Planning and monitoring the foundations for the Øresund Bridge

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SUMMARY

The Øresund Bridge across the sound between Denmark and Sweden is under construction. The road and rail bridge is 7.8km long and consists of a central 1.1km cable-stayed bridge with a main span of 490m. The approach spans are typically 140m. The pylons and many of the 51 piers have to withstand large ship impact forces and all are designed for winter ice loading.

The construction contract for the bridge is a modified 'design and construction' contract. The information supplied at tender stage by the Owner, Øresundskonsortiet and his consultants, contained, in addition to the usual Design and Construction Requirements, also a set of geotechnical Reference Conditions, a set of Definition Drawings and an Illustrative Design.

The geotechnical Reference Conditions contained the ground stratigraphy and a summary of the strength and deformation properties for the ground. The Definition Drawings fixed all visible dimensions for the bridge - foundation types and sizes were not shown. The Illustrative Design was included for information and showed in details a solution fulfilling all the Owner's requirements – approximate foundation details were shown.

The geotechnical Reference Conditions form the basis for all geotechnical design work. Bands of uncertainty were provided within the Reference Conditions and the Contractor accepted these bands as "foreseen" ground conditions. Where the ground conditions were outside the Reference Conditions intervals, the Owner accepted the risk. In only five of the 53 foundation locations were the ground conditions outside the predefined Reference Condition intervals; all of these instances referred to strata levels rather than actual soil or rock strength and deformation properties.

ASO Group is responsible for the bridge design and is the Owner's bridge consultant. During the construction phase ASO is monitoring and auditing the Contractor's work to ensure that the Owner's requirements on quality are fulfilled. ASO Group consists of Ove Arup & Partners (GB), SETEC (F) and Gimsing & Madsen and ISC (DK).

1 INTRODUCTION

The Øresund Link across the sound between Denmark and Sweden is under construction. The Link is owned by Øresundskonsortiet who, with advise from in-house consultants, have let four design and build contracts for the main section of the Link to contractor led consortia. The contractors are responsible for design as well as the actual construction of the Link. The Link is due to open during the year 2000.

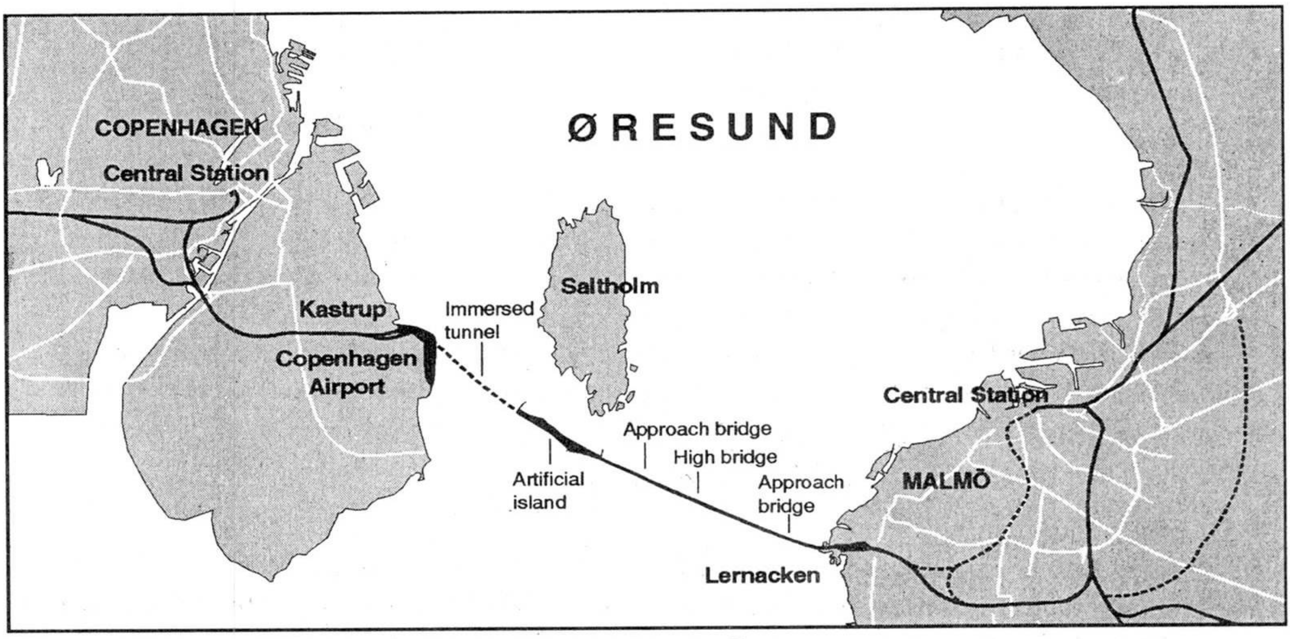


Fig.1. Plan of the Øresund Link

The 15.8km Link comprises, from Copenhagen Airport in Denmark to Lernacken in Sweden, the following main parts (Fig.1):

- a 0.4km reclaimed peninsula,
- a 3.5km immersed concrete tunnel;
- a 4.1km artificial island, and
- a 7.8km bridge, consisting of two approach bridges and a cable-stayed high bridge.

The bridge deck carries the traffic at two levels with the dual two-lane motorway at the upper level and the two tracks for the high-speed railway at the lower level. The bridge superstructure is supported on 51 piers, two pylons 203.5m high and two abutments, one on the artificial island and the other at Lernacken.

This paper describes the Owner's contract strategy in particular with regards to the definition of ground conditions in the form of geotechnical Reference Conditions.

The construction contract for the Øresund Bridge was signed in November 1995 between the Owner, Øresundskonsortiet and Sundlink Contractors consisting of Skanska (S), Hochtief (D) and Monberg & Thorsen and Højgaard & Schultz (DK). The Contractor's detailed designer is CV JV consisting of COWI (DK) and VBB (S).

2 CONTRACT STRATEGY AND DOCUMENTS

2.1 Contract Strategy

The construction contract for the Øresund Bridge was a modified design and construction contract. Prior to the tender stage the Owner and his consultants carried out extensive investigations into the physical conditions along the bridge alignment. These investigations allowed characterisation of the ground conditions prevailing at the site.

2.2 Contract Documents

The Contract Documents provided adequate information on which all tendering consortia could provide a fixed price tender bid. The main documents concerning the design and construction of the bridge foundations were:

2.2.1 Reference Conditions

The Reference Conditions contained a description of the weather and ground conditions (mainly clay and sand tills over layers of limestone), that could be encountered at the site. This ground condition information included a summary of the stratigraphy (the variation in surface level of each stratum along the bridge centreline) and the strength and deformation properties of the stratum (mainly till and limestone); the information provided was sufficient to design the bridge foundations. The Reference Conditions also presented index property test results that demonstrated the variability of materials encountered (especially in the limestone strata). These properties allowed characterisation of the material (based on relatively inexpensive laboratory and descriptive techniques) during the Contractor's ground investigation. The information was provided at tender stage and was used during the basic design stage of the bridge foundations; at this stage of the design process pier specific ground investigation was not yet available. The soil and rock parameters contained in the Reference Conditions were also the basis for the detailed bridge foundation design. However, at the detailed design stage, the Contractor was required to demonstrate (by means of his site specific ground investigation drillings) that the information provided in the Reference Conditions was valid for each and every pier location. Detailed information on the Owners pre-tender ground investigation work carried out during the preparation of the Reference Conditions document are contained in Volume 5 of the 11th European Conference on Soil Mechanics and Foundation Engineering including [1] and [2].

The weather conditions were defined in terms of current, wind and temperature all three of which influence construction activities offshore.

2.2.2 Design Requirements

The contractual design requirements consisted of three parts: Design Requirements, the Project Application Document and the Definition Drawings. As a basis for the design the Eurocode system was adopted. However, not all the relevant Eurocodes were complete at the time of tender, and many existed only in draft form, so to adapt them to this project a set of Project Application Documents was prepared giving amendments to individual Eurocodes (e.g. EC7 for foundations). Partial safety factors were calibrated, and accidental load cases identified and defined to satisfy the operational risk acceptance criteria developed for the completed Link. The Design Requirements document listed specific load cases and methods for calculation of these loads. Critical load cases for foundation design were ship impacts for the central piers and pylons and the serviceability limit case for all piers/pylons.

The Definition Drawings defined all visual geometry of the bridge; there was little geotechnical input here. A parallel document to the Definition Drawings was the Illustrative Design, which was not part of the contractual documentation but included for information only. This set of drawings showed an example design for the bridge conforming to the design requirements.

In terms of review of the Contractor's design the Owner retained the right to approve the basic design for conformance to the Design Requirements. However, the Owner only retained the right for comment on the detailed design and thus did not perform the role of checker. This firmly laid the design responsibility on the Contractor.

2.2.3 Construction Requirements

This document contained the requirements (the minimum requirements) for all anticipated construction activities. Regarding the foundations there where structural related requirements for concrete, there were also requirements for the detailed ground investigations at each pier/pylon location and requirements for the underbase grouting and full-scale trials of this grouting between the underside of caissons and the excavated limestone surface.

The requirements for the detailed ground investigations were such that, assuming good execution of the drilling work, the index properties of the sampled ground (density, point load index and unconfined compressive strength etc.) could be compared with the parameters that were measured during the formulation of the Reference Conditions. This approach reduced the necessary ground investigation at each pier location to a minimum by reliance on the vast amount of pre-tender detailed information that was correlated with the design parameters.

The necessary bond between the bases of the caissons and the intact Limestone was to an extent a function of the Contractor's design. However, even with this condition it was considered necessary to state that a uniform contact between the caisson base and the intact Limestone must be achieved. To enable the Contractor's construction method to be demonstrated the Contractor was required to carry out a full-scale trial (in fact large scale) of the grouting procedure. To enable the robustness of the trial to be proven the trial was required to be carried out successfully twice. The trial grouting area was 8m by 11m in plan and represented the bases of both the pylon caissons (rough) and the pier caissons (toothed). It is noted here that the requirement for trial grouting was so strict that when, on one of the pylon caissons, imperfections were discovered beneath the caisson the need to execute trials of the remedial measures was an accepted part of the repair process.

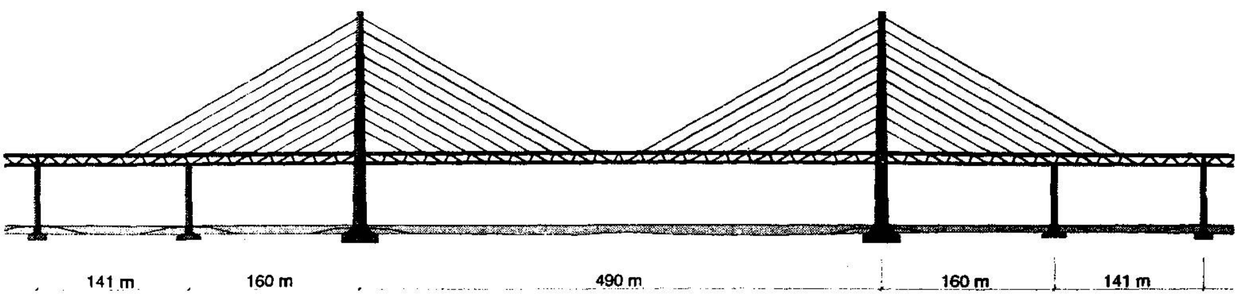
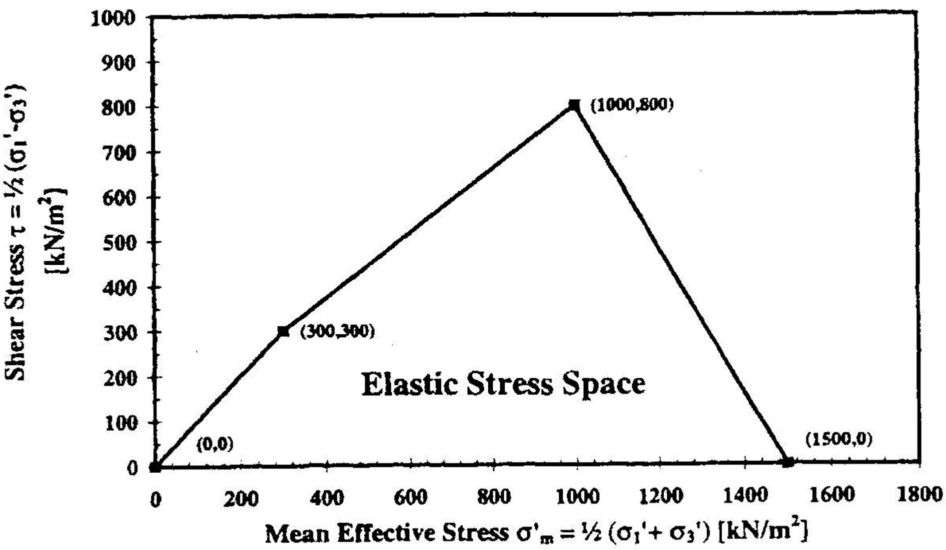


Fig.2 The 490m Main Span crosses an international Shipping Lane

3 MAIN FOUNDATION DESIGN CONSIDERATIONS

The depth of water along the bridge alignment varies from approximately 2m to over 8m. At the high bridge pylons the water depth associated with the main shipping water level resulted in ship impact design forces of up to 560MN being appropriate. Although the pylons were surrounded by protective islands (Fig.2) they were still required to be able to resist the full ship impact force of 560MN ignoring the effect of the protective island. The three adjoining piers were also protected but not required to resist the impact irrespective of the islands. Unprotected piers were designed for ship impact forces up to 211MN. These large horizontal forces combined with the anisotropic strength of the limestone foundation (weak and weathered horizontal layers) resulted in an accidental impact loading that was in some instances the critical load case. Design of the ship impact resistance needed to limit the permanent bridge displacement to 100mm requiring dynamic calculations used whereby the caisson's inertia, movement (acceleration etc.) and the shear resistance of the ground was related to the impact energy and stiffness.



Where :

σ_1' : **Major Effective Principal Stress**

σ_3' : **Minor Effective Principal Stress**

Fig.3 Definition of Elastic Stress Space for Limestone Formation

For all caissons regardless of seabed level a critical load case was that of cyclic degradation of the Limestone foundation material appropriate to the serviceability limit state. The specified design check for this required that the stresses mobilised in the limestone were within a predefined elastic yield loci with bounds related to both shear stresses and normal stresses (Fig.3). The Design Requirements stated that all stress states within the yield loci would result only in elastic strains and thus limit any cyclic degradation of the limestone to a minimum.

For ship impact loading, the anisotropic nature of the limestone was of great importance. Hence, the nature of the site investigations mentioned above was such that low strength layers (called Hi layers of completely weathered limestone) of 100mm or greater had to be identified by means of core recovery and downhole geophysical testing during the Contractors site specific ground investigations. Similarly, occurrence of weak layers immediately beneath the foundation level would invalidate the Elastic Stress Space and would result in large and possibly uneven settlement of the bridge foundations.

In both of the critical load cases the information supplied to the contractor led to the design criteria being easily understood without the need for a comprehensive investigation into the behaviour of the limestone being undertaken during the detailed design stage of the contract.

4 ACTUAL GROUND CONDITIONS AND CONSTRUCTION

4.1 Revealed Ground Conditions

The geological boundaries (the important ones being the seabed level and level of the top of limestone) specified in the Reference Conditions document were given to an accuracy of ±1.5m. Any variation of the level of less that 1.5m from the Reference Conditions was deemed to be at the Contractor's risk whereas any variation beyond 1.5m was deemed to be at the Owner's risk.

As part of the Contractor's design he was allowed to alter the pier locations within certain geometrical constraints. Hence, the pre-tender borings commissioned by the Owner did not, nor were intended to, survey all pier locations. Interpolation between borehole positions was aided by geophysical survey techniques.

In order that there was a thorough check of the information contained in the Reference Conditions the Contractor was required to carry out a specific site investigation at each pier location. The nature of the site investigation was specified in the Construction Requirements document in terms of both borehole dimensions, depth, type of drilling equipment and the regimes for sampling and testing of samples. The specified methods of investigation had previously been tested during the Owners pre-tender investigations and were seen to be the most appropriate for the anticipated ground conditions. The Contractor's ground investigation was not intended to redefine the Reference Condition ground parameters, but was aimed at justifying their use during the detailed design of the bridge. The investigations carried out during the formulation of the Reference Conditions involved sophisticated large scale laboratory testing and complimentary quarry plate load tests, neither of which were part of the Contractor's investigation.

At only 5 of the 53 offshore foundation positions were the Reference Conditions seen to be inaccurate with respect to strata levels. The most notable, though not largest, variation in level was at the West Pylon where the surface level of the Limestone was seen 1.5m lower than the Reference Condition median level. The result of this was that the approved basic design needed to be modified to account for this strata level change. The cost of the physical change was absorbed by the Contractor, the cost of the redesign was, however, absorbed by the Owner due to bad weather conditions delaying the availability of site investigation information. This meant that the Contractor had to start the detailed design without having the results of his site investigation. At the five most easterly caisson locations the Limestone was observed by the Contractor to be more porous and to have thicker highly weathered bands than previously anticipated i.e. that the Reference Conditions were invalid. It was not suggested that the caisson foundation would fail but that larger than usual settlement (and differential settlements) could occur. The Owner noted the concern of the

Contractor's designer and, without agreeing that abnormal ground conditions were present, accepted that precautionary measures should be adopted to limit the implications of larger than the assumed settlements of 30 to 50mm. The design solution was to construct the bearing plate oversized making allowance for possible future shimming and if necessary realignment of the bridge bearings in case larger movements occurred when the full dead load was transferred. The cost of this extra bearing size was shared between the Contractor and the Owner. The Owner accepted that should further modifications be needed he would himself absorb these extra costs. In the end no additional measures were required and the caisson behaviour of the five caissons in question was seen to be similar to other caissons.

4.2 Construction Quality

The Contractor is responsible for the quality of the permanent works. To enable the quality to be monitored by the Owner the Contractor was required to seek approval for his Quality System and his detailed Quality Plans covering all design and construction activities. On site monitoring and assessment of the Contractor's performance by both the Contractor's own quality management and the Owner's Consultant ASO Group, is then carried out on the basis of these approved Quality Plans, the Construction Requirements and the Working Drawings. That the Contractor is responsible for the quality of his own work means that if he finds that the quality is not as required or procedures are not adhered to, then he is required to issue a non-conformance report (NCR) identifying the non-conformance and the proposed corrective action. In case of remedial work being required, approval is required by both the Contractor's designer and the Owner prior to the remedial work being carried out. In the case of the West Pylon foundations faulty underbase grouting was found. The Contractor had located the bad grout, carried out tests and subsequently filed an NCR. The corrective action, which consisted of revisions to method and procedures for the future grouting operation, was agreed as was the remedial measurements required to the actual substandard grout. In other instances where the Owner's Consultant identifies an apparent non-conformance (ANC), the fact is drawn to the attention of the Contractor, and when agreement is reached as to the status of the ANC the Contractor issues an NCR similarly to him having identified the non-conformance himself. Hence, in all instances the Contractor remains solely responsible for the quality and for satisfactory remediation of non-conformances.

5 CONCLUSIONS

The strategy adopted by the Owner with respect to the way in which the ground conditions were treated for the Øresund Link project can be summarised as follows:

- Carry out detailed pre-tender site investigations and interpret all data to be included in the Reference Conditions;
- Accept the risk, and cost/time implications, should the ground parameters and stratigraphy levels found at each pier location be outside the limits of the Reference Conditions;
- Accept no claims for unforeseen ground conditions for ground parameters and stratigraphy levels inside the Reference Conditions; and
- Accept no change in ground parameters resulting in an increased strength utilised by the Contractor without being substantiated by a site investigation at least as sophisticated as the Owner's pre-tender investigations.

This approach resulted in the following benefits relating to the tendering as well as the construction phase of the contract:

- The bids returned by each tenderer were based on the same set of ground conditions and on the same interpretation resulting in a uniformity of tenders for tender evaluation and comparison.
- The Contractor's designer could commence his design prior to the results of the site specific ground investigations becoming available.
- Evaluation and approval of the Contractor's preliminary design was made against the Reference Conditions which were formally adopted within the contract framework;
- The details of the pre-tender site investigations provided adequate information to ascertain if the ground conditions were in accordance with the Reference Conditions by relatively simple means.

At the time of writing all site investigations have been finished offshore. The Reference Conditions have been shown to be reasonably accurate with respect to the level of the different strata and on no occasion has the condition of the Limestone been proven to be significantly worse that the parameters in the Reference Conditions.

REFERENCES

1 Bergdahl U., Möller B. and Petersson E. (1995). Site investigations in limestone in Malmoe

2 Knudsen C., Andersen C., Foged N., Jakobsen P.R. and Larsen B. (1995). Stratigraphy and engineering geology of København Limestone.