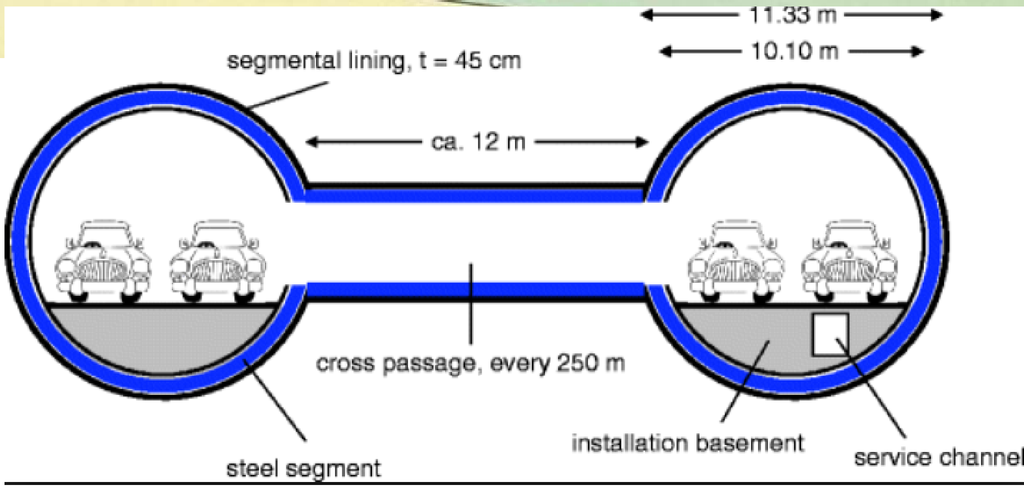
11. Changjiam Under River Tunnels, Shangai

Length:	7.170 m
Inner D:	13,70m
Bore D:	15,43m
Segmental Lining:	~65cm
Radius:	4000m
Gradient:	2,9%
Geology:	Sand, Clay and Rubble
Max Depth:	60m (crown)
Max W. Pressure:	6 bars (at crown)
TBM:	Mixshields
Charachteristics:	2 lanes + rescue lane (upper level) Service and safety tunnel (lower level) Accessible CW

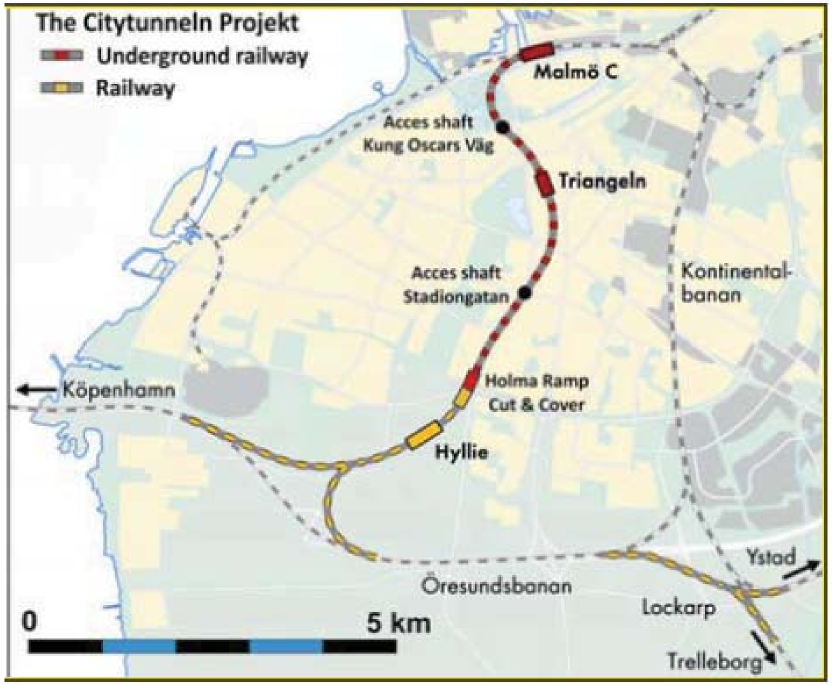
12. Westerschelde,

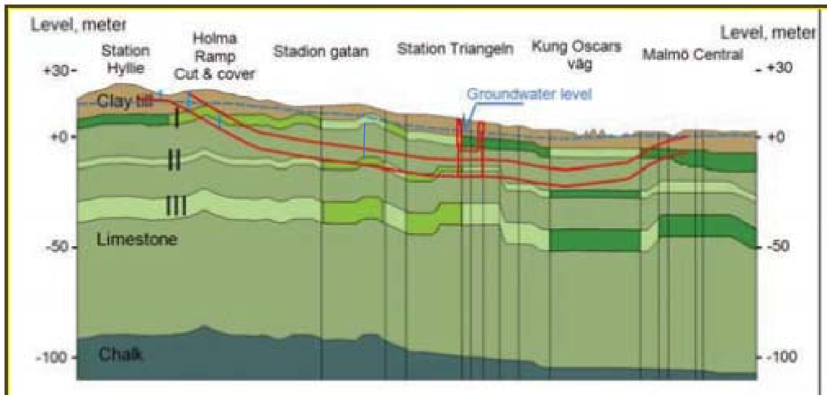
Length:	6.600 m
Inner D:	10,10m
Bore D:	11,36m
Segmental Lining:	~45cm
Radius:	-
Gradient:	-
Geology:	Sand, Clay
Max Depth:	52m (crown)
Max W. Pressure:	7 bars (at crown)
TBM:	Mixshields
Charachteristics:	2 lanes, no rescue lane





RAIL TUNNELS





13. Malmö City Tunnel, Malmö

Length: 4.623 m
Inner D: 7,90m
Bore D: 8,89m
Segmental Lining: 35cm
Radius: 400m
Gradient: 2,2%

Geology: 93% Limestone (anisotrop, strongly weathered), 4% Limestone (strong risses), 3% alluviums
Max Depth: 22m (crown)
Max W. Pressure: 1,8 bars (at crown)
TBM: EPB
Charachteristics:

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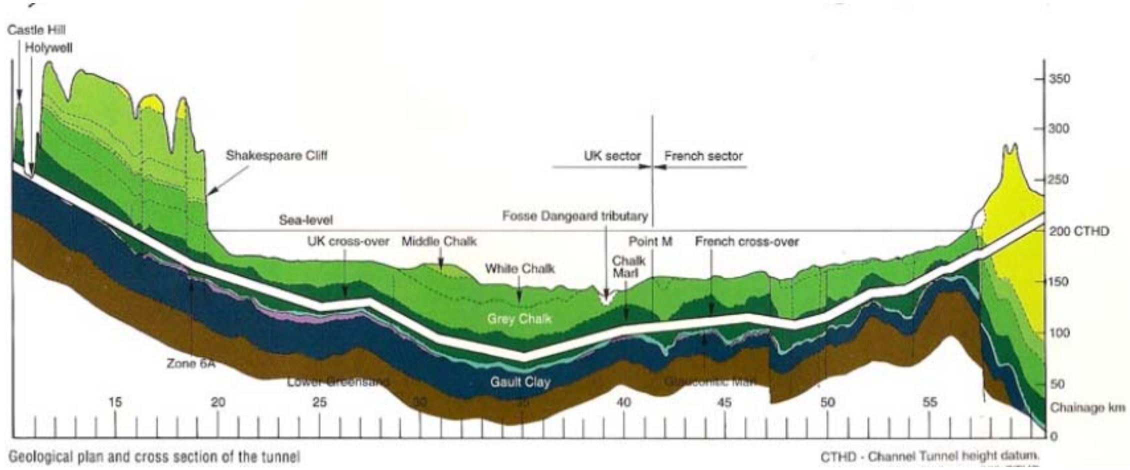
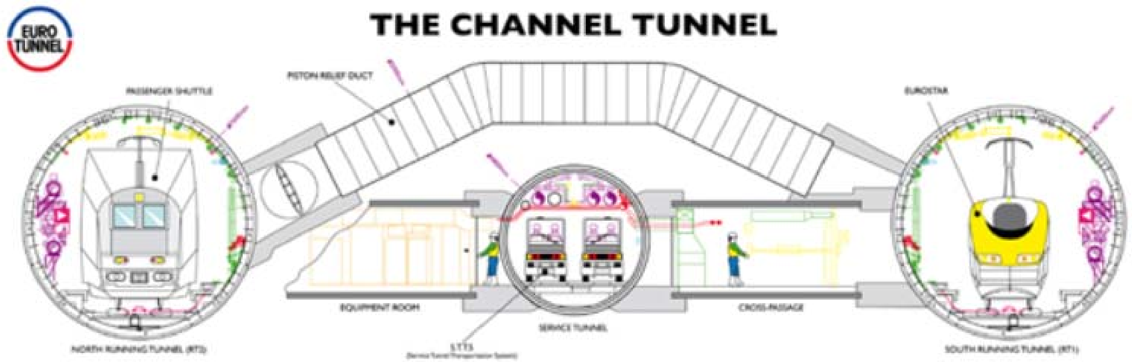
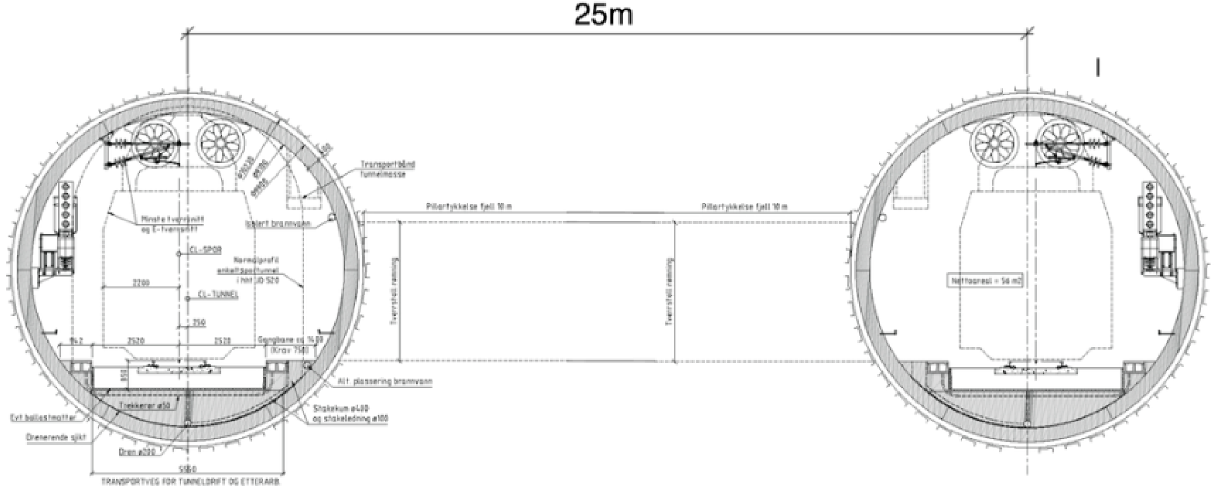
14. Channel Tunnel, England-France

Length:	50.500 m
Inner D:	7,60m
Bore D:	8,8m
Segmental Lining:	45cm
Geology:	Chalk Marl
Max Depth:	75m (crown)
Max W. Pressure:	107 m below water level
TBM:	EPB
Charachteristics:	Service Tunnel D4,8m (TBM 5,6m - 30cm) Piston relief duct





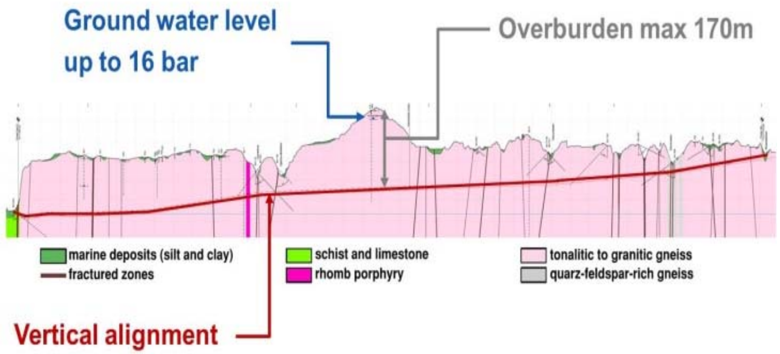
15. Follobanen, Oslo - Ski



Length: 20.000 m
Inner D: 8,75m
Bore D: 9,96m
Segmental Lining: 40cm
Radius: -
Gradient: -

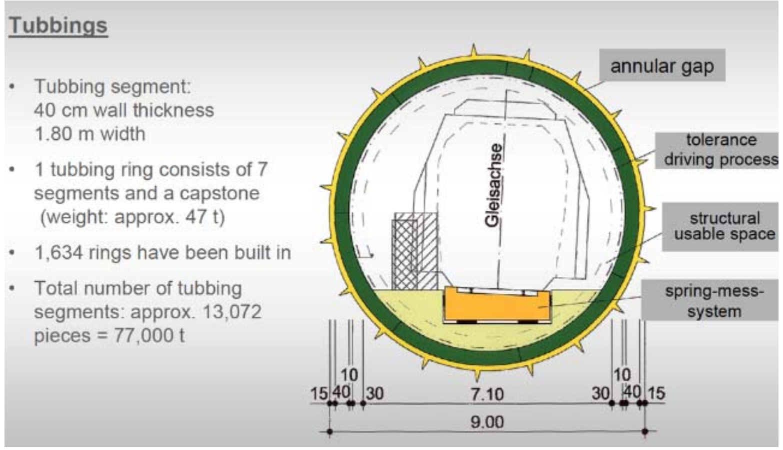
Geology: Precambrian gneiss, Amphybolite dykes and rhomb porphyry intrusions

Max Depth: 170 m
Max W. Pressure: High ground water level
TBM: Double Shield
Charachteristics:



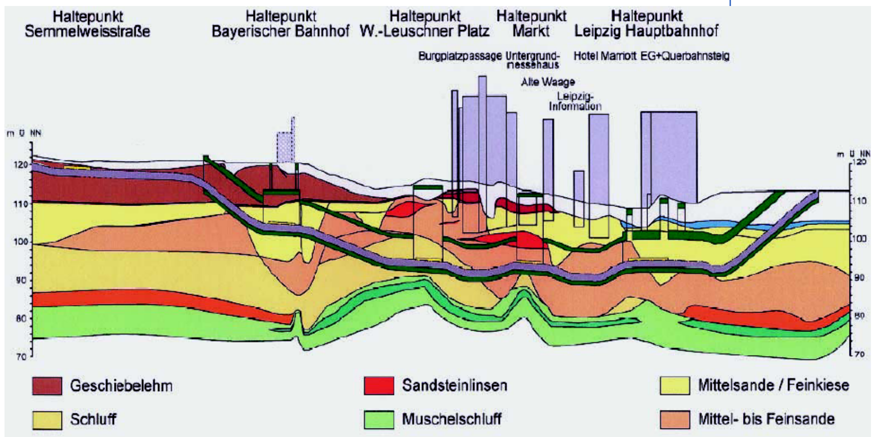
16. Hallandsas, Sweden

Length:	5.500 m
Inner D:	9,04m
Bore D:	10,53m
Segmental Lining:	54cm
Radius:	2.500m
Gradient:	0,3%
Geology:	Gneiss, Amphibolite, Diabase dykes
Max Depth:	-
Max W. Pressure:	High ground water level
TBM:	Convertible (MixShield – Hard Rock)
Charachteristics:	**Design for 15 bar**



17. Leipzig City Tunnel, Leipzig

Length:	**1**.780 m
Inner D:	7,90m
Bore D:	9,00m
Segmental Lining:	40cm
Radius:	360m
Gradient:	3,5%
Geology:	Sand, Silt, Gravel, lenses of Sandstone
Max Depth:	20 m
Max W. Pressure:	1,8 bar (tunnel invert)
TBM:	MixShield
Charachteristics:	



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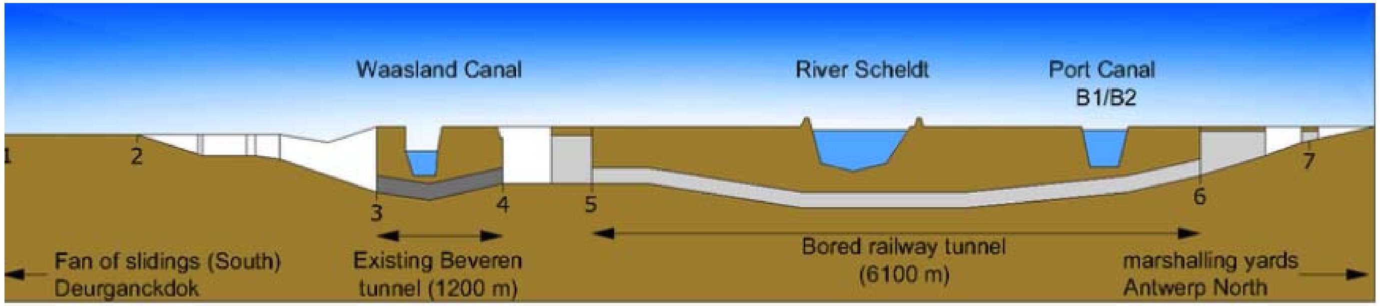
18. Liefkenshoek Tunnel, Antwerpen

Length: **6**.000 m
Inner D: 7,30m
Bore D: 8,39m
Segmental Lining: 40cm
Radius: 500m
Gradient: 2,0%

Geology: Sand, locally Boomse Clay

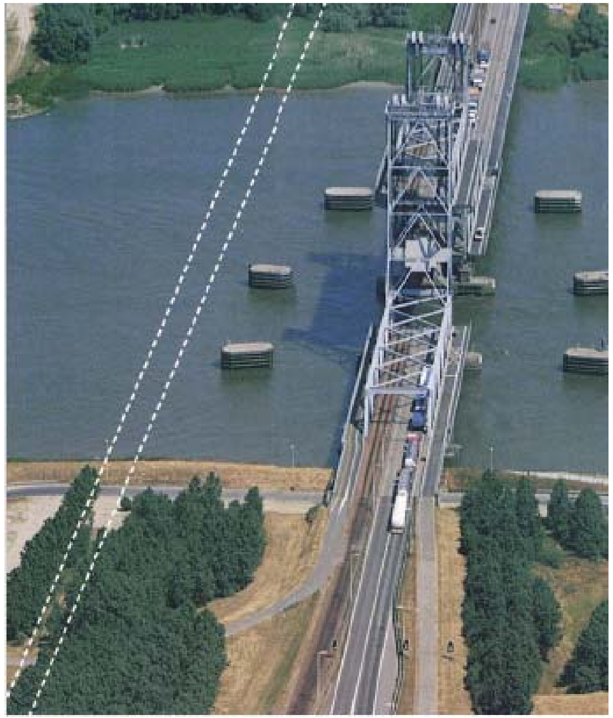
Max Depth: 28 m (at crown)
Max W. Pressure: 2,8 bar 8at crown)
TBM: MixShield
Charachteristics: Designed for 4,5bar

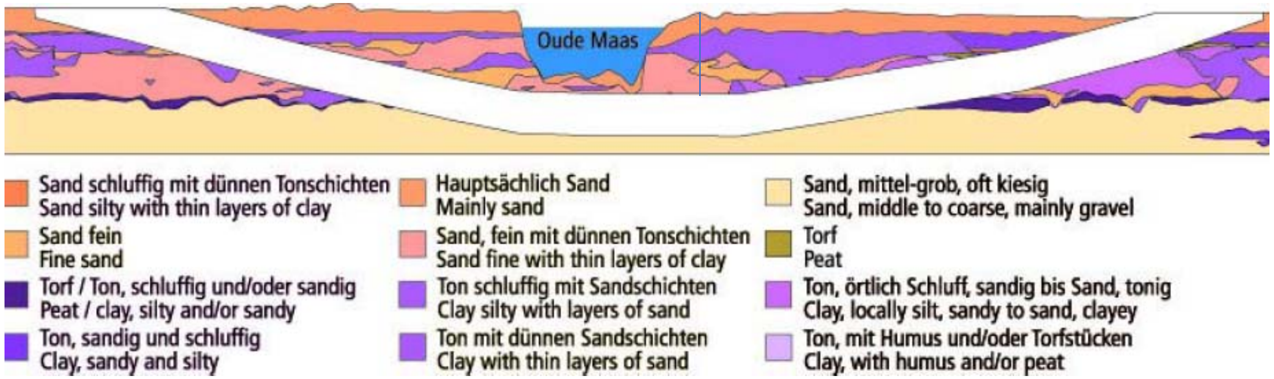


1-2 Zone along E34/N49
2-3 Zone along R2
3-4 Existing Beveren tunnel
5 Departure shaft drilled tunnel
5-6 newly drilled railway tunnel
6 Arrival shaft drilled tunnel
7 Crossing R2

19. Botlekspoortunnel, The Netherland

Length:	1.835 m
Inner D:	8,650m
Bore D:	9,755m
Segmental Lining:	40cm
Radius:	-
Gradient:	-
Geology:	Clay, Coarse and gravelly sand
Max Depth:	~20 m
Max W. Pressure:	~1,8 bar (at crown)
TBM:	EPB
Charachteristics:	Piston Pump Designed for 3bar





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