Invited lecture: Geotechnical aspects of the Storebælt Project

Conférence sur invitation: Aspects géotechniques du projet Storebælt

Niels Krebs Ovesen – *Danish Geotechnical Institute, Lyngby, Denmark*

ABSTRACT: Two major traffic projects are under construction in Northern Europe in 1997: The Storebælt and the Øresund Links. A feasibility study for a similar project is under way for the Femer Bælt. The paper describes three unconventional solutions to geotechnical problems encountered during construction of the railway tunnel in Storebælt. One solution deals with prediction of the probability of occurrence of large boulders in the ground during tunnelling. Another solution concerns the reduction of high hydrostatic pressures in the ground around the tunnel during mining by means of dewatering technology known from onshore applications. The third solution demonstrates the use of a membrane placed at the seabed above a tunnel section damaged by fire to protect crewmen during repair of the tunnel.

RESUME: Deux projets routiers essentiels sont en construction en Europe du Nord en 1997: les liaisons de Storebælt et Øresund. Pour Fehmarn Belt une étude de faisabilité pour un projet similaire est en cours. Cet article décrit trois solutions non-conventionelles aux problèmes géotechniques rencontrés pendant la construction du tunnel ferroviaire de Storebælt. Une solution traite de la prévision de la probabilité de l'occurence de grands blocs rocheux dans le sol pendant la construction du tunnel. Une autre solution concerne la réduction de pression hydrostatique élevée dans le sol autour du tunnel, pendant l'excavation, à l'aide d'une technique d'épuisement connue par ses applications à terre. La troisième solution démontre l'utilisation d'une membrane placée au fond de la mer, au-dessus d'une section du tunnel endommagée par le feu, pour protéger les ouvriers pendant les réparations du tunnel.

1 INTRODUCTION

The Kingdom of Denmark is located in northern Europe. It consists of a peninsula, Jutland, and a large number of islands. Two of these, Zealand and Funen, serve as stepping-stones for the train and road traffic between Scandinavia and the continent. A third island, Lolland, serves in a similar way as a stepping-stone for traffic to Germany.

The land based traffic in the region is met by obstacles in the form of belt crossings as illustrated by Figure 1. The domestic traffic between Zealand and Funen will have to cross Storebælt. The traffic from Sweden to Zealand will have to cross Øresund. Traffic from Denmark to the European continent may cross the border in the southern part of Jutland or cross the Femer Bælt.

A large number of ferry boats serves trains and cars at these belt crossings. A trip by ferry boat may be quite enjoyable. However, the belt crossings constitute a significant geographical impediment to speedy traffic connections. To illustrate the point the traffic volume across the Danish-German border is 4 times greater than the traffic across the Storebælt.

Figure 1. Map of Denmark with the geographical positions of the two projects under construction, the Storebælt and the Øresund links, and the proposed Femer Bælt link.

1.1 *The Storebælt Link*

Storebælt divides Denmark into 2 halves. For more than 100 years a fixed link - bridge or tunnel - between Zealand and Funen has therefore been subject to numerous political discussions.

It was, however, not until 1987 that the Danish parliament made the final decision to commence the construction of a fixed link across Storebælt. This link is in 1997 in its final stage of construction.

The general scheme of the Storebælt project is shown on the map on Figure 2. Located to the left is Funen and to the right Zealand where the Danish capital Copenhagen is located 120 km to the east. Storebælt is 18 km wide and in the middle a small island, Sprogø, is located dividing Storebælt into the Western Channel and the Eastern Channel. The water depth in the Western Channel is about 25 m. In the middle of the Eastern Channel the water depth is 58 m.

The Storebælt fixed link consists of a 4-lane motorway and a 2-track railway and it comprises 3 main projects: A bored railway tunnel and a motorway suspension bridge across the Eastern Channel and a combined motorway and railway bridge across the Western Channel.

The western bridge has a total length of 6.611 km. It consists of two separate bridge decks for railway and road traffic; the two decks rest on common bridge piers. The railway tunnel under the Eastern Channel has a total length of 8.024 km. It consists of twin main bores. The road bridge over the Eastern Channel has a total length of 6.790 km of which 2.700 km is a suspension bridge with a main span of 1.624 km.

The western bridge was completed in 1994. The railway tunnel was completed so rail traffic across Storebælt could begin in June 1997. The eastern suspension bridge is very near its completion,

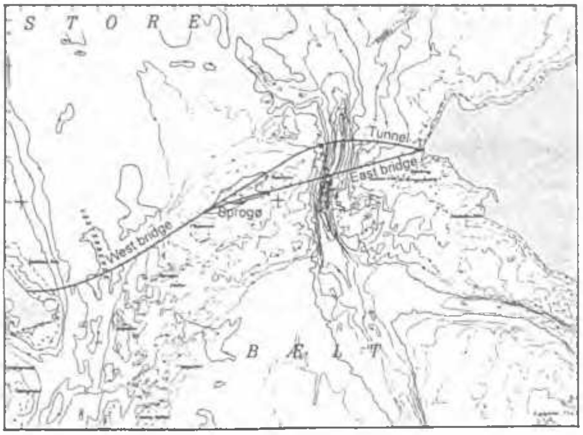

Figure 2. Map of the central part of the Storebælt with the alignment of the Fixed link.

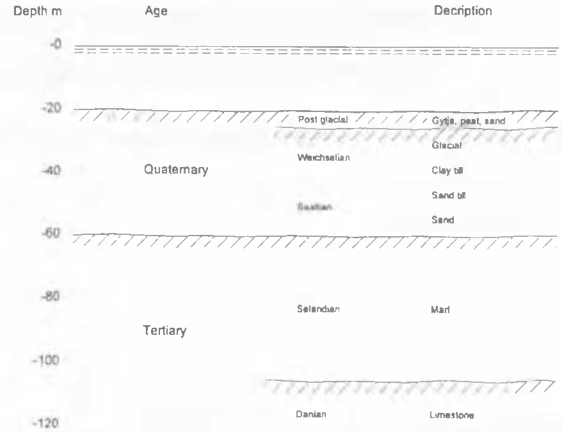

Figure 3. Geological classification of the ground conditions in the Storebælt along the tunnel alignment (depths are indicative only).

and it is expected that road traffic can cross Storebælt from the early summer of 1998.

1.2 *The Øresund Link*

In 1991 the Danish and the Swedish government made a joint decision to establish a fixed link across Øresund between the Danish capital, Copenhagen, and the Swedish city Malmö. In 1997 this project is well under way.

The Øresund fixed link also consists of a combined 2-track railway and a 4-lane motorway. They leave Denmark from Amager close to Copenhagen airport from an artificial peninsula. They run through a 3.5 km long immersed tunnel and come into daylight on an artificial island 4 km long. Then they enter a bridge with a total length of almost 8 km. At the eastern end the terminal area is located at Lernacken just south of the Swedish city Malmö.

1.3 *The Femer Bælt Link*

Around 1994-95 the German and the Danish governments decided to initiate a feasibility study for a fixed link across Femer Bælt. Preliminary geotechnical and environmental investigations were made in 1995-96. The feasibility study is still under way and it could take quite many years before a decision on construction of a fixed Femer Bælt link is taken.

1.4 *Financing of the projects*

The Danish government has established a fully state owned limited liability company called A/S Storebæltsforbindelsen - abbreviated Storebælt - to be responsible for the planning, design, construction and operation of the Storebælt link. The Swedish and Danish governments has established a similar company called Øresundskonsortiet for the Øresund link.

The financing of the Storebælt and Øresund fixed links is based on the principle of user-payment. For practical purposes this means that construction costs and other expenditures during the construction period is funded by loans and such loans will be repaid through tolls levied on the users of the fixed links. The loans are guaranteed by the Danish government for the Storebælt link and by the Danish and Swedish governments for the Øresund link. This arrangement has given both Storebælt and the Øresund Consortium a very high credit rating which helps to secure favourable borrowing terms.

1.5 *Content of paper*

Danish and Swedish geotechnical engineers have had a very interesting professional life for the last 10 years. Geotechnical investigations, geotechnical design aspects and geotechnical execution problems have been numerous on these three projects.

The present paper will concentrate on three not-so-conventional solutions to geotechnical problems encountered in the projects. All three solutions relate to the bored railway tunnel in Storebælt.

Readers interested in detailed information on the design and construction of the Storebælt east tunnel are referred to a book published by Storebælt (1997). Various geotechnical aspects of the Storebælt and Øresund link projects are treated in the Proceedings of the XI European Conference on Soil Mechanics and Foundation Engineering (1995).

2 TUNNEL GROUND CONDITIONS

Site investigations for the Storebælt link have been carried out by the Danish Geotechnical Institute in five campaigns since 1962. The Eastern Tunnel alignment was identified following investigations in 1986 and detailed pre-tender investigations were made in 1987.

The 1987-investigations consisted of 44 boreholes drilled offshore from jack-up platforms. They were drilled within a 200 m wide tunnel corridor using shell and auger techniques in the quaternary and core drilling in the pre-quaternary.

In the upper mainly glacial deposits undisturbed or disturbed samples were taken at 1 m intervals for geological classification and extensive laboratory testing supplemented by in-situ vane tests. In the pre-glacial formations continuous core samples were obtained for classification and testing. In-situ permeability testing and sonic logging were carried out in a number of boreholes.

228 km of analog recorded seismic survey was carried out in the tunnel corridor using Pinger, Sparker and Boomer sources in conjunction with Side Scan Sonar surveys.

During construction the tunnel contractor made supplementary investigations in areas where information from earlier investigations was uncertain or inadequate. These included boreholes, seismic reflection surveys and a large number of pumping and other in-situ tests in connection with the MOSES-project.

The ground investigations revealed that the tunnel would be constructed in glacial soils and underlying calcarious marls. Figure 3 shows a simplified typical ground profile on a location with a water depth of 20 metres.

The Danian limestone and Selandian marl were deposited in a shallow marine basin in the Storebælt area. Ice sheets of the Saalian and Weichselian glaciations eroded the upper Selandian deposits to form an undulating plateau dipping to the North and cut by valleys. The lower glacial deposits contained rafted Selandian material or marl floes. Locally the glacial deposits from the widespread Saalian glaciations which covered Europe north of the southern Holland were largely eroded and reworked by the Weichselian ice sheets.

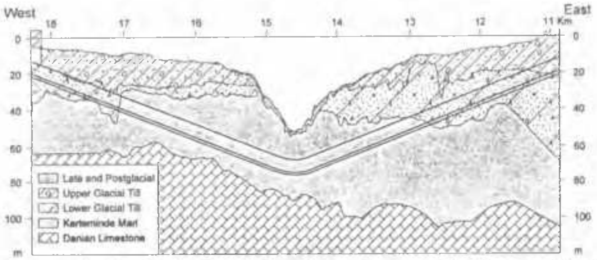

Figure 4. Geological profile along the tunnel alignment in the Storebælt.

The late Weichselian ice sheets developed from the South and the glacial advances, retreats and interstadials resulted in a series of terminal moraine, ice borderline and melt water deposits. These form prominent surface features in the Storebælt area, and the tunnel alignment follows such an ice borderline.

Following the retreat of the ice sheets the glacial deposits were eroded away in a deep channel in the eastern part of the Storebælt. This is evident from the geological profile along the tunnel alignment as seen from Figure 4. In the channel post-glacial deposits are directly overlaying the marl. On the shoulders of the channel till formations cover the marl which again is overlaying the limestone.

The glacial deposits consist of clay till, sand till and silt, sand and gravel lenses and layers. They are divided into the lower till - predominantly sand till - and the upper till - predominantly clay till. Major melt water channel sand bodies are present at the base of both upper and lower tills. Within the lower tills the sand bodies are often hydraulically connected forming extensive aquifers.

Generally, till is classified as clay till when the clay size content is > 10% and as sand till when the clay size content is < 10%. Both sand till and clay till may contain boulders of varying sizes - up to several metres in diameter.

The tills are over-consolidated. Typical values of their geotechnical properties are presented in Table 1. A low water content, a high bulk density and a high shear strength is typical for such a glacial material; its coefficient of permeability may be considered high for clay tills.

Table 1. Typical values of ground parameters for glacial till and marl encountered in the Eastern Tunnel area.

		Glacial till	Marl	
			H1	H2-4
Water content	w %	8-13	25-35	
Unit weight	γ kN/m^3	23	19-20	
Shear strength				
• undrained	c_u MPa	0.1-0.7	0.3-0.6	1.5-10
• drained	c' kPa	20	20-3300	
	φ °	35	28-45	
Coefficient of permeability	k m/s	10^{-7}-10^{-5}	10^{-7}-$5 \cdot 10^{-4}$	

The marl is classified on the basis of a simple indicative strength parameter, induration, in the range H1 to H4. The marl is a rock mass with sub-horizontal parallel joints. The joints form the major flow path in the rock mass. They are formed by the unloading following retreat of the ice sheets. Open sub-vertical fissure systems are locally present giving a high coefficient of permeability. The strength properties fall within a wide range as seen from Table 1.

All relevant geological and geotechnical information has throughout the project been compiled in a 3-D Geomodel for the whole project area. The Danish Geotechnical Institute cooperated in the development of the Geomodel which was used for the alignment studies, during the construction phases and for filing of all relevant geotechnical information.

3 THE TUNNEL

Figure 2 shows the alignment chosen for the tunnel. The reason for selecting a tunnel alignment curving to the North with a maximum distance of approximately 1 km from the bridge alignment is to take advantage of the shallower depth of water there and at the same time observing railway design criteria and also to keep the tunnel within the preferred ground conditions.

The tunnel consists of twin 7.7 m internal diameter main tunnels. They were constructed principally of pre-cast concrete segmental rings bolted together and sealed with synthetic rubber gaskets. The length of each bore was 7.400 km with the rails 75 m below seabed level at the deepest point. The minimum ground cover above the bores was approx. 15 m at tunnel mid-point and approx. 10 m at each end. The main tunnels are separated by 25 meter between centres and connected at approx. 250 m intervals by cross passages to house equipment and to provide emergency escape routes for passengers and railway staff.

4 TUNNEL BORING MACHINES

It was predicted that the marl provided a material well suited for tunnelling and this proved to be true. The problems anticipated were connected to tunnelling in the glacial tills. Two types of problems were foreseen; they may be characterised by the two words: boulders and water.

Special precautions had to be taken in the design and construction of the tunnel boring machines in order that they would be able to tackle these two problems - and many others for that matter.

Storebælt decided that 4 tunnel boring machines should be used to drive the tunnels in order to reduce the time of tunnelling and reduce the consequences of possible machine failures or breakdowns.

The type of tunnel boring machines used was shielded, full face machines able to work against an earth-water pressure of 8 bars. The ground conditions necessitated the use of earth pressure balanced machines.

The cutter-head had a diameter of 8.75 m. It had 188 picks for the soft ground and 56 disc cutters for granite boulders and the marl. Located behind the cutter-head was the main bulkhead which was designed to withstand earth pressures up to 8 bar. The excavated ground was mixed with additives and transported backwards into the machine by two screw conveyors. The bulkhead had an in-built airlock which allowed manned intervention inside the mixing chamber between the cutter head and the bulkhead.

It was necessary on a regular basis to carry out maintenance work inside the mixing chamber. In order to reduce the risk of face instability developing in the glacial tills the high pore water pressure encountered in the ground had to be balanced with the use of compressed air. Tasks to be performed under compressed air included replacement of picks and disc cutters and other repair work.

5 PROBABILITY OF THE OCCURRENCE OF BOULDERS

From the ground investigations it was verified that almost 50% of the length of the tunnel would be mined through glacial tills. It is general geotechnical knowledge that glacial till may include large boulders. In tills in Denmark more than 100 boulders, each with a largest dimension of more than 3 m, have been found during construction work over the years. It was consequently assumed that a traditional tunnel boring technique could be hampered by the occurrence of such boulders.

The boulders mainly consist of granite. In principle it would not be too difficult for the disc cutters at the cutterhead to grind their way through a boulder with a diameter of say 2-3 m. This would only require that the boulder was kept locked in a fixed position in the glacial till. This could, however, not be expected to be the case: after some grinding the boulder would begin to rotate as a result of the forces from the cutterhead. The cutterhead would then have to be stopped in order to cut and remove the boulder manually from inside the mixing chamber. This takes time - and it costs money. As precise knowledge as possible of the size and number of boulders which could be expected to be met in the glacial till was crucial to the tunnelling contractors in their bid for tender.

In order to establish statistical information on the probability of occurrence of boulders which could be included in the tender material a special statistical investigation was therefore initiated.

Prior to this investigation the Danish Geotechnical Institute had in the early eighties attempted to form a rough estimate based upon general experience of geotechnical engineers supported by interviews with qualified contractors, geologists and others. This estimate was mainly based on experience from excavations and other construction work in glacial till.

It was, however, realized that concrete data was needed to form a reliable estimate. That such statistical data could be established became evident when it was realized that on beaches in front of glacial till cliffs remains consisting of gravels, cobbles and boulders from the previous, now eroded part of the cliff are found. Where these remains have been uninfluenced by other activities - e.g. construction of breakwaters - careful counting and measuring of each boulder can be made and related to the estimated amount of eroded fill.

Counting and measuring were made quite easily by aerial photography of cliff beaches with subsequent stereometric measurement on the photographs. The areas of observation were defined as reaching from the foot of a cliff to the waterline. The position as well as main dimensions of each single boulder were recorded at seven locations in the Storebælt area with a total length of 2.200 metres. This represented a volume of 290.000 m^3 glacial till. Boulders larger than 0.4 metres were recorded. They totalled 1.052 boulders.

The analysis revealed a remarkable simple relative size distribution of the boulders. It transpired that the number of boulders whose largest dimension exceeded an arbitrary amount by 0.5 metres decreased by a factor 10 for each such increase of 0.5 metres. In other words the size distribution was exponential.

The usefulness of the statistical information obtained with regard to specifying reference conditions for the tunnel mining naturally depended on whether the unknown distribution of boulder sizes along the tunnel alignment was the same as that found along the 7 cliff beaches. However, a further observation supported this conclusion. The size distribution could not be shown as significantly different at the 7 beach localities even though these localities were widely spread over the entire Storebælt region.

The statistical data obtained from counting and measuring boulders on the beaches were supplemented by observations made from the seismic surveys conducted in the tunnel corridor. Small paraboloid curves on the seismogram could with some reservations be interpreted as defining the presence below the seabed of boulders with vertical dimensions larger than 0.5 metres - one quarter of the wave length of the sonar signal. The results from the seismic measurements fitted well with the observations from the cliff beaches in the Storebælt region.

Figure 5 summarizes the results of the statistical investigation. N is the expected number of boulders with maximum size larger than D per 100.000 m^3 of glacial till. The figure represents the statistical estimate with its 95% confidence intervals, while the shaded area represents a rough estimate made by the Danish Geotechnical Institute during the early eighties. Keeping in mind that a total volume of 400.000 m^3 glacial till was to be mined during tunnel construction, the statistical investigation predicts that between 2 and 8 boulders with a maximum size larger than 2 metres could be expected to be found during tunnel mining.

The result of the boulder investigation was summarized in the contractual reference conditions as a basis for design of the cutter heads and transportation systems of the tunnel boring machines. It was further recognized in the specifications that ground treatment could be required for the removal of boulders from the cutter heads.

Contractor and Storebælt representatives systematically recorded the boulders from the first 61.500 m^3 of tunnel excavation in the upper till. The result of this recording is presented in

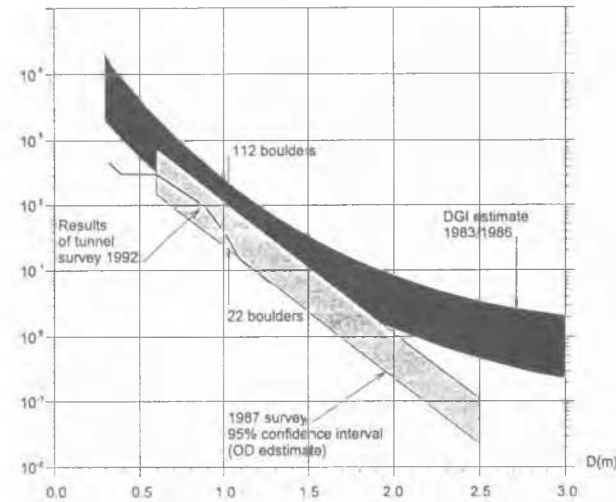

Figure 5. Pre-tender assessment of expected number N of boulders with maximum size larger than D per 100,000 m^3 of till and of direct measurements made during the tunnel excavation in 1992 of the first 61,500 m^3 of till (after East Tunnel (1997)).

Figure 5 for a total of 22 boulders. The number recorded was well within the estimated 95% confidence interval.

No further mentioning was made by the contractor about the number and size of boulders. It may be taken for granted therefore that in general the occurrence of boulders has fallen well within the numbers specified in the contractual reference conditions. In other words, even for such an unconventional problem careful geotechnical investigation may be used to establish a sound basis for design and construction.

6 ACCIDENTAL FLOODING

During one weekend in October 1991 a hydraulic connection was established between the water of Storebælt and the mixing chamber of the tunnel boring machine Jutlandia coming from the west. This hydraulic connection was established through 12 meter of clay till cover while maintenance was been carried out on the screw conveyor. Up until this time the faces seen when entering the mixing chambers in the tunnel boring machines had been stable over long periods. This had led to a false sense of security and on the weekend in question both bulkhead door and man lock were left open and unguarded in contravention of agreed procedures.

Water ingress through the glacial till developed rapidly to such a volume that it was impossible to secure either the access-opening in the screw conveyor or the bulkhead door. As result water inundated Jutlandia and the adjacent machine Fionia and flooded part of the Sprogø work site.

Fortunately there was a jack-up dredger nearby and clay was excavated and dumped on the seabed above the location of the tunnel boring machines. This plugged the hole in time to prevent the flood water rising high enough to damage the groundwater lowering system that was maintaining the stability on the man-made island at Sprogø.

After the situation was considered stabilized, divers entered the tunnel and closed the door openings in the bulkhead and screw conveyor. The flood water could then be pumped out and replacement and reconditioning of all electrical systems and components could start. This was very time consuming and the machines stood still for about eight months.

Subsequent investigations showed the clay till above the tunnel boring machines to be firm and stable. In the clay till a funnel about 2 metres in diameter had been formed. This funnel was eventually permanently plugged from above by concrete. After this incident procedures to ensure that uncontrolled access holes were never opened in the bulkheads or screw conveyors were

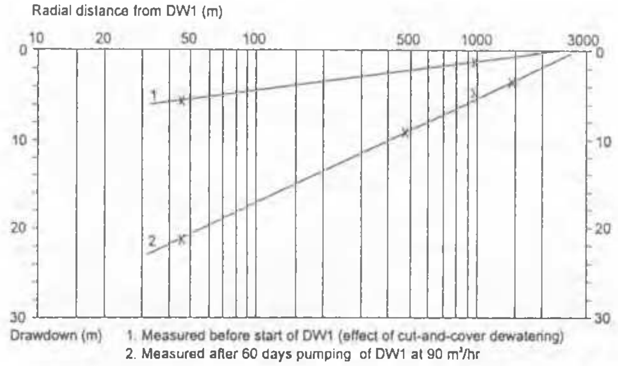

Figure 6. Drawdown in the marl, Halsskov trial (after East Tunnel (1997)).

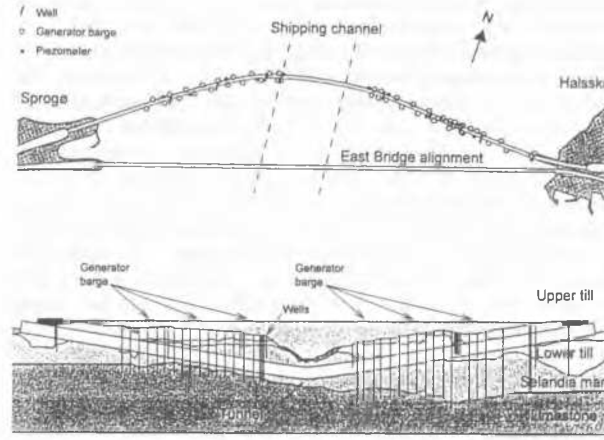

Figure 7. Project MOSES layout (after East Tunnel (1997)).

strictly enforced. In addition manned interventions were to be undertaken only after the face had been examined by experienced geologists.

The flood had a lasting effect on the project. Many working procedures and methods had to be changed.

It was also the flood that inspired geotechnicians to make practical use of observations they had made concerning the effect of ground water lowering in the Selandian marl in connection with the excavation for the ramp and Cut-and-Cover tunnel at Sprogø. It was observed that dewatering for the Sprogø ramp with a yield of about 1200 m^3/h produced draw downs of more than 2 m in geotechnical boreholes for the anchor block west 3 km off shore the ramp area.

A number of test wells were installed on shore as well as off shore and the effect on the pore water pressure due to dewatering was tested by pumping tests. Figure 6 presents results from well DW1 installed in the Selandian marl near the Halsskov ramp area. Line 1 represents the draw down before start of pumping from DW1 due to the effect from the ongoing ground water lowering scheme for the ramp. After 60 days of pumping from well DW1 with a capacity of 90 m^3/h a draw down presented by line 2 was observed. In other words, by pumping from the Selandian marl reduction in pore water pressures could be achieved at distances of more than 2 km away and even considerable pore water pressure reductions in the above glacial tills were observed. This effect was attributed to the fact that water tended to flow horizontally in the formations under the Storebælt.

7 PROJECT MOSES

Against this background the concept of reducing the pore water pressures at the tunnel axis along the alignment by dewatering wells from the seabed was conceived, developed and implemented. This specific project was given the name MOSES - an acronym formed from Method to Obtain Safety by Emptying Storebælt.

The main objective of the scheme was to reduce the pore water pressure at the tunnel axis to 3 bar or less to aid the tunnel boring machine operations so that conventional compressed air techniques could be used for manned interventions into the mixing chamber of the machines.

The project was developed over a 1 year period from mid-1992 and it was gradually adjusted as the results of well drilling, pumping tests and hydrological modelling came in. The general lay-out is shown in Figure 7. Pumping wells were arranged in 6 groups; 3 on each side of the 58 m deep central shipping channel. Each well group was powered from an anchored generator barge and consisted of 5-8 pumping wells and 1-3 piezometer wells.

The wells were generally located every 125 metre along the alignment and alternating 35 m to one or the other side of the alignment. The wells were drilled by the Danish Geotechnical Institute from jack-up rigs. The wells had a 300 mm diameter steel casing in the glacial till; they were un-cased in the marl but with slotted PVC screens at the pumps. The wells were completed by the installation of a stainless steel well-head at sea bottom level. The well-head was installed by divers. It was designed to include pressure transducers and flow meters in order to monitor and control the flow of water from the wells into Storebælt. Grundfoss submersible pumps were used in the wells.

The main data for the MOSES project is given in Table 2. The total number of pumping wells in project MOSES was 49, the total nominal capacity was 3100 m^3 per hours and 12 piezometer wells were installed. The floating barges carried the diesel generators for the pumps. On a continuous basis data from the MOSES system were sent on shore to a control room which was permanently manned.

Over the area of influence the reduction of water pressure over the tunnel axis varied from about 3.5 bar in the marl to 1-2 bar in the tills which achieved the aim of reducing ground water pressure at the tunnel axis to less than 3 bar so that men could enter into the mixing chamber of the tunnel boring machines. Locally, draw-down could be less and recovery rates could be high after pump stopping.

Table 2. Main data for project MOSES.

• 49 pumping wells (12"-16")	
Depth: -35 to -115 m (2,900 m drilled)	
Yield range per well	15-120 m^3/h
Total yield	3,100 m^3/h
Total yield	45,000,000 m^3 during operation
• 12 piezometer wells (8")	
• 6 generators each producing 455 kW	

MOSES could not control the pressure in the central channel, where there was no till cover over the marl. As a result pressures here sometimes approached the full hydrostatic pressure of 7.5 bar at tunnel axis due to faulted marl zones. Also in the tills the benefits of MOSES were occasionally cancelled by over-mucking establishing hydraulic connections to the Storebælt, and thus full hydrostatic pressure.

However, generally the results obtained in reducing pore water pressure around the tunnel allowed manual intervention in the mixing chamber in many areas of the tills and the marls where it would otherwise have been impossible. All the manned interventions were successfully carried out in safety. Some even without compressed air being needed to steady the face. Also the interventions were possible at lower pressures than would otherwise have been the case, which increase the effective working time in the chamber.

The tunnel boring machines were unable to rotate their cutter heads when pressure in the working chamber rose above 2 bar until water was added to lubricate the material. After MOSES had been established less force was exerted in the forward direction.

Consequently mud freely passed between the arms into the chambers where a controlled amount of water was added to condition the mud for easy handling by the screw conveyors.

One disadvantage from the MOSES was that owing to the reduced head it was necessary to delay the final acceptance of tunnel water tightness until the full hydrostatic pressure had been restored. This led to the need to recharge the ground through some cross-passage wells. But this was a minor consequence compared to the benefits.

The total costs of MOSES was some 180 mio. DKK. There is no doubt that such an expense was well justified. Project MOSES considerably reduced the risk of delays to program and as such the results must be assessed on the cost of delays which could have occurred, but may have been prevented by project MOSES.

The scheme worked because of the unique combination of increasing permeability with depth and the permeability of the marl that meant that dewatering could be achieved with a reasonable small number of wells. Although developed to meet the geological and hydrological conditions of the Storebælt and the specific requirements of the tunnel boring machines used, project MOSES proved that with some ingenuity land based dewatering technique can successfully be adapted for marine application.

8 FIRE IN DANIA

In the summer of 1994 when completion of the two tunnels were in sight disaster struck again in the form of a very serious fire. This happened in the northern bore in the tunnelling machine Dania coming from the east. The fire was most likely caused by a bust hydraulic hose. It was established that the fire had been fed by some 2000 litres of hydraulic oil escaping form one of the tanks.

Fortunately, no lives were lost and no one was injured. Unfortunately the controls for the sprinkler and foam systems were not connected to the emergency power supply. The fire brigade therefore had to abandon the tunnel and let the fire burn itself out.

After 36 hours the tunnel had cooled down sufficiently for crewmen to reach the front of the tunnel boring machines were the fire had begun. Here they found the precast concrete lining at the tunnel crown to be severely damaged. Subsequent detailed inspections by engineering staff revealed heavy spalling of the front five concrete rings. At the worst place only 130 mm of the original 400 mm concrete thickness remained.

9 PROTECTION OF WORKMEN IN THE DAMAGED TUNNEL

Emergency repairs by shotcreting were preformed immediately but there was a continued risk of collapse especially because a hydraulic connection to the seabed had developed through the overlaying soil while mining for the damaged rings. The tunnel was therefore abandoned and closed by temporary bulkheads while safe final repair solutions were developed.

The scheme chosen was to protect the damaged rings by an inner lining of cast iron. This reduced the inner diameter of the tunnel by 0.5 meter which necessitated some modifications to the railway installations. To increase safety against collapse the repair operation had to be performed under compressed air so the temporary bulkhead needed to be equipped with both manlock and materials lock.

The scenario was now the following: crew would have to work behind the bulkhead under compressed air repairing the damaged section. If, however, the damaged concrete roof in the tunnel collapsed during repair the workmen would literally have to run for their life in order to escape into the manlock in the bulkhead. This scenario brought the national labour inspection on to the scene. They required that the contractor could warrant that from the time of collapse of the roof a period of five minutes would be available for the repair crew to escape into the manlock before severe floading had developed.

The contractor turned to the Danish Geotechnical Institute in order to obtain an answer to the question: if the concrete roof collapses how many minutes will it then take for a funnel to be formed from the top of the tunnel through the glacial till upwards into the Storebælt? In other words, how many minutes would be required to recreate the initial phase of a flooding like the one that had happened almost three years before with the tunnelling machine Jutlandia coming from the west? The Danish Geotechnical Institute was asked to form an estimate whether it could be warranted that the crew members would have at least five minutes to cover their escape routes.

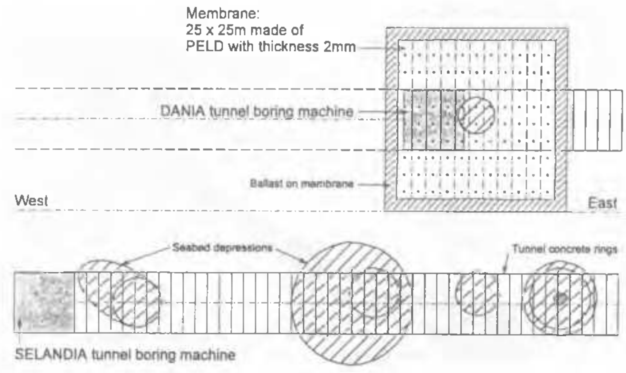

Figure 8. Position of tunnel boring machines Dania and Selandia at the time of fire in Dania and membrane placed at seabed to protect crewmen repairing damaged concrete roof in tunnel.

A closer look at the situation made it clear that quite frequently during tunnelling overexcavation had taken place resulting in hydraulic connections be established from the tunnel to the seabed of the Storebælt. The reason for this was that when excavating with the tunnel boring machines it was not possible to maintain earth pressures in the mixing chamber to balance the full hydrostatic pressure. Such high pressures namely led to blocking of the cutterhead. The tunnel boring machines, therefore, were operated at reduced earth pressures which led to overexcavation resulting in many instances in collapse of the ground above the tunnel. This again resulted in direct hydraulic connections being established to the seabed.

Such overexcavation explains the depressions of the seabed indicated on Figure 8 which gives a plan of the position of the two tunnel boring machines at the time of the fire. The depressions represented a considerably volume of ground. Diameters of five to fifteen metres were common and depths of depressions up to ten metres or more were also common. At the bottom of the depressions a socalled "pinhole" had often been formed. These pinholes had normally quite a small diameter - five to twenty centimetres were common.

During tunnelling the seabed had been kept under observation and the depressions had been refilled with glacial till being dumped from barges into the holes in the seabed.

The damaged concrete rings were located just behind the shield of the tunnel boring machine Dania and that was, unfortunately, just were a depression of the seabed had taken place as indicated on Figure 8. After the fire measurements of the pore pressure in the ground around the Dania tunnel was made from the other tunnel, and these measurements clearly indicated that a hydraulic connection existed between the tunnel and the seabed.

It was under these conditions that a prediction had to be made whether the five minutes escape period could be warranted.

In order to find a solution to this problem it was important to understand the mechanism behind the depressions in the seabed due to overexcavation.

Figure 9 illustrates an explanation of what had happened to the ground above the tunnel due to overexcavation during tunnelling. The tunnel has some twenty metres of ground cover up to the seabed. The tunnel at the location where the fire took place was partly mined in marl. The cover consisted of an upper clay till layer, an upper sand layer, a lower till complex and again a lower sand or gravel layer just above the marl.

The explanation of what happened during tunnelling is as follows: Overexcavation created a void in the sand and gravel

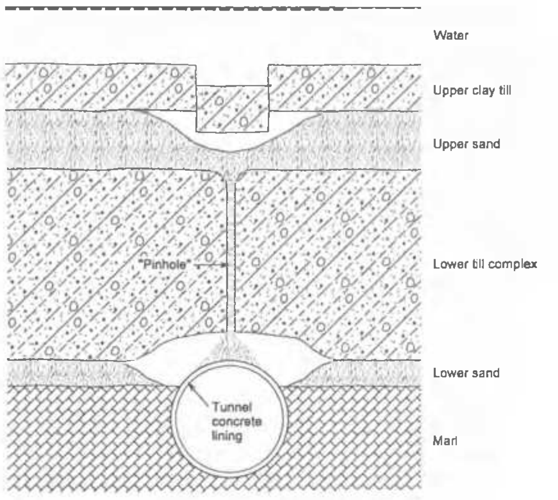

Figure 9. Formation of seabed depressions and hydraulic connections between seabed and tunnel as a result of overexcavation during mining of tunnel.

layers at the interface between the marl and the lower till complex. From this void a pinhole propagated upwards through the till complex towards the upper sand layer. The erosion mechanism in such a pinhole is a gradient controlled erosion in the tip of a narrow hole supported by hoopstresses. As long as erosion takes place a slurry of suspended clay, silt and sand with gravel will flow through the pinhole at a relatively low flow rate. If the pinhole reaches a high permeability sand formation such sand layers may be eroded away through the pinhole and create a local void underlain by a funnel shaped pinhole.

Finally, at a certain erosion stage a plug of upper clay till will be forced by water pressure down into the void as "a cork into a bottle".

A direct connection to the sea may now be established allowing for direct inflow of seawater besides the plug. Then a mechanism of widening the pinhole area can take place with rising erosion and water flow.

The mechanism described seems to fit in well with several observations made during tunnelling. Firstly, it fits well with the observations of the depressions of the seabed. Secondly, it fits well with the observations connected to the flooding of the tunnel boring machine Jutlandia three years earlier.

Now the problem was this: how could a five minutes escape period be warranted knowing that a hydraulic connection of the type shown in Figure 9 would exist during repair of the damaged concrete rings?

A solution was found in close cooperation between Storebælt, the Consulting Engineer, the Contractor and the Danish Geotechnical Institute. It consisted simply of placing a membrane on the seabed to cover the seabed depression. The position of the membrane is shown on Figure 8. It had an area of 25 by 25 m^2. It was made of PELD (poly-ethylene with low density) with a thickness of 2 mm and welded into one piece. The membrane was reinforced with steel-wires and it was placed on the seabed by divers. It was anchored by steel wires and heavily ballasted by sandbags and concrete blocks.

The concept behind the membrane solution was firstly to delay a possibly reopening of a pinhole through disturbed ground within the seabed depression area by the blocking effect of the draw-down of the membrane and the ballast into the pinhole, and secondly to force a possibly creation of a new pinhole to take place outside the membrane through undisturbed soil.

It was on the basis of such considerations that the Danish Geotechnical Institute could warrant for the five minute escape period.

The membrane solution was put into effect. The membrane was on the seabed for three to four months while the repair of the damaged concrete rings successfully took place and it was then removed.

10 COMPLETION OF TUNNELLING WORK

The tunnelling machine Dania was so heavily damaged that it was not put back into operation. Instead the mining operation for the northern bore was completed by the tunnelling machine coming from the west.

The problems encountered during the mining of the two tunnels resulted in a relatively high cost in money and lost time. The original plan was to complete the mining operation in mid 1991. Actually it was not completed before April 1995. After the completion of the mining and the railway installations Queen Margrethe of Denmark officially opened the tunnel for passenger traffic on the 1st of June 1997.

Table 3 gives an overview of the construction costs. According to the original contact the total expenditures would be a little more than 3,000 mio Danish kroner - the equivalent of 400 mio ECU. The total lump sump agreement, however, corresponded very close to a doubling of the original budget. The direct costs of the Moses project and the Dania Fire repair represent rather minor amounts, ever though they have had a considerably indirect influence on the construction costs.

Table 3. Costs of tunnel construction works.

Original contract	3,074 mio. DKK
Price level increase	264 mio. DKK
Agreements	
• claims	465 mio. DKK
• risk sharing	816 mio. DKK
• bonus	375 mio. DKK
• MOSES	180 mio. DKK
• Dania fire	130 mio. DKK
• project changes	850 mio. DKK
Total	6.154 mio. DKK

11 CONCLUSIONS

The Storebælt project has demonstrated that tunnelling in clay till under high hydrostatic pressures can be successfully accompliced but with a relatively high cost in money and time.

It has also demonstrated that a detailed knowledge of the ground and the groundwater conditions is an absolute necessity for the contractor in order to chose suitable tunnelling boring machines and to solve problems during mining operations. Close cooperation between the client, the designer, the contractor and the geotechnical engineers on the Storebælt Tunnel Project has demonstrated that such cooperation may lead to quite unconventional solutions involving

- tender documents giving statistical information on the probability of occurrence of large boulders,
- a reduction of high hydrostatic pressures by means of dewatering technology known from onshore applications,
- an understanding of the ground-collapse-mechanism resulting from overexcavation during mining operations.

ACKNOWLEDGEMENT

The author gratefully acknowledge permission by A/S Storebæltsforbindelsen to publish the paper and express his thanks for their kind assistance in preparing the slides for the invited lecture. Niels Foged, Per Bjerregaard Hansen, Henning Kryger Hansen and Mogens Porsvig are thanked for their assistance in reading and commenting drafts of the paper.

Niels Foged and Jørgen Steenfelt developed the concept presented in Figure 9 of the paper in order to explain the development of hydraulic connections between the seabed and the tunnel front during mining operations.

REFERENCES

East Tunnel. The Storebælt Publications, edited by Niels J. Gimsing with contributions from specified authors, published by A/S Storebæltsforbindelsen, Copenhagen 1997. (Similar books on the Eastern Bridge and on the Western Bridge are expected to be published upon completion (in 1998) of the Storebælt Link Project).

Storebælt and Øresund, 16 papers on geotechnical aspects of the two projects published in volume 5 of the Proceedings of the XI European Conference of Soil Mechanics and Foundation Engineering, Copenhagen 1995. See also J.S. Steenfelt's Keynote Lecture in volume 10 of this conference.