CHAPTER 229

THE GREAT BELT LINK HOW TO ACHIEVE ZERO ENVIRONMENTAL IMPACT ON THE BALTIC SEA

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Abstract

The Great Belt Link crosses the Great Belt (Denmark) which is the major strait connecting the Baltic Sea with the North Sea. A law passed by the Danish Parliament imposes an environmental design criteria of 'zero far field effect' on the Link. This paper describes how the challenge of zero effect is met by compensation dredging. The compensation dredging is designed by the use of highly sophisticated numerical models.

Introduction

The Great Belt is a channel approximately 18 km wide that divides Denmark into Jutland and Funen to the west and Zealand to the east. It is the largest of the three channels linking the Baltic to the Kattegat and North Sea (Figure 1). A major construction project (The Great Belt Link) is now underway to build a rail and road link across the strait and thus replace the busy cross-Belt ferry routes. The strategic location of the link and environmental concern about potential interference in the exchange of water between the Baltic and Kattegat have led to a comprehensive environmental plan.

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The 'Zero Blocking Solution'

In general not much attention is given to the impact of bridges or causeways on the surrounding flow. However, the peculiar hydrography of the Danish Straits

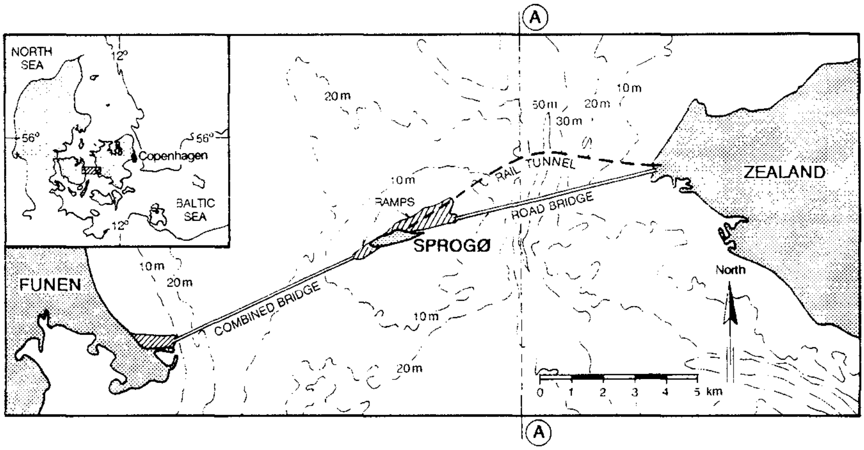

Fig. 1. The Great Belt Link

with a distinct layered flow, results in a flow with a very small hydraulic resistance. Therefore the total resistance may be sensitive to small changes in geometry. For instance, the hydraulic head difference between the Kattegat and the Baltic is normally only 0.2-0.6 m over a length of 300 km with a flow rate of 100.000 m^3/s. Further, bridges built in the Straits will have to be designed for heavy ship impact and for ice loads which make the bridge abutments large, leading to increased blocking.

Most of the hydraulic loss in the Great Belt takes place through 4-5 narrows where the current becomes strong. The fixed link across the Great Belt will span the most constricted narrow of the Great Belt. Since a large part of the salt influx to the Baltic (60-70%) passes through this narrow, concern has been expressed that the construction of causeways, tunnels and bridges may exert a large flow resistance.

It is likely that the consequent reduction in the water exchange would significantly alter the hydrography and environment of the Baltic. A review of the hydrography of the Great Belt is given by Farmer and Møller (1990). To avoid such a change it has been specified in Paragraph 5 of the Danish law for contracting the link that "The work is to be carried out ... in such a way that the water flow through the Great Belt shall remain unchanged ... for the sake of the environment of the Baltic Sea". This somewhat unprecise design criterion has been interpreted by the authors to be understood as: "- The water discharge (m^3/s) through the Belt must not be changed by the crossing.

- The salt balance (kg salt/s) for the Baltic must not be changed by the crossing."

This so called "Zero Blocking Solution" ensures that no environmental impact on the Baltic, be it hydrographical or biological, will originate in the construction of the link.

It is cheaper to build causeways than heavy duty structures like suspension bridges or immersed tunnels. Therefore there is an economical demand for letting part of the Great Belt Link consist of causeways. This contradicts environmental interest which dictates as small a blocking of the flow as possible. A suitable compromise has been reached where causeways are only built in areas of water depth less than 6 metres and the blockage of these causeways and bridge piers has been compensated for by dredging.

Several proposals for compensation dredgings have been made. In the end it turned out that it would be most favourable to place the dredging on the reef East of Sprogø Island, Figure 2. This location was chosen because of high hydraulic efficiency of dredging and because materials form the area can be used for construction of causeways etc.

Designing the Compensation Dredging

The problem arises, how to determine the size and location of the compensation dredging. This engineering design work is carried out according to the following principle.

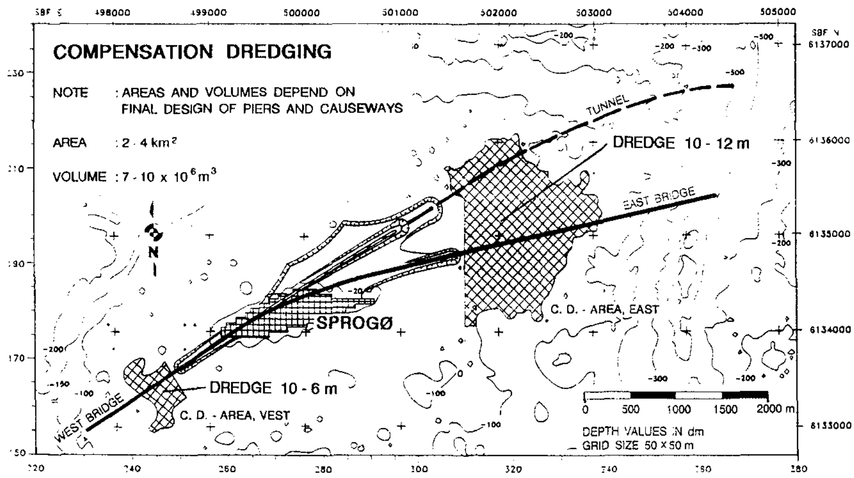

Fig. 2. Typical Compensation Dredging

Given the boundary condition for the flow through the Great Belt the surface current is calculated as it is without the Link, and as it will be with the Link. By calculating the deviation in surface water flow, we have defined a measure of deviation from the zero solution. This measure will depend on the geometry of the Link; large piers and long causeways til increase the deviation, see Figure 3.

Now for a given design of the Link we can introduce a dredging scheme and calculate the resulting deviation caused by the combined Link and dredging. If, for instance, the area to be dredged is kept constant the only parameter determining the efficiency of the dredging is the dredging elevation. By repeating the calculation of deviation for different dredging elevations the deviation is minimized, see Figure 4. The zero solution is reached for minimum deviation.

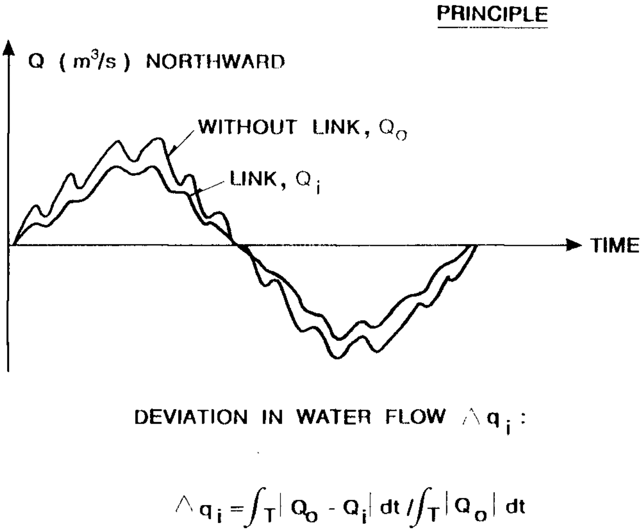

Fig. 3. Definition of Deviation in Water Flow

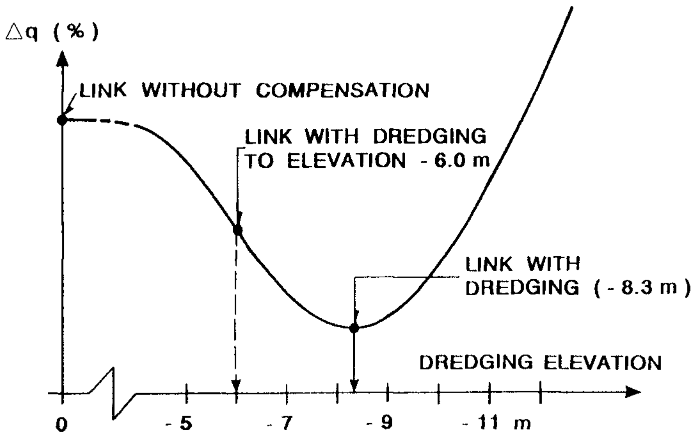

Fig. 4. Water Flow Deviation as a Function of Compensation Dredging Elevation

As demonstrated above not only the surface water flow but also the bottom water flow and the mixing must be kept unchanged by the Link. This is ensured by the use of a verified two layer numerical model.

Numerical Modelling

A comprehensive modelling and field study aimed at designing and controlling the compensation dredging has been carried out. For modelling the hydraulic effects the System 22 two layer numerical model developed by DHI is used, see e.g. Abbott (1979). The model is forced by meteorological data and measured water levels and interface levels at the model boundaries. Results are verified using field data from what is believed to be the most complete field data programme ever dedicated to numerical model verification. The verification includes the model's capability to describe the undisturbed flow field, the effect of ramps, piers and dredging all under baroclinic subcritical as well as supercritical condition. The model area is shown in Figure 5.

The system 22 is a numerical modelling system for the simulation of two-layer stratified flows in two horizontal dimensions. The system computes the surface levels, interface levels and flows in both layers. The mixing between the layers is described in terms of entrainment between the layers. Entrainment rates are determined on the basis of turbulence production for each layer. (Bo Pedersen, 1986).

The equations solved by S22 are those of conservation of mass and momentum. The equations include the effects of:

- Non linear convective and cross momentum terms
- Coriolis forces
- Wind shear stress
- Bed shear stress
- Interfacial shear stress
- Flow resistance due to bridge piers
- Interfacial mixing
- Turbulent momentum dispersion
- Horizontal density gradients.

The Link and the Compensation Dredging are included in model by corresponding changes in model topography. Bridge piers are included by subgrid scaling methods, see Figure 6.

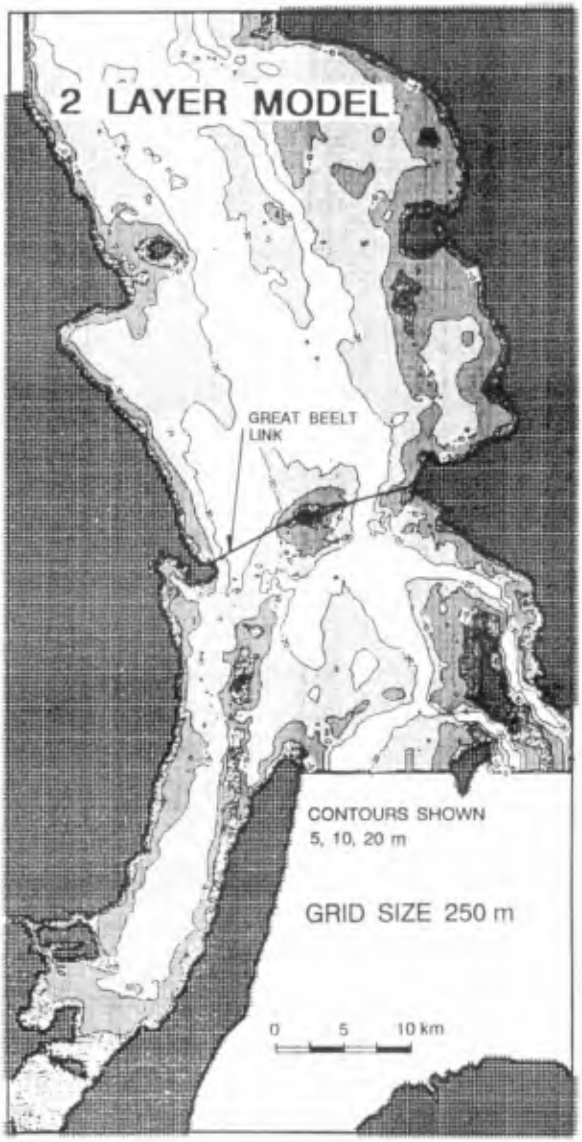

Fig. 5. Model Topography

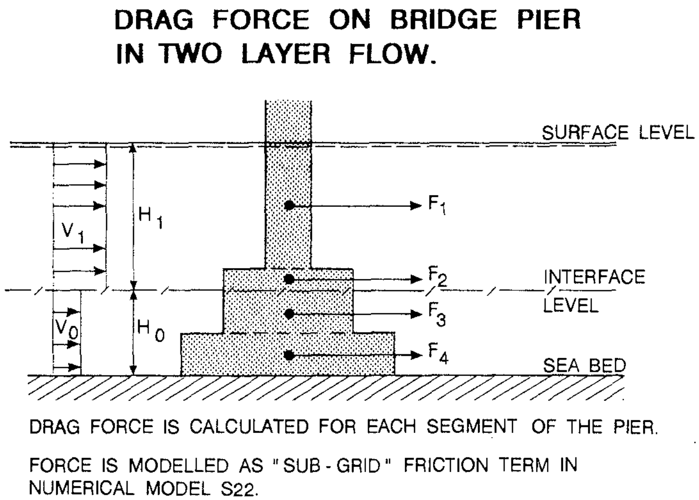

Fig. 6. Subgrid Scaling of Flow Resistance due to Bridge Piers

Model Verification

The method needs verification; will the model describe:

1. The flow in nature ?
2. The effect of the link and dredging ?

These two questions are answered by comparing the model with field observations before beginning the dredging, and after 2/3 of the dredging is completed.

In practice model boundary data and verification data are assembled by a field monitoring programme. Simulations are carried out using measured boundary data. Modelled data are compared with measured data to check the performance of the model. Moreover a feedback mechanism is employed. If the results of the model verification show that the compensation dredging needs adjustment this may be done following the '2/3 through' verification of the hydraulic effect of the dredging.

A thorough description of the verification method is given by Farmer and Møller (1990).

Preliminary results of the verification have shown good agreement between modelled and measured data. Figures 7, 8 and 9.

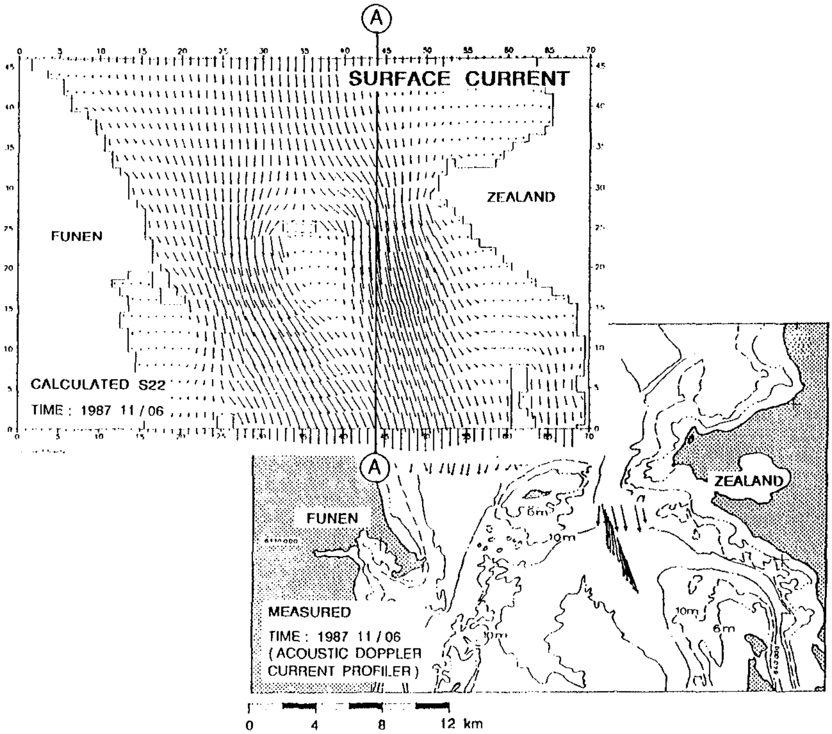

Fig. 7. Measured and Calculated Current Vectors. (Current Vectors in 500 m grid). Section A-A is shown on Figure 1. Synoptic Data from Nov. 6 1987. Measured Data from a Vessel Mounted Acoustic Doppler Profiler (ADCP) Operated by Danish Hydraulic Institute.

An interesting feature of the model is its capability to describe weak internal hydraulic jumps (hydraulically controlled flow), see Figue 8. The presence of hydraulic control has a dramatic influence on the interface position; this is seen both on Figures 8 and 9.

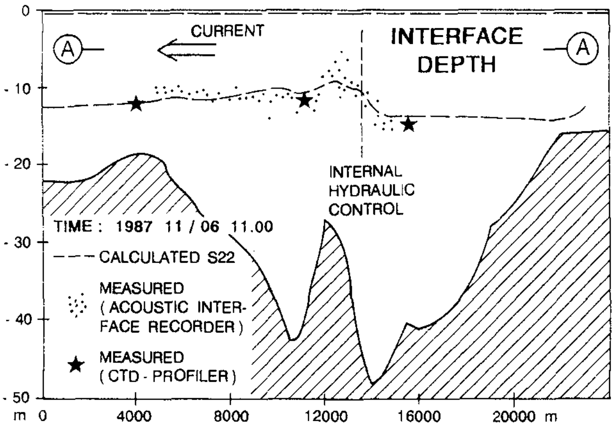

Fig. 8. Measured and Calculated Density Interface. Section A-A is shown in Figure 1. Measured Interface Based on Vessel Mounted Acoustic Interface Recorder developed by Danish Hydraulic Institute and on Conventional CTD-Instrument

Sensitivity Analysis

Based on a sensitivity analysis, where the compensation dredging design has been determined with varying model and boundary data input it is possible to evaluate the uncertainty of the zero solution dredging volume.

The uncertainty of the determined zero solution dredging volume has been found to be less than 10% of the total dredged volume. Given this uncertainty it is possible to evaluate the potential effects on the Baltic Sea due to uncertainty in the compensation dredging design.

In Farmer and Møller (1990) is described a model for the salinity and layering of the Baltic Sea. The LIC-Baltic-model developed by LIC-engineering A/S. By using the resistance of the Great Belt as input data the LIC-Baltic-model calculates the salinity and interface positions in the Baltic Sea. In Table 1 are shown the effects on the Baltic Sea due to various Link designs.

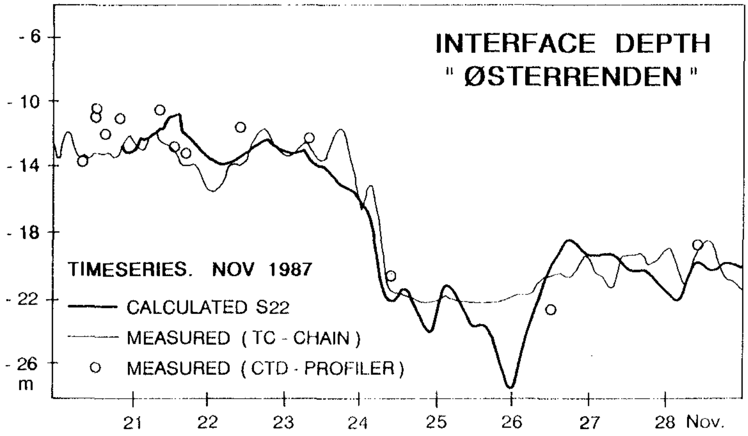

Fig. 9. Time Series of Measured and Calculated Density Interface at Measurement Station 'Østerrende' shown in Figure 8. Note the Rapid Change in Position on Nov. 24. This Change is Associated with the Occurrence of Internal Hydraulic Control of the Two Layer Flow.

It is seen that when the zero blocking solution is exactly reached then by definition no changes will occur in the Baltic.

If the maximum expected uncertainty of the dredging amount is assumed then the effect of the Link measured as change in the Baltic salinity, is reduced by a factor of 10 compared with the case of the Link without dredging. In other words: Even if the maximum error in determining the dredging is assumed then the change in the Baltic salinity will be less than 10% of the change without compensation dredging.

Case	k %	S o/oo	Y m
Undisturbed Storebælt	0.0	7.00	71.0
Link without dredging	+5.0	6.79	71.7
Link with correct dredging (by defin.)	0.0	7.00	71.0
Link with maximum overcompensation due to uncertainty	-0.5	7.02	70.9
Link with maximum undercompensation due to uncertainty	+0.5	6.98	71.1

Table 1 Calculated Change in Total Resistance, k, through the Model Area, see Figure 5. Surface Layer Mean Salinity of the Baltic, S, and Depth to Primary Interface in the Baltic, y.

Conclusions

The Great Belt Link project has initiated remarkable technical developments within hydraulics and environmental protection in association with major marine construction works.

The Great Belt Link project has introduced the concept of 'zero solution' meaning that any potential far field effect on the marine environment shall be compensated in such a way that no effects will occur. This policy is carried out in the Great Belt Link project by carefully compensating the hydraulic effect of the Link by dredging.

The dredging is designed by the use of advanced numerical models. These models are verified by comparison with field data from the Great Belt area.

Acknowledgements

The environmental studies presented here are sponsored by the Great Belt Link Ltd. Further information can be obtained from the Great Belt Link Ltd., Vester Søgade 10, DK-1601 Copenhagen V, Denmark.

References

Abbott, M.B. (1979). 'Computational Hydraulics. Elements of the Theory of Free Surface Flows'. Pitman Adv. Publish. Program. London.

Bo Pedersen, F. (1986). 'Environmental Hydraulics: Stratified Flows'. Springer Verlag.

Farmer, D. and J.S. Møller (1990). 'Measurements and Modelling in the Great Belt' in 'The Physical Oceanography of Sea Straits'. L. Pratt (ed.), NATO ARW series.