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Autor: Feld, Tøve / Juel Petersen, S.
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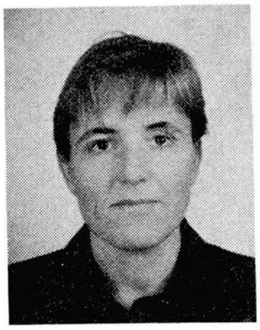
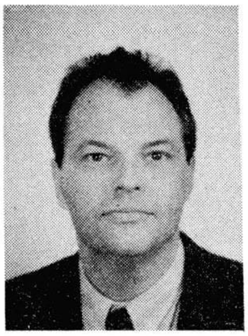
Establishment of Foundation Design Parameters for Limestone

Tove Feld
Project Engineer
L&T-RAMBOLL Consulting
Engineering Ltd. Denmark



Ms. Feld, born 1964, graduated from University of Florida with a Master in Geotechnical Engineering. Since 1991, she has been involved with marine structures and has a profound knowledge of dynamic soil-structure interaction. She has specialized in soil mechanics and foundation engineering with special emphasis on finite element analysis.

S. Juel Petersen
Head of Department
L&T-RAMBOLL Consulting
Engineering Ltd. Denmark



Mr. Petersen, born 1958, graduated from the Danish Technical University in Copenhagen with a Bachelor in Geotechnical Engineering in 1982. Following research at the Technical University and a research-fellowship at the Norwegian Geotechnical Institute, Mr. Petersen joined the private industry in 1985 for participation in, a. o., major bridge projects.

SUMMARY

For the establishment of the design parameters for the foundation design for the stay bridge and the immersed concrete tunnel for the 15 km long Øresund Link Project between Sweden and Denmark, a geological model was first established. The geological model included the method of deposition of the Copenhagen Limestone, and was developed assisted by seismic profiling, boreholes, geophysical borehole logging and visits to quarries.

Based on the understanding of the geological and the depositional models and the assumed behavior of the foundations, series of large scale plate bearing tests and laboratory tests on 0.5 m samples were performed. Further, thin sections of the undisturbed limestone and limestone samples from the plate bearing tests were microscopically investigated after impregnation with fluorescent epoxy.

The test results from the active, passive and shear failure tests showed anisotropic strength conditions for the limestone.

The investigations resulted in a physical understanding of the failure mechanisms and a possible way of deriving the design parameters considering the anisotropic behavior of the Copenhagen Limestone, and distinguishing between active, shear and passive failure conditions.

Establishment of Foundation Design Parameters for Limestone

Tove Feld and S. Juel Petersen

L&T - RAMBOLL Consulting Engineering Ltd. Denmark

Ulf Bergdahl

Swedish Geotechnical Institute. Sweden

1 THE ØRESUND LINK PROJECT

The design and construction of the fixed link across the Øresund between Denmark and Sweden was initiated in 1993. A Joint venture between RAMBØLL, Scandiaconsult, Tunnel Engineering Consultants and Sir William Halcrow named the Øresund Link Consultants were nominated house consultant for the client, Øresundskonsortiet, a joint Danish-Swedish company.

The fixed link 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 7845 m. The combined road and rail link is scheduled to open for traffic in the year 2000.

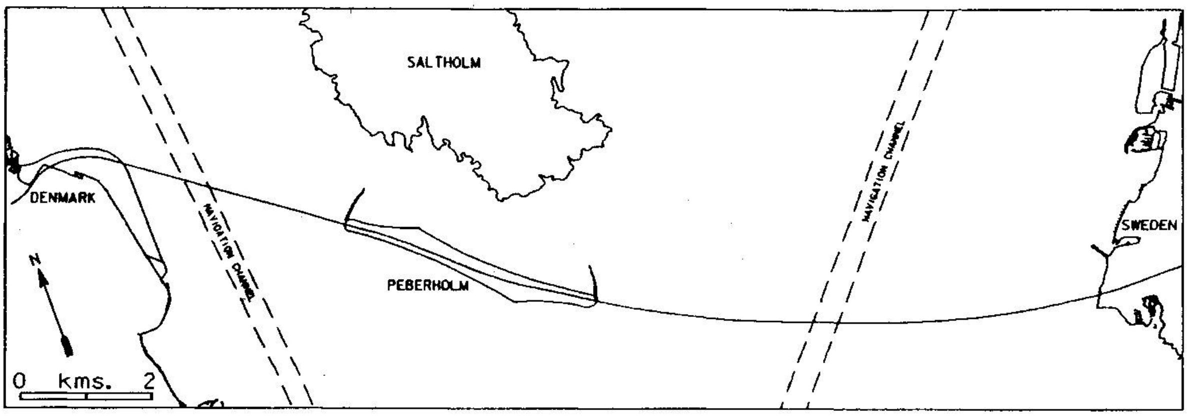


Fig.1 Alignment for the Øresund Link between Denmark and Sweden

2 METHODOLOGY FOR ESTABLISHMENT OF GEOLOGY AND PARAMETERS

Based upon existing knowledge about the geology and the stratigraphy of the Link Area, an Existing Model, ref. Fig.2, for the geology was established. Via this Existing Model additional geological and stratigraphical investigations were planned and executed. These investigations constituted reflection seismic and refraction seismic surveys and borehole logging for assessment of the stratigraphy, performance of core drillings for collection of samples for geological and rock mechanical description and performance of coccolith analysis, and performance of test pits inland on the Danish side, in the Sound and inland on the Swedish side, and investigations of a limestone quarry on the Swedish side. The test pits were performed to extrapolate the detailed investigations in the Sound. These investigations resulted in an Updated Model, ref. Fig.2, for the geology and the stratigraphy. To further assess the rock mechanical parameters and the foundation design parameters for the Copenhagen Limestone large size plate load tests, 0.5 m size laboratory tests and thin sections analysis of the limestone were performed. This finally led to the Updated Model and the Design Parameters for the Copenhagen Limestone. The process and the various activities within the process is presented schematically in Fig. 2., and described in further details below.

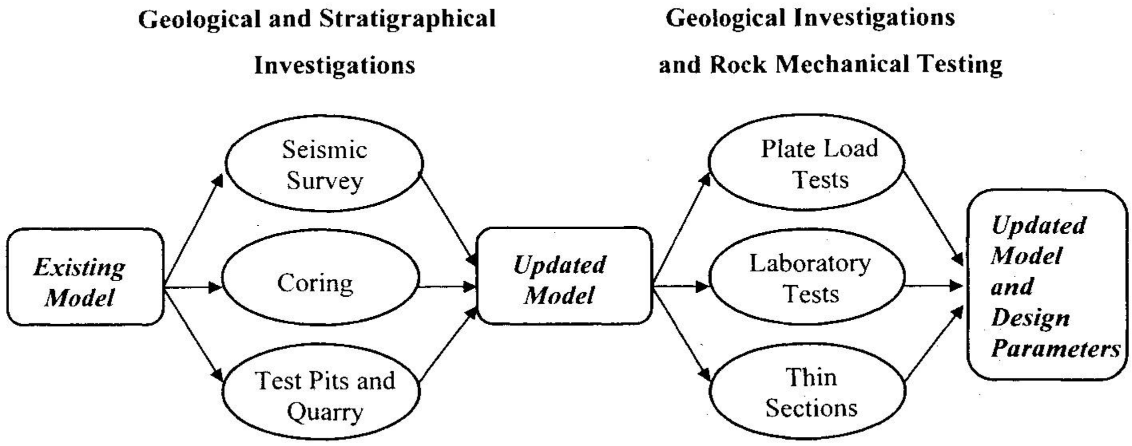


Fig. 2 Methodology for Establishment of Geology and Parameters

3 UPDATED MODEL

3.1 Seismic Survey

In 1993 high resolution seismic surveys were performed in the Link area. The interpretation of the surveys led to mapping of three seismic units separated by two boundaries. The units were interpreted to represent Quaternary glacial deposits, prequaternary, Danian Copenhagen Limestone and Bryozoan limestone. The interpretation changed the structural model in the area from dominantly faulted to dominantly folded, and contributed hereby significantly to a consistent geological model for the Link area.

3.2 Coring

The boring campaign for the Øresund Link comprises an extensive number of borings (core drilling, vibrocores etc.) performed prior to the first tenders for major contracts, forming part of the background information for the geotechnical basis.

Geophysical borehole logging was implemented to the engineering geological and hydrogeological investigations of the Danian limestone. Since the commencement of the offshore investigations in 1992, a large number of geophysical logging types were applied to the exploration of the boreholes. The logging methods respond to the variation in conditions and parameters of the limestone, such as: sediment composition, bulk density, porosity, permeability, seismic velocity and salinity. Based on the characteristic frequency of the strongly indurated high density beds, the observations made it possible to create a stratigraphical sequence for the Copenhagen Limestone [2].

3.3 Test Pits and Quarry

Test pits were performed inland on either sides of the Sound and in the west part of the Sound. The test pit on the Swedish side was located at the site for the performance of the large scale plate bear-ing tests. The test pits enabled a thorough geological, stratigraphical and rock mechanical descrip-tion of the limestone, which, in conjunction with the 60 m deep pit for the quarry at Limhamn in Sweden, gave the opportunity of a correlation across the Sound, of the encountered limestone strata. Later this correlation was extended and refined by the results from the offshore core drill-ings and the geophysical investigations.

4 UPDATED MODEL AND DESIGN PARAMETERS

4.1 Plate Load Test

As part of the site investigations an extensive series of plate load tests were performed at Lernacken close to the landing area on the Swedish side of the Sound. A total of 17 plate load tests were conducted with plate sizes varying from 1.0 to 3.0 m^2. The tests were performed in three different ways, namely as vertical active tests, horizontal passive tests and horizontal shear tests.

The tests, including both static, dynamic and cyclic loading giving both drained and undrained behavior and strength-deformation relations, are described in detail in [2] and [4]. The principle of the different bearing capacity tests are illustrated in Fig. 3.

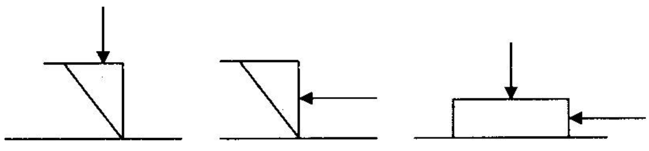


Fig. 3 Definition of active, passive and sliding cases

The different load situations were covered by different test types and different ways of applying the load, elucidating the influence of the anistropic behavior of the horizontally layered limestone, the effect of fissures and other anomalies in the limestone, the effect of cyclic loading and unloading, the effect of strain and strain rate, the effect of unloading and the degradation of the limestone. The tests were performed on slightly indurated and harder limestone

4.2 Laboratory Test

To study the behavior of the limestone at variable stress conditions and to supplement the plate load tests a series of triaxial tests on 0.5 m diameter and 0.5 m high samples were performed as well as direct simple shear tests on 0.5 m diameter samples, ref.[4]. The triaxial testing program included both active and passive shear tests performed on anisotropically consolidated samples. The shearing was performed under both drained and undrained conditions, and both with - and without an initial cyclic loading phase. The direct simple shear testing program included both undrained and drained shearing tests and dynamic failure tests. As it was assumed that the slightly indurated limestone would have a major impact on the bearing capacity of the limestone, all tests were performed on this type of material. The results from the plate load tests and the laboratory tests showed, in spite of the influence from the differences in induration of the limestone, that the strength parameters obtained in the laboratory tests are lower than the parameters obtained in the plate load tests. It was, however, assessed that the parameters from the laboratory tests would be representative for the limestone.

4.3 Thin Sections

To study the physics of the limestone at failure, both undisturbed reference samples and samples of material subjected to shearing at the plate bearing tests were extracted, ref [3] and [5]. Both the reference samples and the sheared samples were impregnated under vacuum by epoxy, to stabilize the samples and to enable a microscopic study of thin sections under UV-light. In the microscopic study the following subjects were analyzed: changes of the porosity, fissures and patterns of fissures, fissuring and movements of

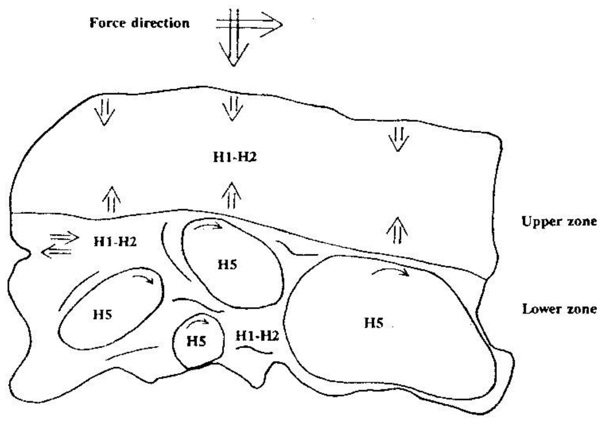


Fig. 4 Principal Sketch of Limestone Sample.

shells and more indurated limestone parts, ductile flow and the directions of deformations of the material within the samples, as depicted in Fig. 4. In the analysis comparisons were made, both between the reference samples and the sheared samples, and within each individual sheared sample. This study provided the information that for slightly indurated limestone without any content of hard nodules, the limestone will experience a reduction of the porosity leading to a stronger material which eventually will endure a higher failure load than limestone with some content of hard nodules. The explanation is that the nodules will prevent the compaction of the limestone during shearing, leading to unchanged strength parameters for the slightly indurated material, and to movement of the nodules which will further cause fissures to open and to destabilize the material. This leads to a comparatively lesser bearing capacity of the material with the content of nodules

5 DETAILED GEOLOGY AND FAILURE MECHANISMS

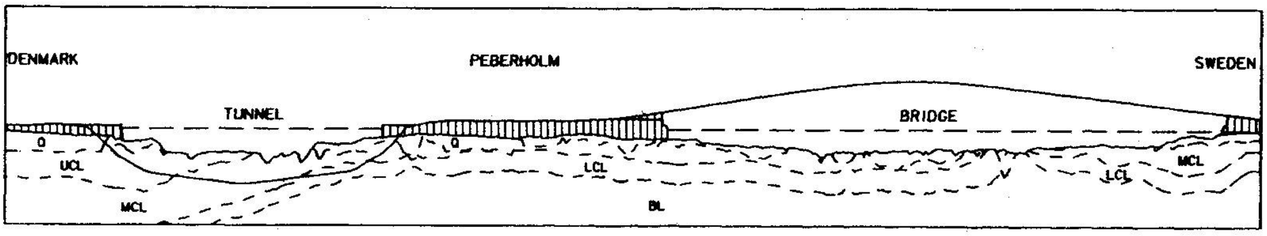
5.1 Stratigraphy

In the Øresund area, the Danian limestone series consist of an upper unit of Copenhagen Limestone up to 40 m thick, overlying Bryozoan limestone.

The Copenhagen Limestone can be subdivided into three stratigraphical subunits, named Upper, Middle and Lower Copenhagen Limestone, the variation and location of the subunits are shown in Fig. 5.

The subunits were identified and mapped through stratigraphical studies based on the geological description of core samples and samples from test pits, supplemented by geophysical logs and reflection seismic [2].

The degrees of induration varies from unlithified to very strongly indurated, due to varying degree of calcite cementation and silicification. The strongly indurated limestone typically occurs as 0.2-0.4 m thick layers intersected by less indurated rock, however benches up to 1.5 m have been found, as have flint layers typically of a 0.5 m thickness. At some locations, the upper part of the limestone series, has been disturbed by glacial processes.



Q = Quaternary/UCL = Upper Copenhagen Limestone/MCL= Middle Copenhagen Limestone/LCL=Lower Copenhagen Limestone/BL=Bryozoan

Fig. 5 Longitudial Profile of the Geological Section of the Øresund Link Alignment.

5.2 Anisotropic Behavior

The Copenhagen Limestone has a cemented structure, but is at the same time anisotropic due to layering and fissuring. The behavior of the limestone can be compared to "an old brick wall". Vertically the brick wall has a high bearing capacity, but against horizontal loading or sliding, the mortar will be the weak element. Correspondingly the unlithified and weaker layer in the Copenhagen Limestone is the fragile area. High stresses or large strains will lead to degradation of the material and the limestone will change into a silty cohesionless material.

The test results from the active, passive and shear failure tests confirmed the anisotropic strength conditions for the limestone and the structures. In any major occurrence of unlithified limestone, excess pore pressures may develop during shearing as a consequence of contractancy.

5.3 Failure Mode

The investigations resulted in a physical understanding of the failure mechanisms and a possible way of deriving the design parameters considering the anisotropic behavior of the Copenhagen Limestone, by distinguishing between active, shear and passive failure conditions.

From the insitu plate load tests performed at Lernacken [4] it became evident that the failure mechanism of the limestone could be divided into active, shear and passive failure conditions, as illustrated in Fig. 3.

In Fig. 6 the principal failure conditions in the mechanism are depicted. This failure surface has previously been introduced [1].

The shear strength at any part of the failure surface can be given by : $\tau_F' = c' + \sigma' \cdot \tan\phi'$.

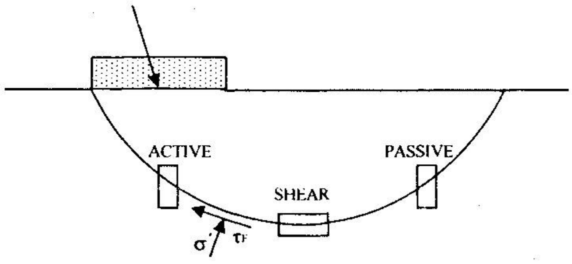


Fig. 6 Principal Failure Conditions

6 CONCLUSION

In conclusion, the applied methodology, by firstly establishing a geological model, secondly obtaining a physical understanding of the behavior and failure mechanisms of the limestone, and finally assessing the strength and deformation parameters through an interpretation of the performed tests based on this physical understanding has succeeded. The use of the methodology has led to design parameters which, to a far extent, represents the true nature of the Copenhagen Limestone.

7 ACKNOWLEDGEMENT

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