3. The Fixed Link across Storebælt

3.1 Components of the Link

The Storebælt Link is 18 km long and consists of three major components: A bored railway tunnel and a high level motorway bridge across the eastern channel, and a low level combined railway and motorway bridge across the western channel, cf. Fig. 1.

![Fig. 1: The Storebælt Link (The Great Belt Fixed Link)](image1)

The task of developing cost effective foundation solutions in deep waters suited for fast track construction and the clay till soils in the area called for new concepts. In the past, massive foundation techniques were based on extensive and risky offshore operations (open dredge or pneumatic caissons). This had to be replaced by methods where the massive foundations could be pre-fabricated onshore and laid directly onto the sea bed in order to minimise offshore works and interference with the extensive ship traffic in Storebælt. The development of foundation concepts based on this philosophy was to a great extent inspired by technologies and designs from the offshore oil industry.

3.2 The West Bridge

The West Bridge is a 6.6 km long multi-span concrete bridge with 51 spans of 110.4 m and 12 spans of 81.75 m, cf. Fig. 2.

![Fig. 2: The West Bridge with the railway to the left](image2)

The superstructures consist of two haunched concrete box girders each supported on separate pier shafts and sharing a common gravity based caisson foundation, cf. Fig. 3.

![Fig. 3: West Bridge cross section](image3)

The overall idea behind the design and construction of the West Bridge was pre-fabrication of mega size elements erected by a huge purpose built crane vessel. This heavy lift technique offshore were well known from the erection of steel topsides for oil platforms, but on this project it was adapted to handling concrete elements in a scale never seen before.

Altogether 324 pre-fabricated units, comprising 62 caissons, 124 pier shafts and 138 bridge girders were cast in a yard close to the bridge site, cf. Fig. 4 and erected by the purpose built heavy lift (capacity 6,400 tonnes) catamaran crane vessel Svanen (The Swan) with overall dimensions 94 x 65 m and 65 m height, cf. Fig. 5.
Fig. 4: Pre-fabrication Yard

Fig. 5: Placing a caisson by Svanen

Fig. 6: Jack-up platform

The caissons placed in water depths up to 30 m have a 1.2 m thick bottom slab and simple vertical walls in a cellular pattern suitable for slip-forming. In order to place the caissons directly on the sea bed with great accuracy it was necessary to construct carefully compacted and levelled stone beds varying from 1.5 m to 4.0 m in thickness. This was done by means of a multi-purpose jack-up platform, cf. Fig. 6, designed to handle all operations such as foundation inspection, placing and compaction of stones and surface levelling to very strict tolerances allowing the caissons to rest directly on the stone bed surface without subsequent under base grouting. Lowering of the caissons onto the stone beds required close surveillance by the survey system giving on-line information to the crane operator about horizontal position, differences relative to exact position, and suggested remedial actions. During lowering the caissons were filled with water pumped in either through holes in the top or entering through flood valves in the bottom slab designed to ensure that the stone beds were kept intact during this operation.

3.3 The East Bridge

The East Bridge is 6.8 km long comprising a suspension bridge with 1624 m main span and 535 m side spans and approach bridges on both sides with spans of 193 m. The navigational clearance of the main span is 65 m, cf. Fig. 7. The superstructures for both the main suspension bridge and the approach bridges consist of closed steel box girders. All other bridge elements are in concrete including the towers of the suspension bridge rising to 254 m above sea level. The overall idea behind the design and construction of the foundations for the East Bridge is basically the same as used for the West Bridge,
Pre-fabrication of mega size elements onshore and subsequent transport and placing these elements directly on the seabed. However, due to the extraordinary large size of the foundation caissons for the towers, anchor blocks and the seven largest approach span piers a different scheme as compared to the West Bridge had to be used for these special elements.

The scheme selected was based on constructing the caissons in a dry dock, towing them to the bridge location where they would finally be sunk by controlled water ballasting to stone beds prepared in advance. It was obvious to choose this technology as it had been used successfully for construction of more than 20 major concrete oil production platforms in the North Sea at the time of planning the East Bridge.

Two separate dry docks, cf. Fig. 8, were purpose made for the project in a harbour 30 nautical miles from the bridge site. Casting of the cellular 78 m x 35 m and 20 m high caissons for the pylons, and the two anchor block caissons and the seven largest approach span piers, respectively, took place in the two docks.

The anchor block caissons have a rectangular base 121.5 m long and 54.5 m wide and 16 m high divided into approximately 100 cells. The caissons weighing about 50,000 tonnes were towed by tug boats to the bridge alignment and sunk unto the stone beds with great accuracy, cf. Fig. 9. Finally, under base grouting was performed followed by ballasting with sand. It was essential to confine the grout and ensure that the void between the stone bed and the bottom slab was completely filled. Therefore, the underside of the base was divided into smaller compartments with roof shaped surface by a system of small skirts designed to penetrate into the upper 300 mm non compacted part of the stone bed.

The main geotechnical challenge in connection with the anchor block design was the mere size of the horizontal force (~550 MN) to be transferred to the ground being beyond normal experience and Codes of Practise. Therefore, very thorough investigations and careful assessment of the safety by applying several independent analysis models were made.

As a result of the anticipated construction method requiring underwater excavation to remove unsuitable postglacial deposits it was expected that the underlying stiff pre-consolidated clay till being the primary foundation strata would be disturbed and have reduced sliding resistance.

Fig. 8: Anchor block caissons in dry dock

Fig. 9: Placing of anchor block caissons

This question was thoroughly studied by conducting several series of large sliding box and direct shear box tests in the laboratory as well as 28 field sliding tests using 1.2 m² concrete blocks. A detailed description of these tests and the results for the sliding resistance achieved considering a variety of parameters is given in Steenfelt (1992).

To avoid sliding failure along a thin weakened zone of the excavated clay till surface several solutions for improvement of the soil-structure interaction were investigated such as short steel skirts penetrating the weakened zone and large diameter steel pile dowels. However, the preferred solution turned out to be two separate stone wedges with an inclination of 16° to ensure that the combined vertical and horizontal load would be almost perpendicular to the stone/clay interface thus effectively reducing the shear stresses, cf. Fig. 10.
The idea described above to reduce shear stresses in the weak interface between structure and soil was inspired by the solution developed earlier for the other large suspension bridge in Denmark, the Lillebælt Bridge. For this bridge the anchor blocks were designed as thick slabs each covering a base area of 3,300 m², the base sloping 10.4° with the horizontal, cf. Fig. 11. The combined action of the horizontal cable pull and the self weight of the concrete slab and the soil ballast on top would then be almost perpendicular to the interface between the slab and the soil eliminating any risk of sliding failure. Comprehensive soil-structure interaction analyses were made to determine the overall safety for transfer of the large resulting forces on the anchor blocks, cf. Fig. 12.

Due to the importance and complexity of the design three independent methods were used to determine the capacity of the anchor blocks. These comprised: upper bound theory, limit equilibrium analyses and finite element analyses.

The results of five benchmark cases tested were in the same range for all three methods (Sørensen et al, 1993).

The critical rupture figures determined for the upper bound method and for the finite element model are shown in Fig. 13 and Fig. 14. It is noted that the critical rupture figures goes through the intact clay till, i.e. sliding failures through the stone beds or at the stone bed/clay till interface are not critical.
3.4 Project MOSES

On the morning of October 14, 1991 a sorry sight met the eyes of spectators at the tunnel ramp area on Sprogø, as seen in Fig. 15. The ramp area and the two eastbound tunnel tubes were inundated in what is referred to as the Jutlandia incident.

During a period of maintenance stoppage of the TBM Jutlandia a chimney-like connection to Storebælt formed allowing ingress of sea water into the tunnel. Both TBMs and tunnel tubes were successfully evacuated without loss of lives, but both ongoing mining operations had to be stopped for a long time (restart of first eastbound TBM in August, 1992) to allow remediation and to ensure that a similar incident would not occur again at any of the four TBM-positions.

In order to control the mining operations project MOSES Method of Obtaining Safety by Emptying Storebælt, was set in action. No doubt the acronym was coined with some knowledge of Eckersberg’s wonderful painting seen in Fig. 16.

Project MOSES entailed large scale dewatering below the seabed with the objective to improve the safety of mining operations.

The immediate aim was to reduce the pore water pressure at the TBM axis by 3-4 bar in order to arrive at a nominal pore pressure of 3 bar at the tunnel axis, compatible with the use of compressed air for manned intervention in the TBM head. Furthermore it was important to improve soil stability at the cutter head and as a side effect to reduce the need for local dewatering at cross passages (more information may be found in Biggart et al, 1993; Odgård et al, 1993).

The first hint in the direction of the MOSES project was found when an onshore dewatering scheme was started in 1989 for the tunnel ramp area on New Sprogø. The horizontal extent of the dewatering was considerable as first experienced by the caretaker at Sprogø, as the sweet water well here dried out in October/November of 1989. During the 1990-91 boring campaign for the East Bridge, it was confirmed that the extent of the Sprogø dewatering was large enough to produce down drags of the order 2-10 m in boreholes for anchor block west and approach piers some 1-3 km away from the ramp area.

In effect the Sprogø dewatering with a yield of 1100-1300 m³/h produced down drags of 25-34 m in the ramp area with a radius of influence of 3-4 km. This constituted the factual background for initiation of project MOSES.

During July to October 1992 a conceptual scheme for sub-sea dewatering was developed and in August ’92 the Danish Geotechnical Institute conducted preliminary investigations sinking a number of boreholes and conducting trial pumping for the MOSES project on Halskov and Sprogø sides. This provided a platform for the initial test programme which allowed fundamental insight into the geologic-geotechnical-hydrologic conditions pertinent to the success of the scheme.

The well heads were prototyped and manufactured by the Danish Geotechnical Institute. After completion of a well, installation of well head, submersible pumps, pressure transducers, flow meter and discharge pipe the well was connected by seabed cables to the contractor’s set-up. The MOSES set-up is shown in Fig. 17, with the marine spread and the wells.
The original design objective, to reduce the water pressure to a nominal 3 bar at the tunnel axis, was by and large achieved by the MOSES project together with the secondary objective, to reduce the water inflow indicated by the site investigations and trials. The lowering of the groundwater pressure furthermore improved the conditions for site investigations and reduced the extent of ground treatment required for the construction of the cross passages. Even under the Nadir a significant reduction in pore pressure was achieved.

With project MOSES tunnelling was resumed after the 1991 incident with rates of up to 134 m/week. During the 30 months of operation of MOSES some 45 million m$^3$ of water was extracted from the Selandian marl and the glacial tills.

The costs of 27 M Euro may seem high. But the added safety and overall feasibility of actually completing the tunnels by reducing delays which might have occurred without MOSES in all likelihood recovered the costs many times over. Project MOSES demonstrated that when client, contractor and designer meet in a co-operative approach then new borderline techniques can be successfully adopted for special applications.

### 3.5 Storebælt Link Spin-off and lessons

In many ways the completion of the Storebælt Link was an eye-opener for the geotechnical engineers.