THE ØRESUND LINK IMMERSED TUNNEL

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SYNOPSIS

The 3.8 km enclosed tunnel for motorway and railway under the Drogden Channel, currently under construction and scheduled to open in the year 2000, will be the largest of its kind in the world. The Drogden Tunnel is a significant feature of the Øresund Link, connecting the Danish capital Copenhagen with the Swedish city Malmö. The toll-funded link will be owned and operated by Øresundskonsortiet, a Swedish-Danish joint venture, which is also responsible for the construction of the 16 km coast-to-coast section of the link. The Drogden Tunnel accommodates two tubes for the dual track railway, two tubes for the four lane motorway, and a central installation and escape gallery. Under normal conditions longitudinal ventilation is provided by the piston effect of the traffic, but jet fans located in the ceilings will automatically be triggered by set levels of noxious fumes in the air.

The tunnel construction was tendered in late 1994 as a design and construct contract, the conceptual design being carried out by the Øresund Link Consultants (OLC), house consultant to Øresundskonsortiet. The USD 670 million contract was awarded to the Øresund Tunnel Contractors (OTC) in July 1995. To meet the tight construction schedule OTC has devised an innovative production scheme, based on precast segmental construction and incremental skidding off a fixed casting bed. The 175 m tunnel elements are composed of eight 7000 t segments, match-cast in single concrete pours, and joined by temporary prestressing. The segments are fabricated under factory conditions in two production lines located above sea level, obviating the need for time-consuming excavation and dewatering of a conventional casting basin. The completed elements are launched and lowered to sea level by means of a lock system, and then towed to the tunnel site for immersion.

Fig 1: The Øresund Link Coast-to-Coast Section
The toll-funded motorway and railway link across Öresund will connect the city centers of Copenhagen in Denmark and Malmö in Sweden. The approximately 16 km coast-to-coast section comprises the following key elements (see Fig 1):

- An artificial Peninsula extending 430 m from the Danish coast at Kastrup.
- An immersed Tunnel 3,510 m long under the Drogden navigation channel.
- An artificial Island 4,055 m long south of Saltholm.
- A western Approach Bridge 3,014 m long between the Island and the High Bridge.
- A cable-stayed High Bridge 1,092 m long over the Flintrännan navigation channel.

- An eastern Approach Bridge 3,739 m long from the High Bridge to the Swedish coast at Lernacken.
- A terminal area with toll station and Link Control Center located at Lernacken.

The Öresund link shall be owned and operated by Öresundskonsortiet, a Swedish-Danish joint venture, indirectly owned by the two governments (see Fig 2.) The two partners - Öresundsförbindelsen and SVEDEAB - are directly responsible for the Danish, respectively the Swedish, landworks, ie the traffic infrastructure connections to the city centers, whereas Öresundskonsortiet is in charge of the coast-to-coast section.

Fig 2: Öresund Link Ownership Organization Chart

The major construction works are covered by three contracts tendered in 1994: Dredging & Reclamation, Tunnel, and Bridges. In July 1995 the USD 670 million Tunnel contract was awarded to the Öresund Tunnel Contractors (ÖTC), a joint venture between NCC Contractors (Sweden), Dumez GTM (France), John Laing (UK), Pihl & Søn (Denmark) and Boskalis Westminster (Netherlands). Detailed design of the permanent tunnel works is being performed by Symonds Travers Morgan under a subcontract to ÖTC.

The Tunnel was tendered as a design-and-construct contract, implying that the contractor is responsible for the detailed design, based upon a conceptual design prepared by the Öresund Link Consultants (OLC), acting as house consultant to the owner. OLC is a joint venture between RAMBOLL (Denmark) Scandiaconsult (Sweden), Halerow (UK) and Tunnel Engineering Consultants (Netherlands), in association with architects Dissing + Weitling (Denmark).

To ensure the owner's control of the environmental and aesthetic qualities of the Link the conceptual design is quite specific regarding geometry, dimensions, and major features. Furthermore, it is required that the design be performed in accordance with the Eurocodes, which is made possible by means of a Project Application Document, prepared by OLC.
Fig 3: Cross-Section of the Drogden Tunnel

The Drogden Tunnel is motivated by the proximity of the link to the Copenhagen airport at Kastrup, which precludes a high bridge over the busy navigation channel. The tunnel cross-section accommodates two tubes for the dual track railway and two tubes for the four lane motorway. A central installation gallery between the motorway tubes doubles as a safe and smoke-free escape route in case of emergency (see Fig 3).

The tunnel contract comprises three main components (see Fig 4):
- Ramp and portal building on the Peninsula
- Immersed tunnel under the Drogden navigation channel
- Ramp and portal building on the Island

The portal structures accommodate underground service buildings with rooms allocated for tunnel installations, i.e. road lighting, ventilation, drainage, communications and energy supply. These installations constitute an essential part of the overall tunnel performance noticeable to the users.

The immersed part of the tunnel consists of 20 elements, each approximately 175 m long, resulting in a total immersed tunnel length of 3,510 m. Each element is made from 8 sections, joined together by temporary post-tensioning cables. The outer cross-sectional dimensions are 8.6 m by 38.7 m, and the element weight is approximately 54,000 t.

Fig 4: Longitudinal Section of the Drogden Tunnel
The elements are placed in a pre-dug trench, and founded on a gravel bed. Backfilling along the sides and on the roof is designed to offer a permanent cover and protection of the tunnel in all situations. The final tunnel profile is in general below seabed level, and at the Drogden navigation channel the top of the cover is 10 m below water level.

The motorway tubes are equipped with New Jersey safety barriers, wall panelling, fire insulation layer, and a central sump. Lighting is continuous throughout, with transition zones at either end to enable road users to adjust to the difference in light intensity. A special feature are the daylight screens above the tunnel entrances, which reduce the black hole effect, and give motorists time to adjust to the lighting difference.

The roofs and outer walls of all tubes are protected with fireproof insulation material. Emergency installations containing fire-fighting equipment and telephones are placed at 88 m intervals, where safety doors are provided between the two railway tubes, between the railway and the motorway tube, and in the walls giving access to the escape gallery. This layout constitutes a safe exit for all tunnel users in case of emergency.

3.0 RAMP CONSTRUCTION

The ramps on the Peninsula and on the Island are part of the reclamation work performed within bunds placed along the perimeter of both relocations. Cut-off walls are placed in the bunds to seal against incoming water, reducing the requirements to temporary ground water lowering. The areas where the ramps are located will be backfilled in parallel with the ramp construction, which is very similar for both the Peninsula and the Island.

From the deep end, the ramps are divided into four parts:

- Cut and cover tunnel
- Portal structure with building
- Open troughs for motorway and railway
- Open cuts with membrane

The works begin with the open excavation for the cut and cover tunnel, and installation of a temporary dewatering system. The cut and cover tunnel is divided into sections with joint details as in the immersed tunnel elements, cf. below. Construction starts at the immersion joint for the first tunnel element to be installed, wherefore the joint cross-section matches the immersed part. The tunnel sections are constructed by first pouring the base slab, then the inner walls, and finally the outer walls and roof, using cooling pipes to avoid thermal cracking. The sections are backfilled after completion, giving the necessary deadweight against uplift once the dewatering is discontinued. For the portal structures the same construction method is used as for the cut and cover tunnel.

The control facilities, including monitoring equipment, are located above the tunnel, but below the reclaimed ground level, which is at 3.5 m above sea level. From this building the portal continues as U-shaped dead weight structures with precast beams as permanent struts. The water retaining walls continue to a level 3.5 m above sea level.

At the beginning of the daylight screens the portal structure stops, and the open through continues. Uplift of the structures is counteracted by permanent ground anchors drilled into the limestone, each with a 60 t working load. The ground anchors are prestressed with compression in the grout body, and have a double corrosion protection. In this section the retaining walls terminate at 1 m below sea level. The side slopes are provided with a membrane reaching to a level of 2 m.

For aesthetical reasons it was decided to have more green slopes instead of concrete walls, so an open cut with membrane is adopted. This section starts where the extra deadweight of the soil on the membrane can resist the groundwater uplift. The membrane is continued until the motorway reaches ground level at 3.5 m.
Fig 5: Layout of the Tunnel Element Production Plant

All 20 tunnel elements are fabricated above sea level in a purpose-built casting yard at the Nordhaven area of Copenhagen Harbour, using a novel concept based upon a high level of factory production (see Fig 5). Each approximately 22 m long, 7000 t segment is cast in one single pour of 2.800 m$^3$ on a fixed casting bed over a 24-hour period. By casting an entire segment in a single operation the production cycle time is sped up, and the entire tunnel cross-section is allowed to thermally expand and contract as a single unit, thus reducing the risk of thermal cracking.

Factory conditions are achieved by the erection of sheds where the reinforcement is assembled and prefabricated. For each segment the reinforcement in prefabricated panels is assembled into a 130 t cage. A central shed covers two production lines, where two segments are cast per week, in order to meet the time schedule. Each segment is constructed on elevated formwork, which allows even cooling of the entire tunnel cross-section.

After three days of curing the segments are ready for the skidding step. The base formwork and exterior side forms are released, and the section is jacked forward with the interior formwork. Once the base formwork is released the section is resting on six skidding beams, positioned underneath the tunnel walls. These concrete beams are continuous over 290 m, and surfaced with stainless steel plates on top. Six hydraulic bearing pads per section are placed on each beam, so that a total of 36 pads support each section. A high density polyethylene pad is glued to the bottom of each bearing to facilitate skidding on the steel plate. Jacking is performed with six hydraulic jacking assemblies riding on top of the skidding beams, one 600 t capacity jacking unit per skid beam.

After jacking the completed segment through 22 m the following section can be made, starting with the positioning of the prefabricated reinforcement on the base formwork. Later the formwork for the inner and outer walls is placed in position, and the segment is cast against the previous one, to give a perfect match at the joint. The only connection between neighbouring segments are intermittent shear keys and a continuous groutable waterstop in the slabs and outer walls.

When the last segment of the element is cast and cured for three days the entire element is jacked approximately 100 m, out of the casting shed and into the outfitting area beyond the sliding gate. The 100 m distance allows the casting cycle to continue on the next pair of tunnel elements, while the former elements are outfitted and launched.

In the outfitting area the GINA rubber profiles for sealing the immersion joints are attached to steel frames, which are cast into each end of the element. Additional outfitting includes placing of ballast concrete, water ballast tanks, temporary end bulkheads, and post-tensioning of the element for transport to the immersion site. Upon completion of the outfitting of both elements the sliding gate to the production facility is closed in preparation for filling up the basin to float the elements, and pull them to the waiting area.
5.0 TOW-OUT AND IMMERSION

When the sliding gate and the exit gate are sealed water is pumped into the basin to a level of +9.9 m. The two elements, resting on the skidding beams, are ballasted in such a way that they will float in a level position. Once afloat the elements are pulled towards the deeper end of the basin, and each one is moored at two dolphins. The water in the basin is then lowered back to sea level, the exit gate is opened, and one by one the elements are towed out by tugs directly to the tunnel trench or to a temporary mooring location near the casting yard, depending upon weather conditions or work progress at the immersion site (see Fig 6).

The transportation distance to the tunnel site is approx. 18 km, and the route followed is based upon ensuring a 1.0 m keel clearance for the element. The towing configuration is with two leading tugs and two assisting tugs, ie one at each corner of the element. As the transportation will be immediately followed by immersion the catamaran type pontoon and hoisting points are already attached to the element at the start of tow-out, and as soon as the element is towed into position in the trench mooring lines are connected to anchors laid out in the vicinity of the trench.

Before start of any trench operation cleaning has been performed to ensure that no soft material is left. The cleaning is carried out with an environmental grab, or in case of a tangled mass of sediment and plant matter (locally known as ‘fedtmog’) with a dustpan suction system. Constant trench surveying with echo sounder and supported by Remotely Operated Vehicle techniques ensure that the trench is clean. Just prior to tow-out of the tunnel element the gravel bed foundation is placed. A vertical fall or feeder pipe is used to position the bedding in one continuous operation to a level tolerance of ± 25 mm.

To model the transportation and immersion conditions extensive model tests are carried out. All critical activities are tested in calibrated conditions for various wave and current scenarios. In the Øresund velocities exceeding 1.0 m/s frequently occur. The test results have been used in the element design, and in the procedures for gravel bed preparation and immersion.

The immersion operation commences with water ballasting of the element to a negative buoyancy. Hoisting points are via cables connected to the cross-beam of the catamaran pontoon to ensure height and vertical stability of the element. The cables are connected to the element roof at the longitudinal fifth points along the outer walls. The element is lowered in steps, the control of movements increasing with each step. In the longitudinal direction the element is controlled by mooring lines located in the middle of the element roof, one of the lines pulling the element against the previously installed one.

The element is lowered onto the gravel bed, and guided into relative position by the use of tapered guides mounted on the previously placed element. Once the position is surveyed within tolerance the immersion joint is pumped dry by opening a valve in the bulkhead. The hydrostatic pressure now compresses the GINA profile and keeps the element in position. At this point the horizontal alignment is again surveyed. If the element is found to be out of tolerance hydraulic jacks mounted in the exterior walls at the immersion joint are used to realign the element. Finally the element is ballasted to a safe minimum dead weight.

6.0 TRENCH BACKFILLING AND FINISHING WORKS

Immediately following immersion granular backfill material is placed between the tunnel walls and the trench slopes. The backfill locks the position of the element, and contributes to the passive deadweight of the structure, as this material also lies on top of the toes of the tunnel cross-section (see Fig 3).

The tunnel is protected with a layer of rock designed to withstand a falling or dragging anchor, or a sunken ship. Furthermore the protective layer is stable against scour and erosion caused by currents or ship propellers.

After backfilling and placing of ballast concrete the temporary works are rounded off by removal of the bulkheads and water ballast tanks. The immersion joints are completed by the placing of an OMEGA profile rubber seal to give permanent watertightness.

As a final step the prestressing tendons are cut between the segments of the element.

The first stage of the internal finishing is the installation of the fire insulation material, followed by mounting of the wall cladding, consisting of Glusal type panels giving a smooth and aesthetically pleasing finish to the tunnel. The reflection capacity of these panels is used to give an even light distribution in the tunnel cross-section, ensuring road users a clear and pleasant passing. Additional finishing work in the motorway tunnel includes paving, installation of New Jersey barriers, and completion of the central gallery with mechanical and electrical installations. The railway tubes are finished by completion of the walkways/derailment barriers, and placement of the track slab.

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7.0 INSTALLATIONS

Ventilation of the tunnel is necessary to ensure:

- Smoke reduction in the event of fire so that evacuation can take place
- Acceptable working conditions during maintenance work

- An acceptable low level of pollution by vehicle exhaust gasses
The road tubes are ventilated in the longitudinal direction. Under normal traffic conditions the piston effect of the vehicles will ensure sufficient air exchange, but if the traffic speed is very low the necessary ventilation will be generated by jet fans. Visibility, as well as the contents of carbon monoxide and nitrogen oxides are monitored continuously, and the ventilation is controlled by the measured values.

In case of a fire the ventilation system can be directed to control the smoke and the heat, facilitating the work of the fire brigades and rescue teams. It also serves to provide oxygen to avoid the accumulation of unburned gases, which might impose an explosion risk. The jet fans will remain operational for at least an hour, even at a temperature of 250°C. Fire hydrants with connectors for both Danish and Swedish fire fighting systems are placed at the walls to the central gallery, next to the escape doors. Fire hydrants are also placed 300 m outside the tunnel portals for fighting fires in trains which have been driven out of the tunnel.

The railway tubes are ventilated in the longitudinal direction by the piston effect of the trains, but if necessary jet ventilators can be started up to increase the airflow, or to clean the tunnel, e.g., when diesel locomotives are used.

The tunnel is provided with a drainage system to remove water and any liquid spillage from the road and the railway. The 2% cross-fall of the carriageways leads liquids to drain pipes with inlets and water locks every 50 m. The tunnel tubes have separate pump sumps with spare pump capacity, fire detectors, and automatic foam extinguishing systems. The pump sumps are equipped with seals as well as oil and sediment separators.

The entire coast-to-coast link is supplied with high-voltage power in a ring connection, which can be fed from Danish as well as Swedish high-voltage grids. This ensures a high reliability of supply, as loss of high-voltage power would require at least two consecutive failures, the risk of which is negligible.

All essential power consumers are connected to Uninterrupted Power Supply (UPS) units with battery back-up. The batteries of the UPS are automatically charged during periods of normal power supply, and the UPS systems take over immediately in case of public power supply failure.

The lighting system for the road tubes is designed to ensure that a motorist under all conditions can see his surroundings, as well as other motorists.

The Øresund Link is provided with a computer control system to monitor road traffic, and control all installations. The SCADA system communicates via an optical fibre system (a 'data highway'), and can be operated from control centres as well as locally.

The Øresund Link accommodates a two-track railway linking up with the Danish and the Swedish railway networks in Kastrup and Malmö, respectively. The installation of the catenary system, power supply, and signalling for the railway is part of a separate contract. The electrical coast-to-coast railway line is designed for train speeds of 200 km/h for passenger trains, and 120 km/h for freight trains. Diesel trains will also be used occasionally.

The track system consists of rails weighing 60 kg/m, fixed to concrete sleepers placed in rough ballast on the ramps (as on the rest of the Link). In the enclosed tunnel, however, the rails are fixed directly to the concrete base, resulting in a lower construction height than for ballasted track, justifying the extra cost of the directly fixed track system. The reduced tunnel height permits the use of the compressed catenary suspension system developed for the railway tunnels under Storebælt. This system has been tested as a full scale prototype on one of the main railway lines of the Danish State Railways.

8. Conclusions

The Øresund Link Immersed Tunnel when completed will be the largest immersed tunnel ever built. The design and construction of this 3.8 km marine tunnel for both road and railway in just five years from award of contract is a major challenge. However, the unique size of the Øresund Tunnel provides the answer to this challenge by making it economically feasible to design and construct a high production precast facility that meets the demands of economy, quality, and on-time completion.

The precast facility will be applying production techniques developed and tested in the construction of precast segmental bridges over the last 20 years. This, however, will be the first time these techniques have been applied to immersed tunnel construction, and the first time these techniques have been used to cast and incrementally launch segments weighing up to 7000 t and elements of 54000 t.
The floating tunnel element is now towed from the casting yard at the North Harbour to the excavated trench.

A gravel bed is placed at the bottom of the tunnel trench. The tunnel elements are ballasted and lowered into the trench.

The rubber profile (GINA) forms a reservoir between the two bulkheads.

Water is pumped out of the reservoir, causing the GINA to compress and seal the joints.

The bulkhead are removed and a second rubber profile (OMEGA) completes the joints.

Following the positioning of the elements, the tunnel trench is backfilled.

A rock protection layer is placed on top of the elements.