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Geotechnical design considerations for Storebælt East Bridge and Øresund High Bridge

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SUMMARY

The fixed links crossing the 18 km wide Storebælt and the 15 km wide Øresund are the first two of three major infrastructure projects – Storebælt Link, Øresund Link and Femern Bælt Link – that will eventually link Denmark internally and externally to its neighbours. By their extent and complexity, these projects have been a great challenge to all engineering disciplines. The paper describes the investigation strategies employed and the geotechnical design of the bridge foundations. In both projects it was necessary to combine several theoretical models in order to meet the design requirements. Some of the challenges offered by such large projects will be illustrated by two examples: 1) Investigations for and design of anchor blocks founded on gravel wedges and clay till for the Storebælt East Bridge and 2) Investigations for and design of heavily ship impact loaded piers founded on limestone for the Øresund Bridge.

1 INTRODUCTION

This paper presents the Storebælt East Bridge and the Øresund Bridge from a geotechnical point of view. For both projects comprehensive ground investigation programs were carried out in order to establish the geotechnical basis. The strategies for and analyses of the tests were different for the two projects even though very similar analysis methods were used. The aim of this paper is primarily to demonstrate the interaction between the ground investigation program and the development of the analysis models. Finally, the analysis models and the safety strategies for two of the critical foundation problems are considered.

1.1 The Storebælt East Bridge

The East Bridge is one of the major components of the fixed link across Storebælt established from 1986 to 1997. The 6.8 km long motorway suspension bridge includes a main span of 1624 m with a navigational clearance of 65 m, see Fig. 1.

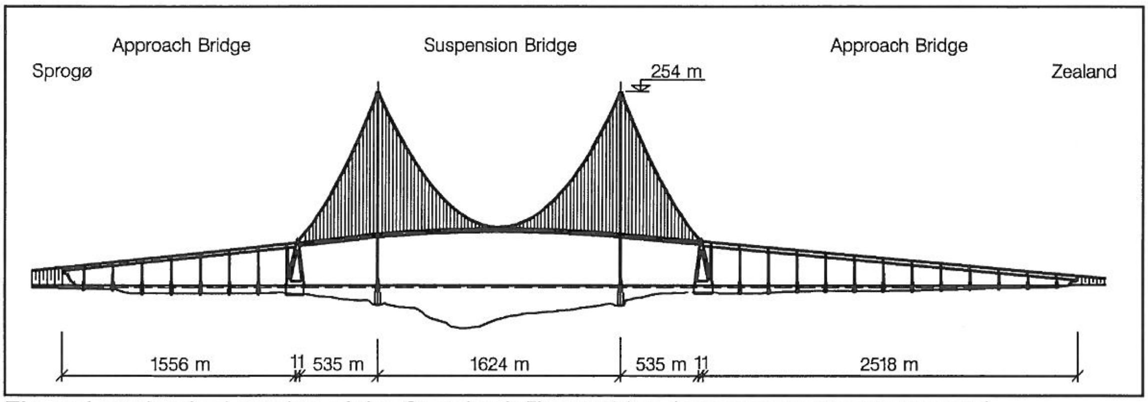

Fig. 1: Longitudinal section of the Storebælt East Bridge (exaggerated vertical scale)

The foundation conditions were good, consisting of 20-70 m firm clay till on top of Kerteminde Marl and Danian Limestone. A comprehensive geological description is given by e.g. Foged et al. [4].

Based on the West Bridge experiences, it was decided that all piers, pylons and anchor blocks should rest on caissons placed on compacted gravel pads of crushed rock. All caissons should be manufactured onshore with a skirt system designed for penetration into the gravel pad in order to establish an ambient space for grouting below the caisson base slab. Special attention was given to the design of the pads beneath the anchor blocks, cf. Section 2.1.

1.2 The Øresund Bridge

The Øresund Bridge is part of the Øresund Link (established 1995-2000) linking Denmark and Sweden. The fixed link will carry rail and road traffic. It comprises a 3510 m long immersed tunnel, a 4055 m long artificial island and a high bridge and approach bridges of a total length of 7810 m. The cable stayed high bridge has a free span of 490 m with a navigational clearance of 57 m. A section of the Øresund Bridge appears from Fig. 2.

The foundation conditions in Øresund are dominated by the Copenhagen Limestone, see e.g. [7]. The

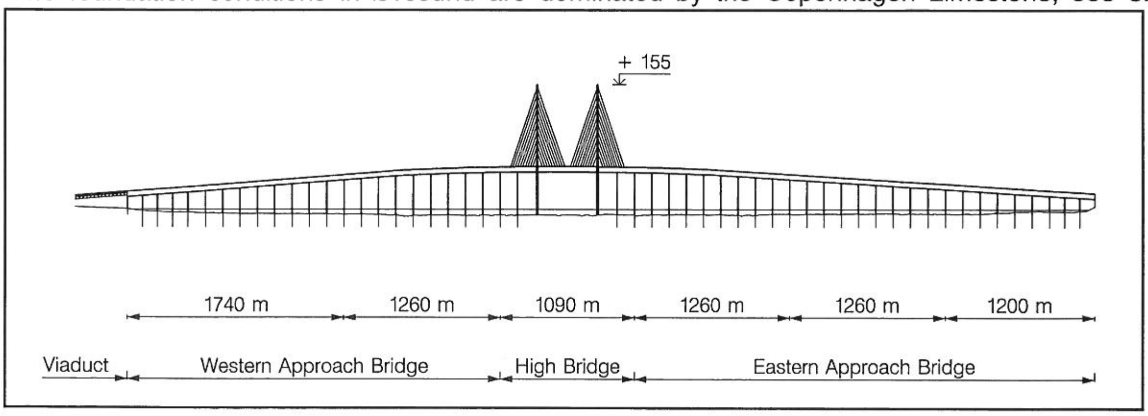

Fig. 2: Longitudinal section of the Øresund Bridge (exaggerated vertical scale)

limestone is generally a competent foundation base, but regions with unlithified limestone or fissures could give problems. Furthermore, it is vital to consider the effects of a reduction of the limestone strength at large strains, [2]. The ground investigations therefore aimed at identifying potential problem zones.

Shallow direct foundation was found to be the most economical foundation due to the competent limestone in Øresund. It was decided that the Øresund Bridge piers should rest on a thin cement grout layer cast after the pier caisson foundations were installed. To secure proper grouting conditions the caissons were temporarily placed on three small footings and a temporary curtain was mounted on the sides of the footings.

2 GEOTECHNICAL INVESTIGATIONS

The ground investigation programs were for both projects extensive. With direct implication on the assessment of critical foundations such as the anchor blocks at Storebælt and the ship impact loaded piers and pylons at Øresund, the geotechnical investigation programs included large scale tests in test pits, [1], [2]. These tests were designed specifically for calibrating the strength models used in the assessment of the bearing capacities.

A significant difference in the two test strategies was that the East Bridge investigations were performed to obtain material parameters to already established calculation models. At Øresund a test program was carried out by the bridge owner prior to the detailed design of the bridge. The challenge for the geotechnical engineer was thus to define and calibrate a suitable model to be used in the ship collision analyses.

2.1 The East Bridge investigations

During the ground investigations for the West Bridge a thorough knowledge of the geotechnical conditions was obtained. The ground investigation for the East Bridge, comprising 100 geotechnical borings and 400 CPTs, thus served to give site specific information and to enhance the geotechnical design basis. Laboratory tests for classification and determination of strength and deformation properties of the insitu soils were carried out. Furthermore, the properties of the crushed rock used in the gravel pads were determined using large scale triaxial and shearing tests. These tests were used to defined a strength model for the clay till and the crushed rock used for the gravel pads, [1], [9].

Of special interest was the foundation of the anchor blocks. Using several different models it was found that the critical section was the gravel pads on which the anchor blocks were founded. Hence a calculation model for the interfaces between concrete caissons, gravel pads and clay till was established. Three principally different types of failure modes are possible for each foundation pad depending on load inclination, see Fig. 3. The critical mode for a given case will depend upon geometry, soil strength, and the inclination of the resultant force. A more detailed discussion of the failure mode that involves sliding along the disturbed clay till surface was presented by Mortensen, [8].

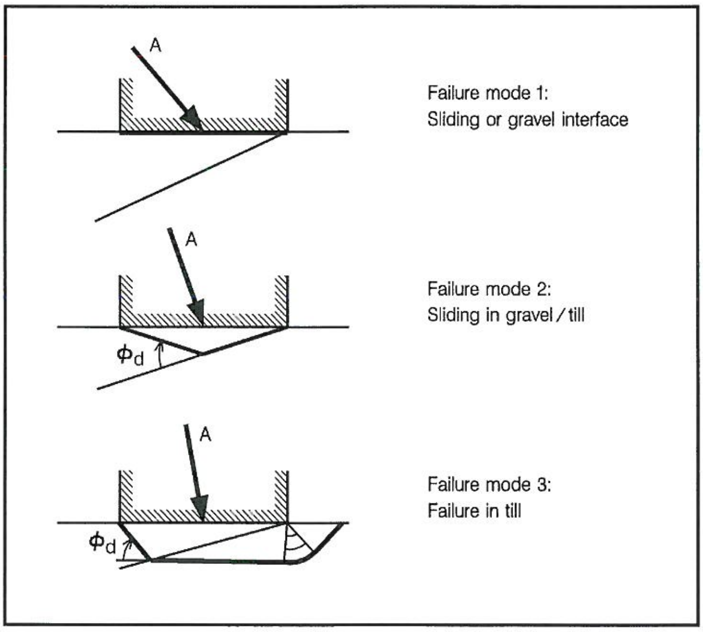

Fig. 3: Foundation pad failure modes

The sliding issue were dealt with by performing large scale sliding plate tests onshore at Sjælland on intact as well as remoulded clay till. The results from these tests were used to calibrate the analytical and numerical calculation models, [1],[11].

2.2 Øresund

The geotechnical investigations on Øresund was concentrated on the determination of the location and characteristics of the Copenhagen Limestone. The ground investigations for the bridge comprised 55 geotechnical borings and ca. 200 soundings. Particular emphasis was given to geological/geotechnical features that, if present, could present particular problems in relation to the foundation design:

- Highly crushed or fissured limestone.
- Extensive zones of unlithified limestone.

- Voids or cavities due to solution of limestone (karstic limestone).
- Soft sediments in depressions between mounds of bryozoas, especially in the transition between Copenhagen limestone and Bryozoan limestone.

The experience of with foundations on the limestone was very sparse. Therefore extensive laboratory testing and medium scale shear plate tests were carried out, [2].

A vital issue in the design of the foundations was the accidental ship impact. As part of the tests carried out in advance of the design, several large scale shear plate tests were carried out on limestone onshore at Lernacken on the coast of Øresund. The vertical and horizontal plate loading tests were large enough to represent the rock mass properties of the limestone. Hence the results from the tests would be a indicator for the behaviour of the limestone when subjected to large horizontal forces, as for example during ship collision. The limestone was further investigated in triaxial and shear tests in the laboratory. The results of the investigations were synthesised into a constitutive model, see Fig. 4. This model served as basis for the definition and calibration of a computer model used to model ship collision in ABAQUS, [6]. Hence, in contrast to the Storebælt investigations no supplementary tests were necessary in order to calibrate the computer models used for assessment of the foundation design.

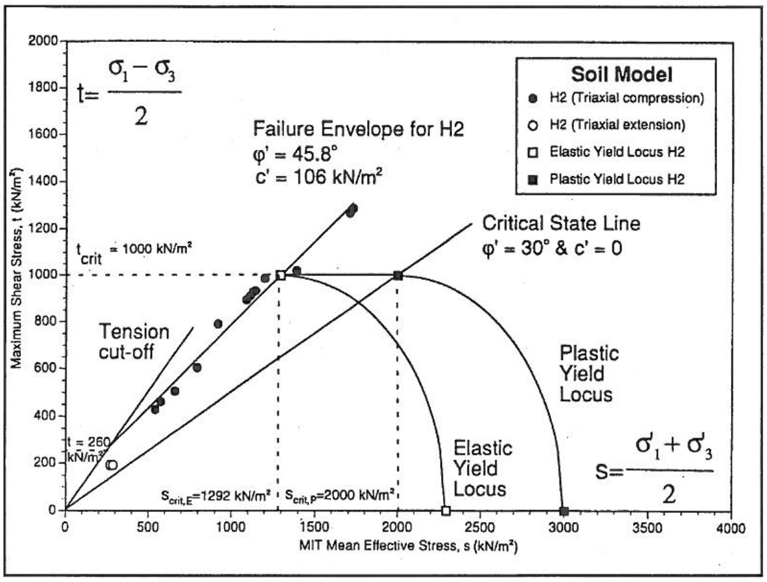

Fig. 4: Principle model for Copenhagen Limestone, [2]

3 GEOTECHNICAL DESIGN

The size and complexity of the projects were beyond normal experience and codes of practice. The safety strategies employed for the two projects were slightly different. At Storebælt the safety level was determined in terms of the safety factor β. The method giving the lowest possible safety factor was to be decisive for the design. The Øresund project was based on the Eurocode system (ENVs). Hence the design basis reflected the safety implied in this code system. For the ship collision case the verification of the material model used in the FE analyses demonstrated a significant conservatism in the design parameters when used with the chosen material model, [6].

A thorough evaluation of different calculation tools and their suitability in design was carried out prior to and during design. Three independent calculation methods were used:

- Upper Bound Theory
- Limit Equilibrium Analysis
- Finite Element Analysis

3.1 Storebælt anchor blocks

As part of the East Bridge Project all three methods were subjected to benchmark calculations. The governing load case for the anchor blocks was mainly due to the permanent load in suspension cable, see Fig. 5. One of the benchmark problems was the Anchor Block Case with a geometry and soil parameters close to those of the real anchor block.

The distance between and shape of the two foundation pads implied that their failure modes did not interfere. Hence the bearing capacity could for both the Upper Bound Theory and the Limit Equilibrium Method be determined by combination of two solutions to the basic failure modes shown in Fig. 3. A elasto-plastic 2D finite element analysis of the anchor block confirmed the assumptions of the two theoretical solution. It gave almost the same bearing capacity and the plastic zones in the non-linear model coincided with the theoretical failure lines, [10].

From the benchmark tests it was concluded that all three methods could be applied to problems of combined sliding and vertical load. That is, of course, provided that the model parameters are carefully calibrated.

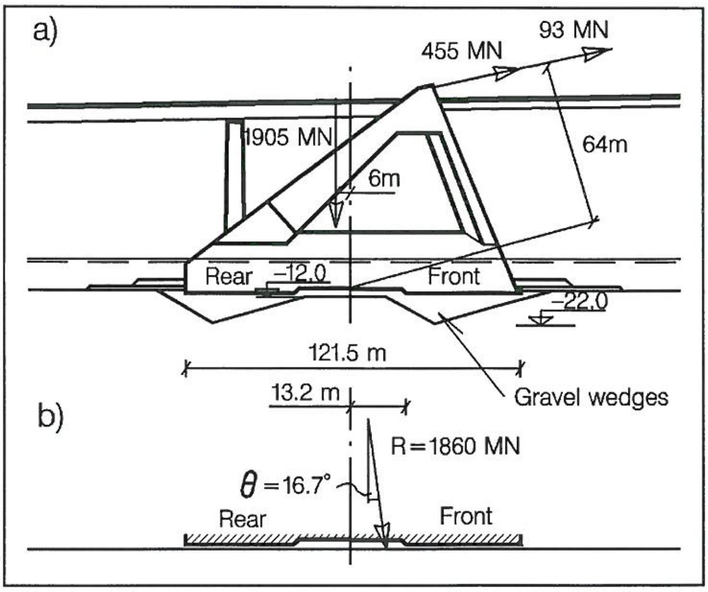

Fig. 5: Principle section and loading of the anchor block.

3.2 Ship collision at Øresund

Ship collision is the governing load case for the design of most of the piers, see Fig. 6. Due to the large horizontal load, the effective width of the footings will be only 3-4 m even with high mobilisation of the passive resistance on the sides of the caissons.

The three above-mentioned calculation methods were used for Øresund in spite of the conclusions drawn from the Storebælt investigations: *".....as long as the bearing capacity is governed by the clay till, the differences between the selected analysis methods will be small. ... For cases where the strength of the frictional material dominates the bearing capacity, care will be needed when deciding upon the analysis method to be used"*, Sørensen et al., [10]. This warning caused fundamental calculations as the bearing capacity for the footings was primarily dictated by the limestone's frictional strength parameters. The assessment of the bearing capacity therefore implied a reassessment of the applicability of the three methods in a case with friction material and strongly eccentric loading.

The Upper Bound Theory was used to calculate the bearing capacity of the rupture mechanism for the foundations. Further, the theory was used to evaluate whether it was the peak or the residual strength parameter that should be used to calculate the peak bearing capacity of the footing. It was concluded, [5], that the peak strength should be used and that the friction angles should be corrected for the influence of dilatancy not satisfying the associated flow role.

Also the Limit Equilibrium Analysis was used with the same purpose. Two limit equilibrium computer programs were used. The first program, BEAST, is based upon the method of slices, The second program, WEDGE3, was developed as a part of the studies carried out. The results for both programs were comparable with the other methods. See also [3].

Finite element analyses using ABAQUS were performed to verify the capacity against accidental ship impact. The foundations should, according to the design basis for accidental ship impact, not only be able to withstand the maximum ship collision force, but furthermore, the maximum permanent displacement was not to exceed a given limit value. FE analysis was a means to assess both requirements in a consistent way. The FE models comprised 2D plane strain elements with a material behaviour, that was calibrated to match several large scale plate tests carried out at Lernacken, [2]. The calibration and application of the model to ship impact is described in a fellow-paper, [6].

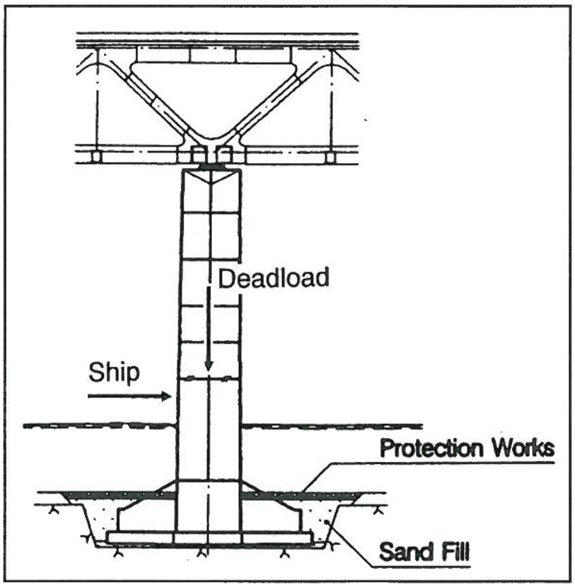

Fig. 6: Principle section in the pier foundation

The finite element calculations confirmed the results from the Upper Bound Theory and the Limit Equilibrium Analysis. Furthermore, the use of FEM made it possible to calculate the expected permanent displacements resulting from a ship collision.

4 CONCLUSIONS

Some of the most important considerations regarding the geotechnical design for the Storebælt East Bridge and the Øresund Bridge have been presented. The two projects clearly demonstrated two important issues in modern bridge design:

- Careful design of the geotechnical investigations, test pits and laboratory tests is necessary in order to calibrate the design models for critical elements in modern bridge design. The tests are important in order to minimise the costs while preserving the proper conservatism of a highly critical infrastructure component, such as a bridge.
- The application of several independent tools in the assessment of the bearing capacities of anchor blocks and ship impact loaded piers has proven successful and necessary. The increasing focus on a combined design criterion consisting of both strength and displacement requirements makes the use of numerical methods such as finite element analysis an essential part of the designer's documentation. First of all the FE model can give estimates on bearing capacity and the associated deformations. Secondly, FE analysis may be used to assess the applicability of the simpler models, which are more suitable for design.

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