Application of geophysical techniques for major bridge projects in Denmark

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Henrik Olsen, born 1957, got his M.Sc. and Ph.d. in geology at the University of Copenhagen in 1984 and and 1987, respectively. For ten years he was involved in geological and geophysical research and university teaching. Since 1994 Henrik Olsen has been employed at RAMBØLL in Denmark where he has been involved in several major construction projects.

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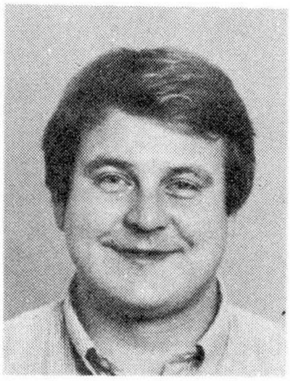

Carsten Ploug, born 1957, got his M.Sc. and Ph.d. in applied geophysics at the Technical University of Denmark in 1983 and 1991, respectively. He has been involved in reflection seismic research for a number of years. Since 1992 Carsten Ploug has been employed at RAMBØLL in Denmark where he has been involved in several major construction projects. Dr. Ploug is head of Geophysical Department.

SUMMARY
Geophysical techniques have been an integratal part of the soil investigation programs for all major bridge construction projects in Denmark during the last two decades. The projects include the 18 km Storebælt Link in central Denmark, the ongoing 15 km Øresund Link between Denmark and Sweden and the planned 17 km Fehmarn Bælt Link between Denmark and Germany. The present paper describes the increasing implementation of geophysical techniques in the feasibility studies and lessons learned in the major projects.

1 INTRODUCTION

Geophysical techniques have been integrated in the feasibility studies for all major bridge construction projects in Denmark during the last two decades, including the Storebælt Link in central Denmark, the Øresund Link between Denmark and Sweden and the planned Fehmarn Bælt Link between Denmark and Germany (Fig. 1).

A range of geophysical metods have been applied to these studies and the experiences from the early projects have been used to further develop the soil investigation programs towards a multiple technique appoach.

The advantage of integrated geophysical investigations is outlined as well as the interpretation approaches applied to the different projects.

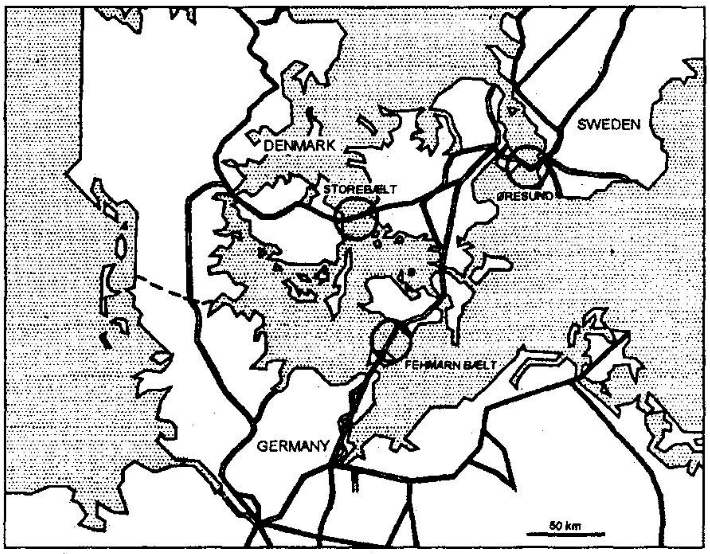

Fig. 1. The locations of the three major infrastructure projects in Denmark: the Storebælt Link, the Øresund Link and the Fehmarn Bælt Link.

2 THE STOREBÆLT LINK

2.1 General

The 18 km fixed link across the Storebælt sound in central Denmark is composed of three main components: 1) The West bridge, a 6.6 km low bridge for rail and road; 2) The East Bridge, a 6.8 km suspension bridge for road; and 3) The East tunnel, a 7.4 km bored tunnel for rail. The construction was completed in June 1998.The geological succession is generally (from the top): Quaternary Post/Late-glacial fines, Quaternary glacial till, Tertiary marl and Tertiary limestone.

2.2 Geophysical investigations

The geophysical methods applied in the feasibility studies were mainly restricted to analoque reflection seismic techniques. A total of more than 3,000 km seismic profiling was carried out by the Danish Geotechnical Institute /1/. At a very early stage, in 1962, reflection seismic investigations were carried out in the entire suggested alignment corridor. The method applied was single channel boomer seismic. In 19977-78 renewed boomer seismic investigations were carried out in the entire corridor with improved technology.

The boomer seismic data from the 60'es and 70'es formed the geophysiscal basis for the realization of the bridge projects commencing in 1986. In the tunnel alignment, however, additional single channel sparker seismic data were acquired in 1987 to obtain information of deeper geological features. The investigations were carried out simultaneously with or subsequent to geotechnical drilling operations.

2.3 The role of geophysics

The reflection seismic data formed a very important input for the 3D geological/geotechnical data base - Geomodel Storebælt /2/ - established especially for the Storebælt project. The early phase in which the seismic data were acquired made it possible to optimize the geotechnical drilling programme for the bridge projects.

In contrast, optimum benefit from the seismic data was not obtained in the tunnel project because the seismic data were not available prior to the drilling operations. Accordingly, the seismic data were not used for identifying possible problem areas for subsequent direct sampling but as means of interpolating the major lithological boundaries between borehole data points /3/. The resulting understanding of the geology was, however, governing for the tunnel alignment and profile.

3 THE ØRESUND LINK

3.1 General

The 15 km fixed link across the Øresund sound between Sweden and Denmark (Fig. 1) is currently under construction. The construc tion will consist of a 3.8 km immersed tunnel in the west, a 7 km suspension bridge in the east and a 4 km low bridge across an artificial island in the central part ofvthe sound. The construction works for the Øresund Link commenced in 1995 and the fixed link iis expected to be completed in the year 2000. The general geological conditions in the Øresund alignment corridor is a Quaternary glacial till succession on top of a Tertiary limestone succession.

3.2 Geophysical investigations

The feasibility studies for the Øresund Link included reflection seismic studies, refraction seismic studies, vertical seismic profiling and wireline/borehole logging.

3.2.1 Reflection seismic

Reflection seismic investigations were carried out in 1993-1995 in the entire alignment corridor and in selected areas of special interest. The investigations were performed by DGI and comprised single channel boomer as well as six channel water gun seismics /4/. In contrast to the Storebælt investigations, the acquisition in Øresund were digital, providing basis for postprocessing. The seismic data were interpreted mainly in order to provide a structural geological model for the limestone succession.

3.2.2 Refraction seismic

Refraction seismic investigations were carried out by Geomap in 1992-93 along the western part of the alignment /5/. The seismic data were interpreted in order to provide information about the velocities of the geological layers and to define possible glacially disturbed limestone successions in the upper part of the limestone.

3.2.3 Vertical seismic profiling (VSP)

VSP investigations were carried out by RAMBØLL in 1993-1994 along the entire alignment /6/. VSP was carried out in boreholes by use of a hydrophone streamer with 12 hydrophones. Vertical data point spacing was 0.5 m. The seismic data were interpreted in order to define the seismic velocities of the geological units.

3.2.4 Borehole logging

Borehole logging was carried out in 1992-1994 by RAMBØLL in boreholes along the entire alignment and in boreholes situated in areas of special interest. The borehole logging programme included a large suite of advanced logging techniques, including: natural gamma, induction conductivity, guard resistivity, neutron porosity, gamma density, sonic, fluid conductivity and fluid flow. The logs were interpreted in order to establish a detailed log stratigraphy and to provide information of physical properties and ground water flow characteristics of the limestone /6, 7/.

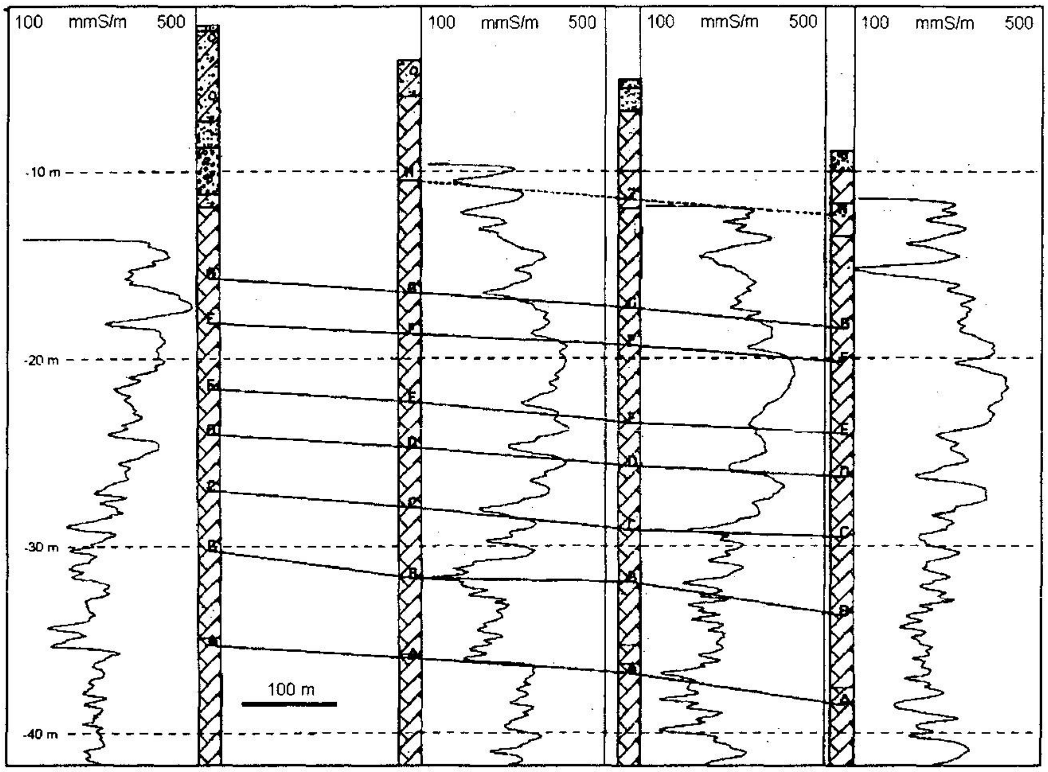

Fig. 2. Stratigraphic correlation of the limestone in four boreholes in the western part of Øresund using the information from induction conductivity logs. Modified from /7/.

3.3 The role of geophysics

The combination of a multiplum of geophysical investigation techniques proved very useful for the Øresund Link project. Although the importance of the different methods was variable the suite of methods provided complementary information, impossible to attain by means of only a single method.

3.3.1 Reflection seismic

Prior to the seismic investigations depth variations in marker horizons in the limestone were ascribed to faulting. The seismic data revealed, however, that these depth variations could be explained by folding.

The boomer data proved very useful. The water gun data were expected to provide data from significantly gtreater depths than the boomer data. The water gun data did not, however, provide significant improvement because only limited attenuation of the seabed multiple was possible /4/. The reason for this is believed to be inadequate move-out correction, mainly due to the limited number of hydrophone groups and limited length of hydrophone spread.

The collection of digital data also proved a success. In the construction phase reprocessing of the data could be performed providing additional details of great use for the project.

3.3.2 Refraction seismic

The refraction seismic data were used for defining the extent of glacially disturbed limestone. The results were not, however, equivocal. For definition of deeper geological successions the method was inadequate, because an internal low velocity layer prohibited precise information for deeper lying successions.

3.3.3 Vertical seismic profiling

The VSP data were very useful. The limestone succession was subdivided in successions with characteristic seismic velocities, indicating geotechnical bulk characteristics. The VSP data were also useful for depth conversion of the reflection seismic data so that correlation with borehole data was possible.

3.3.4 Borehole logging
A detailed metre scale stratigraphic subdivision of the limestone succession was defined on the basis of the borehole logs (Fig. 2). The log stratigraphy proved very useful in veryfying the structural geological model.

The logs also provided important information concerning the ground water flow characteristics. Distinct inflow horizons were observed in certain stratigraphic successions indicating that fractures act as hydraulic corridors.

Physical properties of the limestone rocks were accounted for on a decimetre scale, providing important information for the prediction of geotechnical properties. As a consequence, it was decided to use borehole logs also during the construction phase for detailed site investigations for all bridge piers.

4 THE FEHMARN BÆLT LINK

4.1 General
Feasibility studies are currently being carried out for the planned 17 km Fehmarn Bælt Link between Fehmarn in Germany and and Lolland in Denmark (Fig. 1). At present the link has not been politically decided. The general geological succession in the Fehmarn Bælt include (from the top): Quaternary Late/Postglacial fines, Quaternary glacial till, Tertiary clay and Cretaceous limestone.

4.2 Geophysical investigations
In 1995 geophysical investigations were carried out as part of a geological/geotechnical feasibility study /8/. The investigations included shallow reflection seismic surveys applying pinger and sparker, and deep reflection seismic applying air gun and a 24 channel hydrophone array. VSP was obtained from the boreholes drilled during the feasibility study. A suite of borehole logs comparable to the Øresund Link investigations was also applied. The shallow reflection seismic investigations were carried out by DGI whereas RAMBØLL performed all other geophysical investigations.

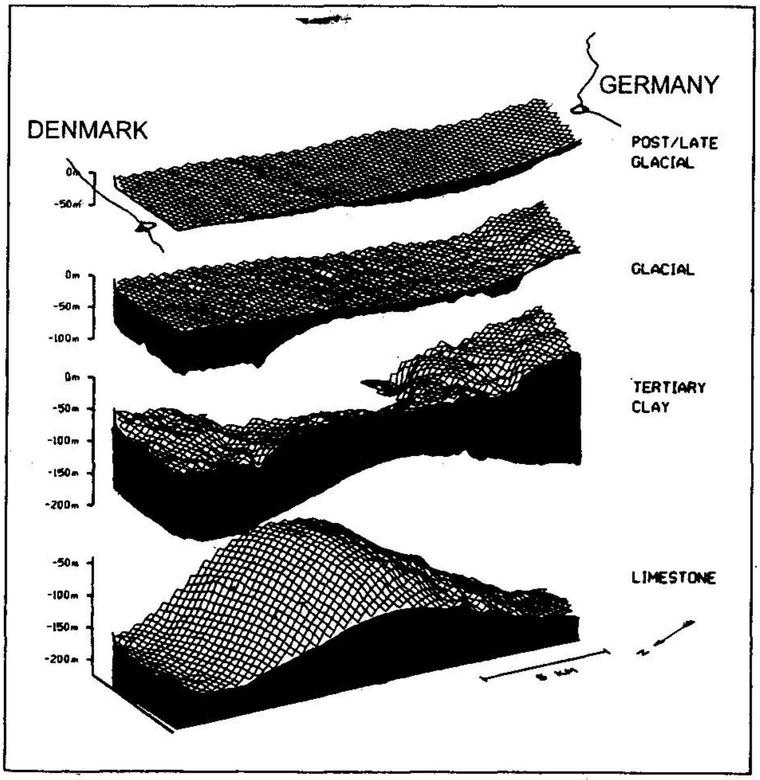

Fig. 3. Geological model from Fehmarn Bælt based on reflection seismic data. High resolution was obtained in the Quaternary Post/Late-glacial and glacial deposits by single channel shallow reflection seismic methods. The deeper lying Tertiary clay and Cretaceous limestone units were excellently outlined by the multichannel seismic method. Modified from /8/.

4.3 The role of geophysics

The shallow reflection seismic provided detailed information of the geological strata in the upper tens of metres. The experiences from the Øresund investigations were used to design a multichannel seismic setup capable of suppressing the multiple reflection and enhancing the geological stratification in deeper levels. Accordingly, the multichannel seismic data made it possible to improve the structural geological model significantly. Significantly the deeper seismic data showed the existance of a domal shaped limestone surface, interpreted to be a result of salt upheaval in deeper levels. In addition the presence of structural deformations could be outlined on the basis of the deeper seismic data. The VSP was primarily used for depth conversion of the reflection seismic data. The borehole logging formed an important supplement to the drill core data and an initial basis for log stratigraphic subdivision.

5 LESSONS LEARNED

The lessons learned during the three major construction projects can be summarized as follows:

1) *The right method at the right time.*
Geophysical investigations shall be performed at an early stage to form a guidance for drilling operations so that the drilling sites and numbers can be optimized. Moreover, careful evaluation of the techniques shall be made as to the effectiveness of the technique for the particular geological conditions. Courage and visions of the owners resulted in introduction of new methods hitherto not used for this kind of projects.
2) *Using the experiences from previous projects*
By evaluating the experiences from previous bridge construction projects it was possible to enhance the profits of the geophysical techniques.
3) *The advantage of integral geophysical investigations*
By combining different geophysical methods it has been possible to obtain complementary data which greatly enhance the value of the individual techniques.

6 ACKNOWLEDGEMENTS

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