The Øresund Tunnel - "Design and Build" in Practice

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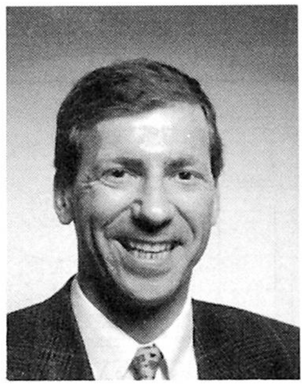

Summary

This paper describes some aspects of the design and construction of the Øresund Tunnel. The aim of the paper is to illustrate how the partnership between designer and contractor, made possible by the 'design and build' form of contract, has contributed to the project, with benefits for all parties involved. Particular issues discussed include tender preparation, early age stresses, joints, reinforcement, marine operations and the tunnel foundation. The paper concludes with some comments on the benefits of design and build and some suggestions for how to use this form of procurement to best effect in the future.

1. Introduction

The Øresund Tunnel is a 3.5km long road/rail immersed tunnel, forming part of the Øresund Link between Copenhagen in Denmark and Malmö in Sweden. It is being constructed on behalf of the Øresundskonsortiet (a client company set up and owned jointly by the Danish and Swedish governments) by Øresund Tunnel Contractors (ØTC), a joint venture comprising NCC AB of Sweden, John Laing Construction Ltd of the UK, Dumez-GTM SA of France, Boskalis Westminster Dredging BV of The Netherlands and E Pihl & Son A/S of Denmark. Design of the tunnel is being performed on behalf of ØTC by UK consultant Symonds Travers Morgan (STM).

2. Contractor's Contract Philosophy

ØTC appointed a designer early, some six months ahead of invitation to tender and before the joint venture itself had been fully established. Thus from first concepts, the designer and contractor were able to develop design ideas and construction methods in a fully integrated way. The aim through the pre-tender and tender phases was to develop winning designs and methods which neither party could have developed alone.

3. Preparation of Tender

The tender documents issued by ØSK contained detailed specifications for many aspects of the works. The key opportunity for the tendering contractor to create an advantage lay in the construction method for the tunnel. Due to its exceptional size and length, methods which are usually uneconomic for immersed tunnel construction became viable. The chosen solution, which involves many innovative features, was developed jointly by contractor and designer during the tender phase. The method, which is described in more detail in another paper, involves casting each 22m long tunnel segment in a single concrete pour in a purpose built factory. Completed segments are stressed together in groups of eight and jacked about 300m into a dock before being floated. Figure 1 shows the tunnel casting facility.

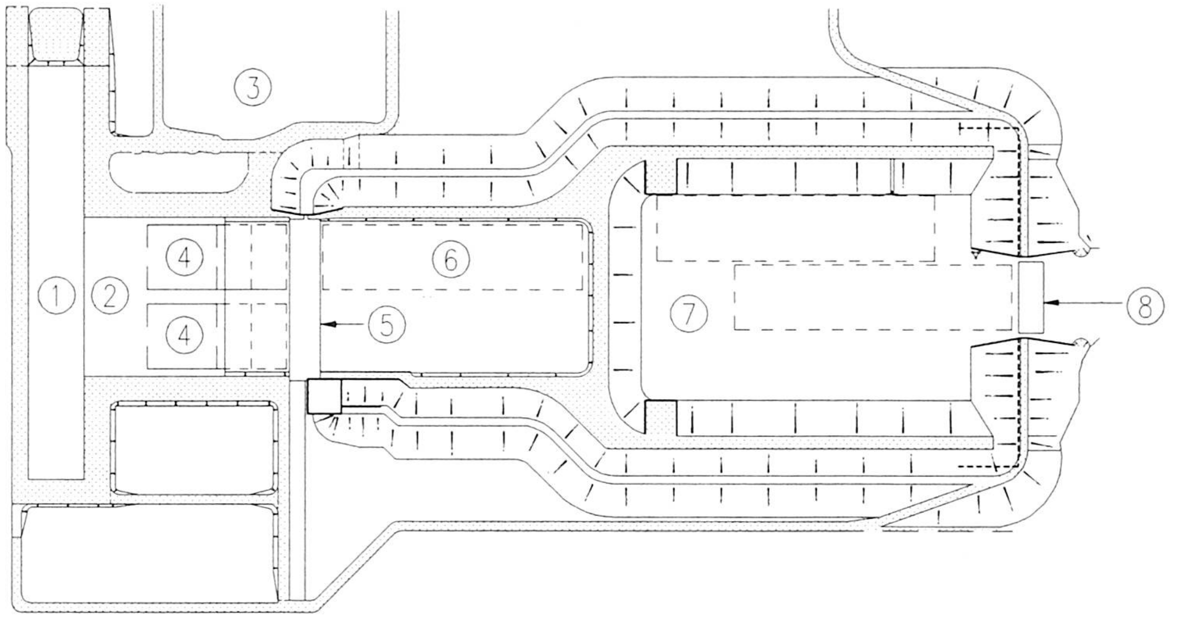

Figure 1 Tunnel Element Casting Yard

In developing this method, the key permanent works design consideration was the early-age stresses arising in the tunnel cross section from the combined effects of curing temperatures, self-weight stresses and foundation distortions, particularly during jacking. Extensive analysis was performed at tender stage, both to prove the method in principle, and to determine the optimum pour sequence, stripping times, jacking method, temporary foundations and bearing system. All of these considerations involved close contractor/designer co-operation without which the very real pressure to revert to a more traditional construction method would have been irresistible.

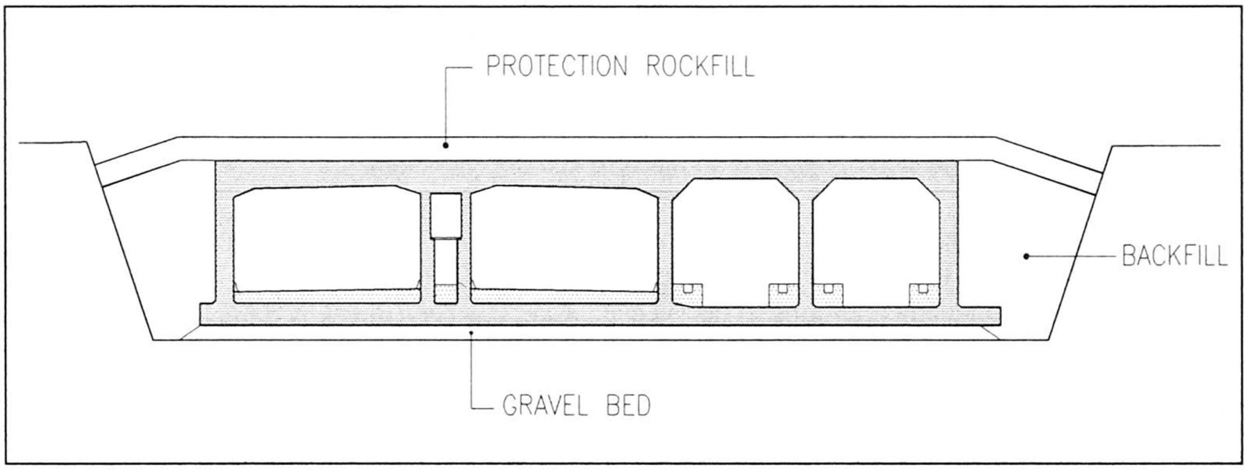

Figure 2 Typical Tunnel Element

4. Early Age Stresses

Early age stresses in concrete immersed tunnels, particularly those associated with thermal effects, can cause through-section cracking in the tunnel exterior, resulting in leakage. Traditional construction, in which the tunnel cross section is cast in three stages, exacerbates this problem, since restraint afforded by the base concrete restrains the later-cast wall concrete, resulting in severe tension stresses in the walls. These are normally moderated by cooling the concrete using cast in water pipes.

The Øresund Tunnel has largely avoided this problem by casting each tunnel segment in a single pour, and cooling pipes are not therefore used. However, early-age stresses have been an important consideration throughout, since the chosen construction method superimposes self-weight and differential foundation movement stresses on the structure at early ages, at which time the thermal effects are still significant.

Thus to safeguard the permanent works, the design of the temporary works has been carefully customised. Particular aspects influenced in this way include tunnel foundations, temporary bearings, pour sequence, ambient temperature control in the factory, selective thermal insulation of the concrete and the timing of all aspects of the pour, strip and jack sequence.

5. Joints

5.1 Immersion Joints

In conventional designs, the final alignment of the immersed tunnel relies on accuracy of immersion joint construction. Strict tolerances are specified and these are met through a two stage process by welding a plate to each steel end frame after casting the element and grouting behind the end frame. There is no recognised way of correcting the alignment after immersion.

It was soon realised on this project that given the unusual length of the tunnel, and number of elements, the conventional solution was too uncertain to rely upon to meet the correct horizontal alignment. A positive means of aligning the tunnel elements had to be found. To this effect, a realignment system has been developed, where three 500 tonne jacks are incorporated in each external wall. The system is activated after dewatering the joint chamber between the two bulkheads and the tunnel element is realigned from its natural position (dictated by the tolerances of the joint) to the correct final position. The jacks are then locked and are only removed after permanent ballast and enough backfill are in place to stabilise the element.

A special soft-nosed Gina gasket has been developed for the project in order to allow both for primary watertightness at first contact when dewatering the joint chamber and for permanent watertightness in realigned conditions. This special gasket has been developed in close co-operation with Trelleborg-Bakker of The Netherlands.

The logical consequence of the above has been to make possible a relaxation of the tolerances on the joint end frame, which led to simplified joint detailing with an L profile replacing the conventional H profile, and no secondary welded plate. This simpler detail is one of the key factors favouring better quality and durability through ease of construction (simpler concreting and less welding). Figure 3 compares the final joint design with the original.

Key dimensional data relating to the immersion joint are as follows:

- Casting tolerances: ± 5mm
- Horizontal positioning tolerance: ± 25mm
- Realignment capacity: 25mm at joint (gives 180mm at secondary end of element)

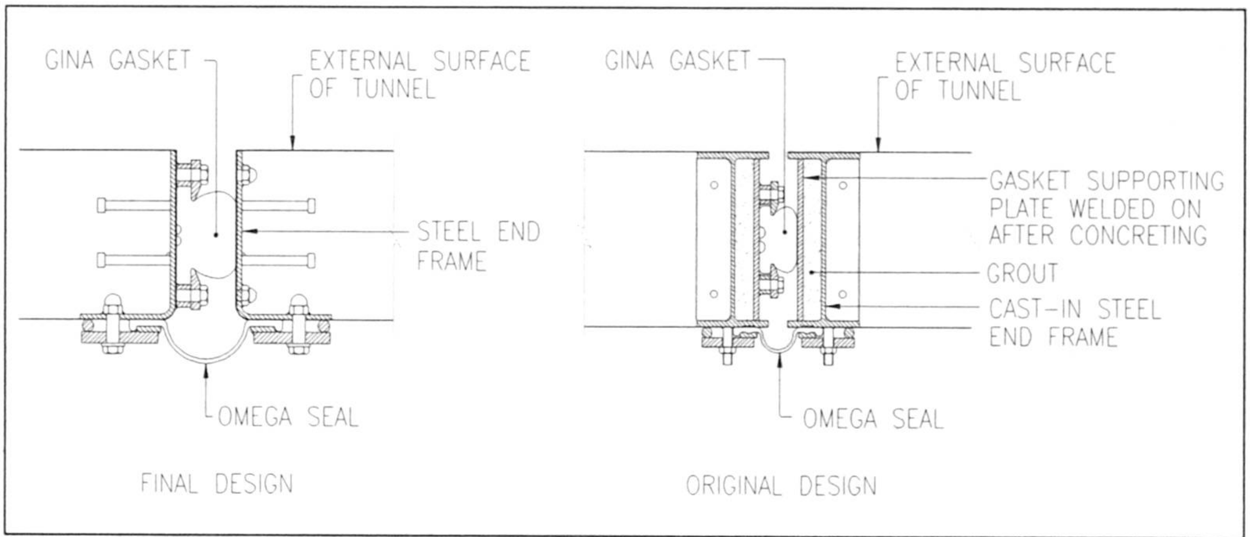

Figure 3 Immersion Joint - Comparison of Original Design with Final Design

5.2 Tunnel Segment Joints

The contract requirement for tunnel segment joints specifies a continuous half-joint around the tunnel perimeter sealed with a groutable waterstop. Whilst this is a common detail, the half-joint itself is difficult to concrete, and the resulting joint provides vertical shear resistance in the slab members and horizontal shear resistance in the walls - the opposite of where the natural shear strength of the structure is to be found.

An alternative joint design, developed jointly by contractor and designer, was proposed. The alternative replaces the half-joint with a plain joint, and introduces discrete shear keys in the walls (plus one in the base to resist horizontal shear). This solution, accepted by the owner, places shear forces in appropriate structural elements and simplifies construction, with consequential benefits for the quality and durability of the structure.

6. Tunnel Reinforcement

6.1 Aims of the Design

The weight of reinforcement in the immersed tunnel is approximately 40,000 tonnes, making it one of the contractor's largest single costs on the project. The challenge for the design and construct team was to develop a tunnel reinforcement scheme which met all the following aims:

- contract compliance;
- sound design, particularly from the point of view of durability;
- buildability, taking into account the unusual construction method;
- minimum quantity of steel.

6.2 Key Design Features

To achieve these aims, a major preliminary design/planning exercise was undertaken between the designer and contractor. This involved establishing the order of magnitude of steel required in key parts of the cross section, then developing bar arrangements which fitted all the stated aims. An extensive preliminary effort was justified in this case given the degree of repetition afforded by the 160 tunnel segments. Key features of the resulting design included the following:

- All reinforcement is set out on a standard 150mm/300mm grid to facilitate the use of prefabricated jigs in the casting yard.
- Sophisticated handling equipment in the casting yard permits extensive use of longer bars (up to 21m in length) thus minimising the need for laps.
- The basic transverse reinforcement arrangement consists of a complete frame of 25mm diameter bars at 300mm centres. Where local bending stresses cannot be resisted by this quantity of steel, additional bars are introduced in between the frames, and subsequently by bundling, but none of these additional bars is lapped. This is illustrated in Figure 4.
- Small box-outs and recesses are detailed independently from the main reinforcement, the latter being detailed as if there were no recesses and subsequently cut to suit on site.
- The use of shear reinforcement is kept to a minimum, but cannot be avoided altogether. Where it is required, *shear assemblies* are adopted. This technique achieves adequate shear resistance, but avoids the need for shear reinforcement to pass around the main bending reinforcement, thus greatly simplifying fabrication.

6.3 Reinforcement Handling

In the context of a line factory prefabrication process, the reinforcement fabrication is kept off the construction critical path (which goes through the casting process); complete reinforcement cages for each segment are assembled upstream in the rebar shed, then moved to a buffer area before finally entering the casting area. Each reinforcement cage is made of separately prefabricated subassemblies which provides further flexibility in the process (Figure 5).

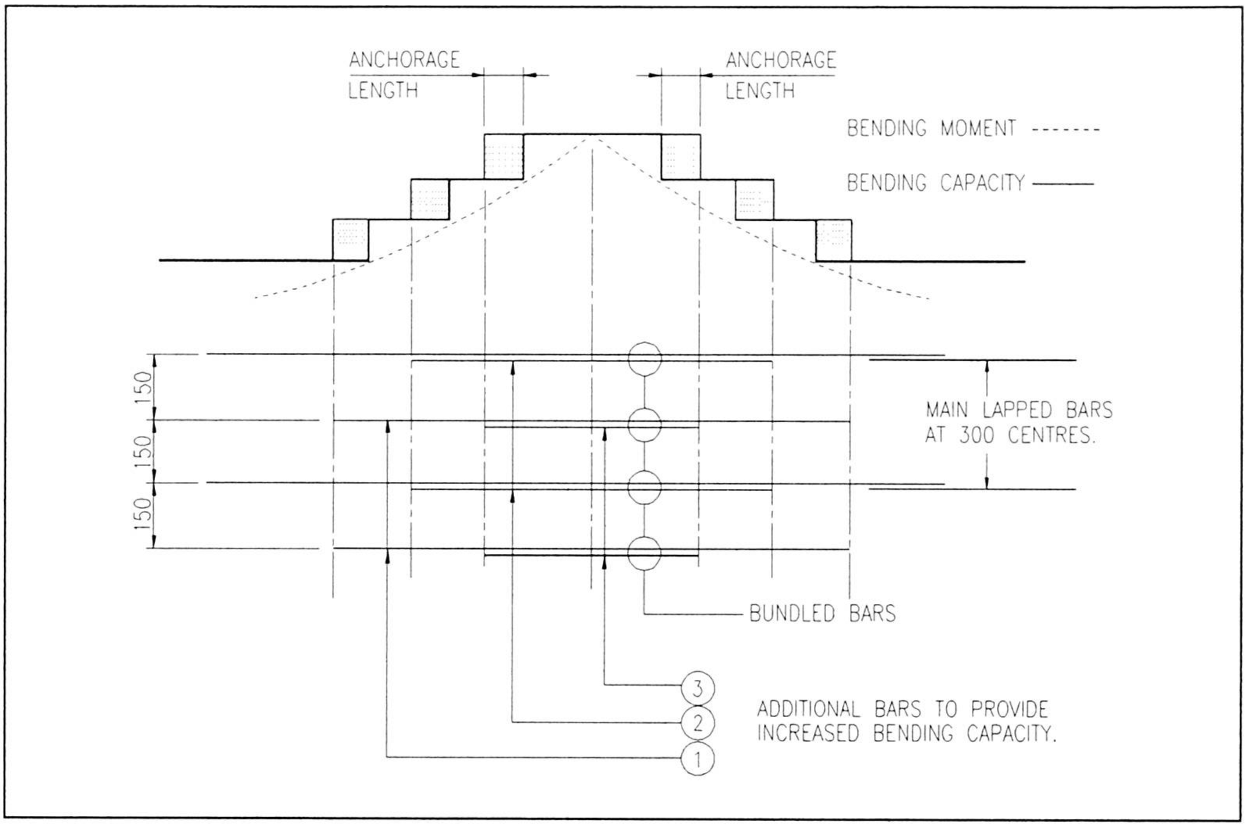

Figure 4 Reinforcement in Areas of High Stress

The subassemblies have been chosen by designer and contractor to suit both the constraints imposed by design and the lifting and handling capacities available in the shed. They comprise the base slab (assembled directly on the transfer rails to the buffer area), the six walls, and various panels for the top slab. The completed cage must be self-supporting, since it is assembled remote from the casting cells. This is achieved by the incorporation of fixing frames comprising steel angle trusses inside the cage; these provide the necessary stiffening.

The cage is moved from the final assembly zone to the buffer area on rail-mounted trolleys pulled by winches and from the buffer area to the casting cell on inflatable rails on needle bearings. Trial tests of the equipment and the experience on the first segments have enabled the contractor to fine tune the system to ensure that the cage arrives in the casting area in the correct position and with minimal distortion.

As well as removing the reinforcement from the critical path, this method also simplifies many other activities such as the incorporation of embedded items in the cage, since they can be performed with the cage completely unencumbered by shuttering.

From a design point of view, the reinforcement solution minimises steel tonnage without in any way compromising the quality of the finished product. This is achieved partly by the detailing measures described above, and partly by very careful attention to accurate curtailment of reinforcement, with each element of the tunnel being the subject of a separate design.

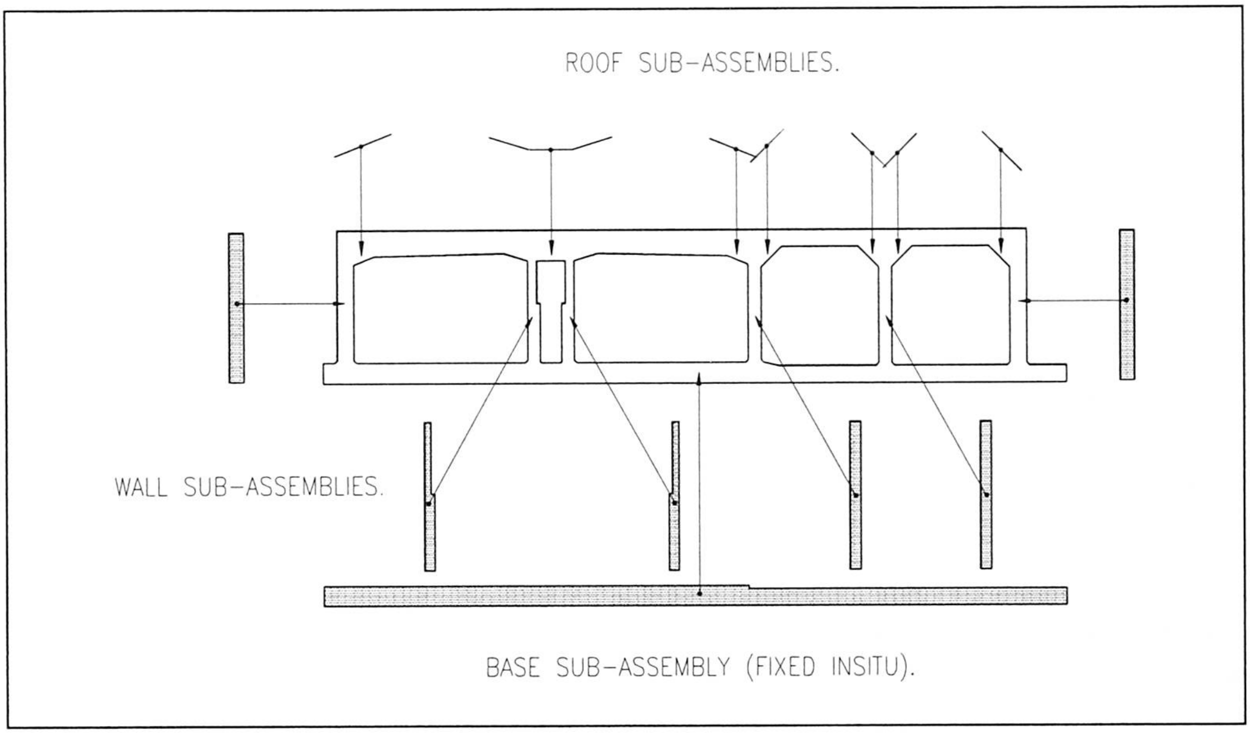

Figure 5 *Reinforcement Sub-assemblies*

7. Marine Works

7.1 Marine Engineering Philosophy

The marine engineering for an immersed tunnel is dominated by the construction considerations of how to transport, manoeuvre and place a tunnel element. For economical as well as practical reasons, the different construction stages should have little or no impact on the permanent works design other than the necessary temporary works provisions (i.e. temporary prestress cables to hold the segments together during transportation and immersion, and marine works outfittings).

A "weather window" philosophy has been adopted for all marine works activities whereby a suitable hydrological and climatological window for the various marine operations is defined. The requisite window for an operation depends on the type and expected duration of the works. Forecasts of hydrological and climatological conditions are used to determine a duration which is suitable for performing the operation and which can be forecast with sufficient confidence.

The operational factors which have been considered are water depth, wave condition, wind, current, water level, salinity, ice, visibility, temperature and passing shipping. The operational limits are a function of tunnel element design assumptions, equipment and materials used and the nature of the marine works in question. Where appropriate, a distinction is made between survival (ultimate) design conditions and operational conditions. In practice, decisions are taken on suitable operational windows based on 24, 48 and 72 hour weather forecasts. Should such forecasts prove unreliable, and conditions deteriorate during an operation, a decision is taken either to continue, to go to survival positions, or to return to a safe harbour.

The main permanent works design considerations relating to marine works are tunnel foundation (see section 8), temporary prestress, vertical balance of tunnel elements during float-up, transport and immersion, effect of marine outfitting on the structure, and design of tunnel rock protection.

7.2 Temporary Prestress

The design of temporary prestressing is a hybrid between temporary and permanent works, since its purpose is to safeguard the permanent works during element transport and immersion, yet its life is temporary, since the tendons are cut once the element is on its foundation. The prestress is designed to accommodate two distinct loading conditions, each of which is separately evaluated for normal operational conditions and for survival conditions:

- loads arising due to sea conditions during transport;
- loads arising from placing the element in the tunnel trench.

Due to the form of foundation the latter case is never critical, and the tendons are designed to ensure that the segment joints remain closed during transport and immersion. The main loadings come from waves, partly direct and partly transmitted through the immersion pontoons. Loading due to waves was derived by the contractor, based on physical model tests performed by the Danish Hydraulic Institute and hydrodynamic modelling performed by SIMTECH of The Netherlands, a specialist marine engineering consultancy. The final structural design, in terms of quantity of prestress, anchorage design and disposition of tendons within the structure was the responsibility of the designer. A particular issue here was finding sufficient space in the slabs for the tendons, whilst successfully avoiding other obstacles, notably bulkhead fixings and ventilation fan niches.

For the purposes of tendon design, 'survival' condition bending moments were determined about both horizontal and vertical axes from the following parameters: significant wave heights 1.25m in 10m of water and 1.60m in 15m of water; wave period 4.5 seconds. The expected ultimate limit state failure mode of the structure under such loading is a shear failure at one of the segment joints. Failure is induced by combined shear and tension in the shear key, the latter induced by friction as the joint begins to open. For design purposes therefore, 'failure' was defined as the point at which the compression stress due to prestress at any point in one of the shear keys drops to zero (i.e. the point at which longitudinal tension can be induced in the key).

7.3 Vertical Balance of Tunnel Elements

An immersed tunnel has to be designed to be buoyant for transportation purposes, and stable against uplift once immersed. The change from one condition to another is typically achieved first by the introduction of temporary water ballast and subsequently by its replacement by permanent concrete ballast. For the Øresund Tunnel, an additional complicating factor was introduced by the asymmetry of the tunnel section, which is significantly heavier on the motorway side of the box than on the railway side (a symmetrical arrangement of bores was not possible due to constraints on road and rail approach alignments on the Danish coast).

For transport of the elements, uniform freeboard is achieved by construction of part of the permanent concrete ballast in the element casting yard. This is sufficient to balance the element, but leaves little margin for error in freeboard calculations, since the tunnel is close to minimum freeboard once sufficient ballast is added to make it float level (Figure 6).

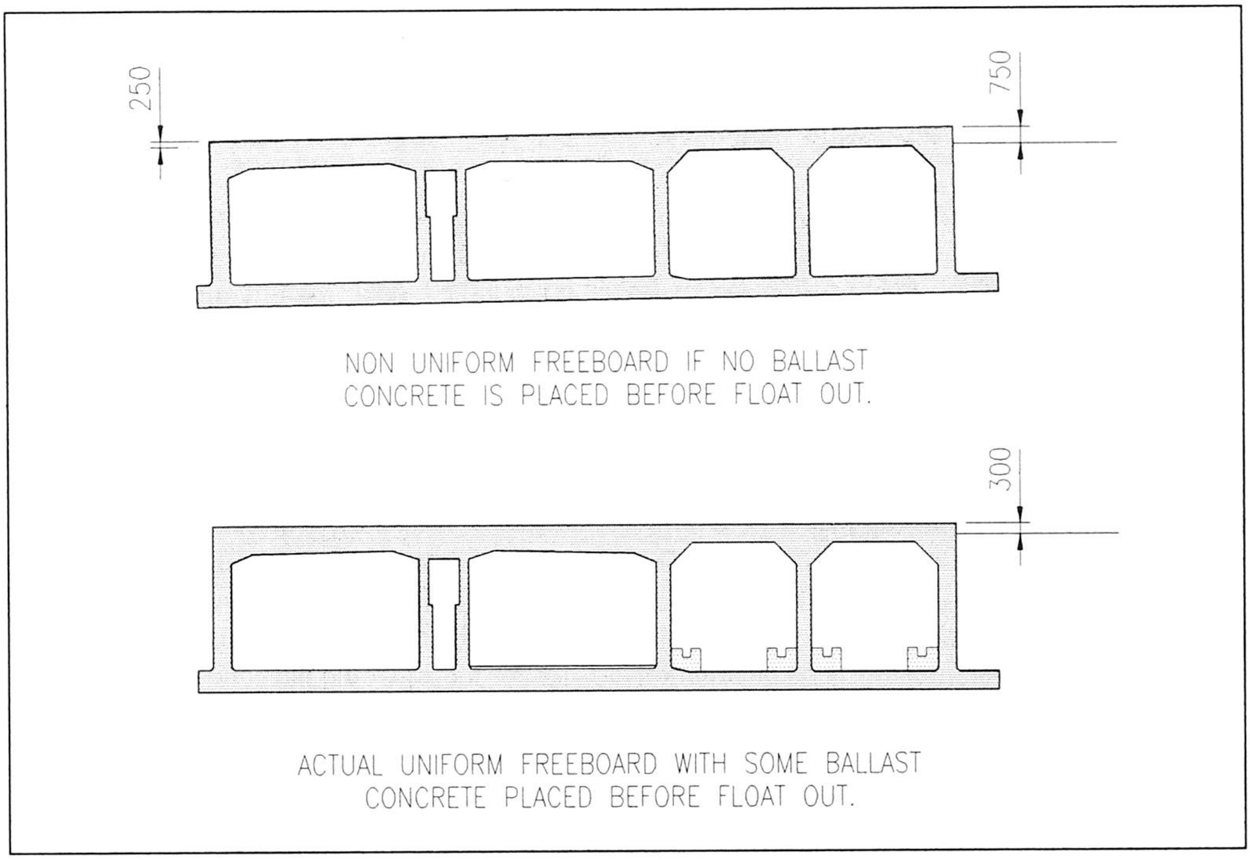

Figure 6 Tunnel Element Freeboard

In the permanent condition, the majority of the remaining ballast has to be added in the motorway bores, as little space exists in the railway; this results in a tunnel with uneven ground bearing pressures. Whilst this is theoretically acceptable, the designer deemed it desirable for the long term integrity of the works that bearing pressures be approximately uniform under the cross section. This was achieved by extending the base outside the external walls asymmetrically, with a 0.8m toe on the motorway side, and a 2.25m toe on the railway side.

7.4 Marine Outfitting

For purposes of transport and immersion, each tunnel element has to be fitted out with an access snorkel, survey towers and towing bollards. All of these are temporary works items, but all have to be attached to the tunnel structure, in many cases with large anchorage and fixing devices. Design of the temporary items themselves is performed by the contractor, fixings to the permanent works by the designer. This requires care at the interface, since it is a critically important point of design principle that in the event of unforeseen loading, for example due to storm conditions, the first point of failure should be in the temporary works item, without any damage to the permanent structure; thus it is essential not to over-design the temporary items, but instead to ensure that the weak link is outside the permanent structure.

7.5 Tunnel Rock Protection

The tunnel is protected from sunken ships, anchors, propeller-induced scour and current-induced scour by a layer of crushed rock placed on the tunnel roof. Two sizes of rock are used, a nominal 500mm rock in and adjacent to the main Drogden shipping channel, where the critical design consideration for rock size is propeller scour, and a nominal 300mm rock closer to shore, where current and anchor considerations are critical in determining rock size. The layer thickness throughout is 1200mm, which arises from the falling anchor load case.

Rock placement is performed using a grab which is brought as close to the tunnel roof as possible before opening. By specifying a closely controlled placement method, it has been possible to eliminate the need for any additional protection layer between the tunnel structure and the rock protection.

8. Tunnel Foundation

8.1 Choice of Foundation Type

At tender stage, options for foundation construction were studied in some detail. A screeded gravel bed, of the type traditionally used for steel immersed tunnels, was rejected since the typically achieved tolerances of such construction (±50mm or more) would introduce unacceptable stresses into the relatively wide, flexible concrete box proposed for Øresund. At tender stage, therefore, a conventional concrete tunnel solution - temporary jacks combined with pumped pancakes of sand - was proposed.

Early in the contract, ØTC developed an alternative foundation proposal for consideration. This consists of a gravel bed, placed in such a manner that no subsequent screeding of the gravel is necessary. Based on experience gained by one of the ØTC joint venture partners on another project, it was forecast that such a bed could be placed to an accuracy of ±25mm. A detailed study was performed to compare the two options, and the gravel bed was in due course adopted. The most important benefits afforded by this change were:

- programme considerations (the gravel bed is off the critical path for the marine works as it is laid *before* immersing the tunnel element);
- elimination of the temporary supports (which are subject to a risk of overload during ship passage over a tunnel element);
- elimination of the risk of siltation beneath a placed element;
- elimination of a complex system of large cast-in pipes (with their associated leakage risk) for the sand flow system;
- no requirement to make good openings in the structure arising from the sand flow system and jacks, thus improving structural integrity.

In opting for the gravel bed, a number of important technical issues had to be addressed. The most important among these were:

- gravel placing methodology and ØTC's ability to design and deliver the placing equipment;
- choice of gravel materials and bed geometry;
- bed level accuracy - both placing accuracy and accuracy with which the finished bed levels could be measured;
- stresses in the tunnel structure due to imperfections in bed level; this was not just a question of absolute level tolerances, but crucially of the *distribution* of high and low parts of the bed.

8.2 Foundation Placing Methodology

The basic principle for placing the bed is to feed gravel down a pipe directly into position on the trench floor. The lower end of the pipe is equipped with a screeding plate which moves slowly across the trench, leaving the top of the gravel at the correct level *as it is placed.* The process is continuous, and there is no secondary screeding operation.

The feeder pipe equipment is mounted on a multi-purpose pontoon, fixed temporarily in position by spuds. The equipment is arranged such that each pass of the feeder pipe tracks in a straight line across the full width of the tunnel trench. During each pass, gravel supply is controlled such that the feeder pipe is never empty.

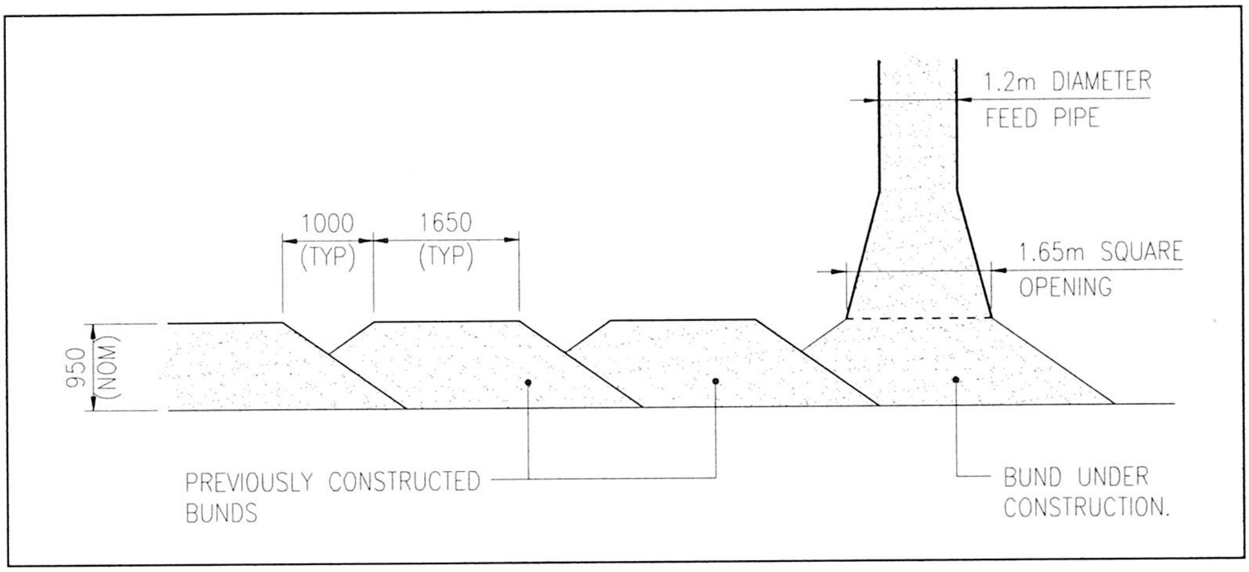

Figure 7 Gravel Bed - Placing Technique and Bund Geometry

8.3 Material Specification and Bed Geometry

Each pass of the feeder pipe places a line of gravel approximately 1.65m wide. During development of the method, it was recognised that a risk existed that the feeder pipe would disturb already placed gravel as it placed the adjacent line. It was therefore decided that each pass of the pipe should create a bund of gravel, separated at the bed surface from adjacent bunds. The final chosen geometry, illustrated in Figure 7, also has the merit of creating a drainage path for water as the tunnel element makes contact with the bed. The individual bunds thus produced were analysed to determine long term stability. This resulted in an angle of internal friction of 40 degrees being specified for the bed material.

8.4 Accuracy of Construction and Survey

It was recognised at the outset that the gravel bed proposal would not be viable unless accurate bed levels could be achieved. The system finally specified is capable of delivering an overall level accuracy of ±25mm from the design line throughout. This is achieved by a laser levelling system linked by computer to hydraulic cylinders on the feeder pipe. The system is sufficiently responsive to maintain the pipe level against wave-induced movements of the pontoon.

During development of the proposal, it was recognised that *demonstrating* that the gravel had been placed accurately to level was going to be no easier than constructing the bed accurately in the first place. Levels of the finished bed are measured (independently of bed construction) by means of a row of echo-sounders mounted on the feeder pipe. The design can accommodate inaccuracies in the levelling system (allowing for errors in the echo sounders, in the position of the fall pipe and in the laser measurements), of up to ±23mm; performance on site is confidently expected to better this figure.

8.5 Effect of Bed Levels on Tunnel Stresses

Due to the sensitivity of the tunnel box to even quite small distortions, the accuracy of the gravel bed levels is an important permanent works design matter. To define an acceptable bed level is not simply a matter of specifying the ±25mm tolerance; much smaller deviations can be unacceptable if they follow a regular pattern (for example a consistent pattern of +10mm under the middle of the tunnel base and -10mm under both edges would be unacceptable, even though well within the overall tolerance). To address this, it has been specified that variations in bed level must be distributed in a random pattern.

A study has been performed to determine what precisely is meant by 'random' in this context, and a numerical test has been developed which can be applied to any actual bed level data set to test for the needed degree of randomness. Beds which pass this test will be accepted for tunnel immersion directly, whilst any that fail the numerical test will trigger a check analysis of the element in question for the as-built bed. This will either result in the bed being accepted as-built, or recommendations for remedial action being put forward. Possible remedial works include local removal of high spots without reinstatement, or more extensive removal of out-of-tolerance construction followed by reinstatement.

9. Conclusions

A "design and build" type of contract is recommended for major projects as it provides substantial benefits for both the designer/contractor team and for the owner. The designer and contractor can combine their efforts and make maximum use of their potential and experience in optimising the design and the construction methods in an integrated fashion. Consequently, the owner is assured of good value financially, and is able to minimise his involvement throughout the design and construction phase.

In order to make "design and build" successful, the contract needs to allow the fullest possible flexibility to the designer/contractor by depending on performance specifications, and keeping firm, specific requirements to a minimum.

For the Øresund Tunnel in particular, "design and build" has created the opportunity for tunnel design to be optimised to a degree impossible under more traditional forms of procurement, and has permitted the development of an exciting and innovative construction method customised to the challenges and opportunities of this particular project.