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The Great Belt Link: Zero Environmental Impact on the Baltic Sea

Impact "zéro" du Great Belt sur l'environnement de la Mer Baltique

Die Grosse-Belt-Verbindung: Umweltneutrale Verwirklichung für die Ostsee

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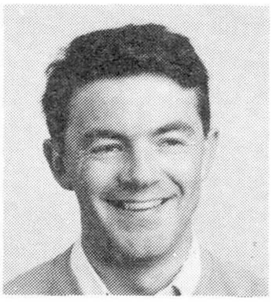

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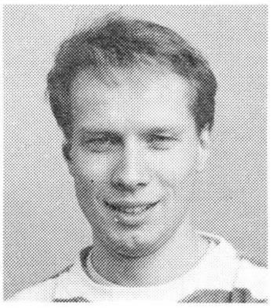

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SUMMARY

The Great Belt Link is located in the main outlet from the Baltic Sea, and the changes in the flow conditions caused by the Link may influence the environment of the Baltic Sea. This paper shows how these possible effects are avoided by the design of compensation dredging. The design work has involved comprehensive use of a numerical hydrodynamic two layer model, the model and the design method being described as well as some special problems related to the stratification of the Great Belt waters highlighted.

Impact "zéro" du Great Belt sur l'environnement de la Mer Baltique

Résumé

La liaison du Great Belt se trouve au débouché principal de la Mer Baltique. Des changements importants dans les courants causés par la liaison pourraient influencer l'environnement de la Mer Baltique. L'article montre comment de tels effets peuvent être évités par un dragage de compensation. L'étude comprend une application extensive d'un modèle hydrodynamique numérique à deux couches. Le modèle et la méthode de projet sont décrits et quelques problèmes particuliers liés à la stratification des eaux du Great Belt sont présentés.

Die Grosse-Belt-Verbindung: Umweltneutrale Verwirklichung für die Ostsee

Zusammenfassung

Die Verbindung über den Grossen Belt liegt im wichtigsten Wasserdurchlass der Ostsee. Ihre Lage verursacht Veränderungen der Strömungsbedingungen, die die Oekologie der Ostsee beeinflussen könnten. Dieser Artikel zeigt, wie diese möglichen Nebenwirkungen durch den Entwurf von Ausgleichsbaggerungen vermieden werden. Die Entwurfsarbeit bediente sich in grossem Umfang eines numerischen hydrodynamischen Zwei-Schichten-Modells. Modell und Entwurfsmethode werden zusammen mit einigen speziellen Problemen der Wasserschichtung des Grossen Belts beschrieben.

1. INTRODUCTION

The Great Belt is the main outlet from the Baltic Sea. At the site of the Link the small island of Sprogø divides the Belt into an eastern and a western channel. The Link will consist of a combined road and rail bridge across the western channel. On Sprogø the traffic is divided and the road traffic continues to Zealand on an elevated bridge, whereas the rail traffic will continue in a bored tunnel beneath the 70 m deep eastern channel.

Since the Great Belt is forming the transition between the saline North Sea and the brackish Baltic Sea, the Belt can be considered the "Gibraltar Strait" of the Baltic Sea. Because of this delicate location changes in the flow conditions of the Great Belt due to the Link will influence the hydrography and hence the aquatic environment of the Baltic Sea.

The potential effects of restricting the flow through the belt by building causeways and bridge piers have raised concern for the environment of the Baltic Sea. This concern has lead to a new and very strict approach to the environmental impact design criteria: the so-called zero effect solution or the "zero solution" which is included as §5 in the Act of Parliament concerning the Great Belt.

§5 can be translated into English as:

"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 marine environment of the Baltic Sea".

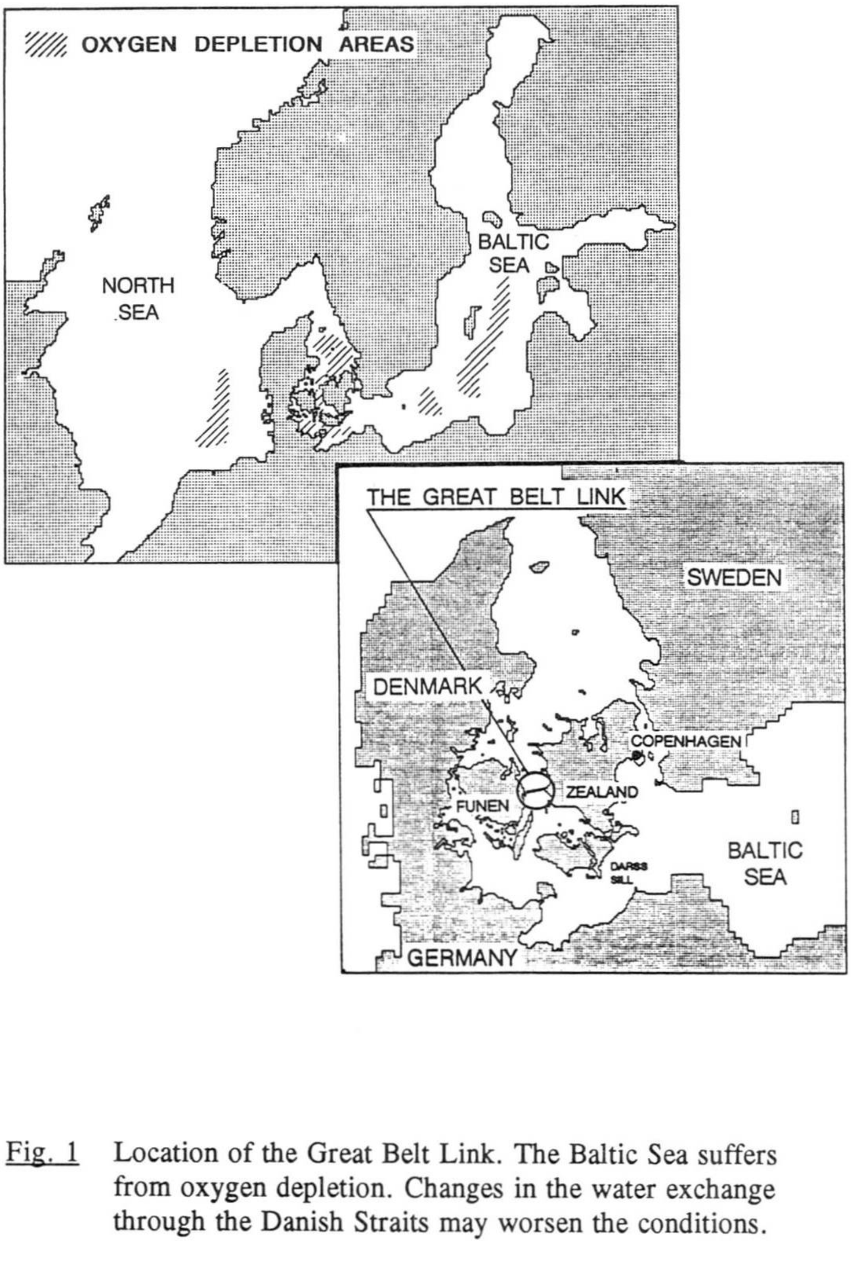

Fig. 1 Location of the Great Belt Link. The Baltic Sea suffers from oxygen depletion. Changes in the water exchange through the Danish Straits may worsen the conditions.

The legal requirement is interpreted into the following requirements to the design of the Link:

1. The water flow through the Great Belt must not be changed by the Link.
2. The salt balance for the Baltic Sea must not be changed by the Link.

The basic idea of the zero solution is to keep the hydrography of the Great Belt and hence the Baltic Sea unchanged by the Link. This is achieved by compensating the flow resistance and mixing due to the piers and causeways by dredging.

2. ZERO SOLUTION CONCEPT

During construction of the Great Belt Link efforts have been made to reduce the flow resistance of the construction elements:

- The tunnel is bored below the sea bed.
- The embankments have been shortened.
- The bridge piers have been streamlined.

The remaining blocking has to be compensated. This is done by executing compensation dredgings on mainly the East Reef of Sprogø, see Fig. 2. Approach channels on the West Reef for manoeuvring the vessel employed for construction of the West Bridge and realignment of the navigation channel (Route T) are also causing a minor compensating effect.

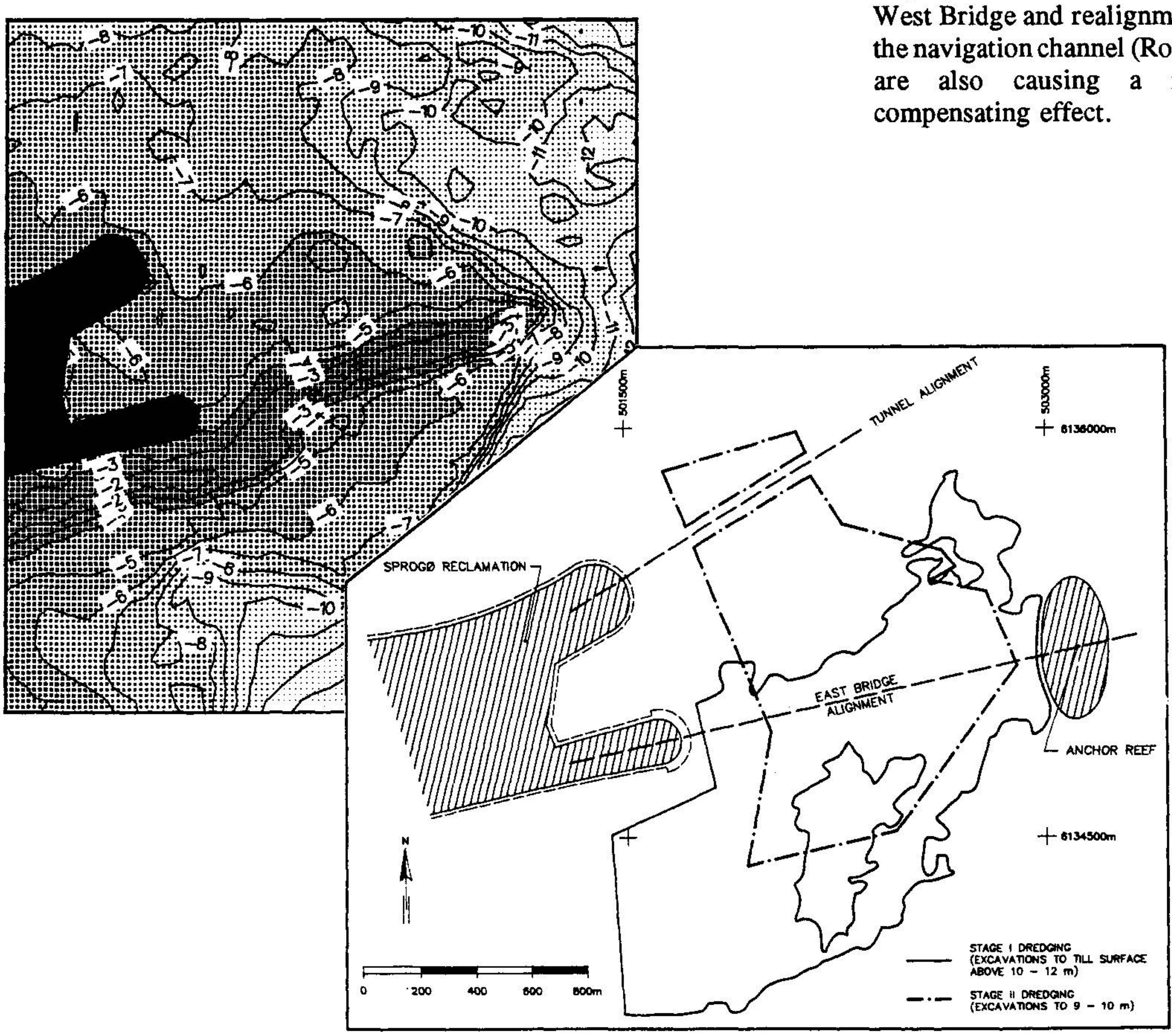

Fig. 2 A: Original bathymetry. B: Compensation dredging area. See Fig. 6 for a key plan.

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

Given the boundary condition for the flow through the Great Belt the surface current is calculated as it was 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 cause-ways will increase the deviation.

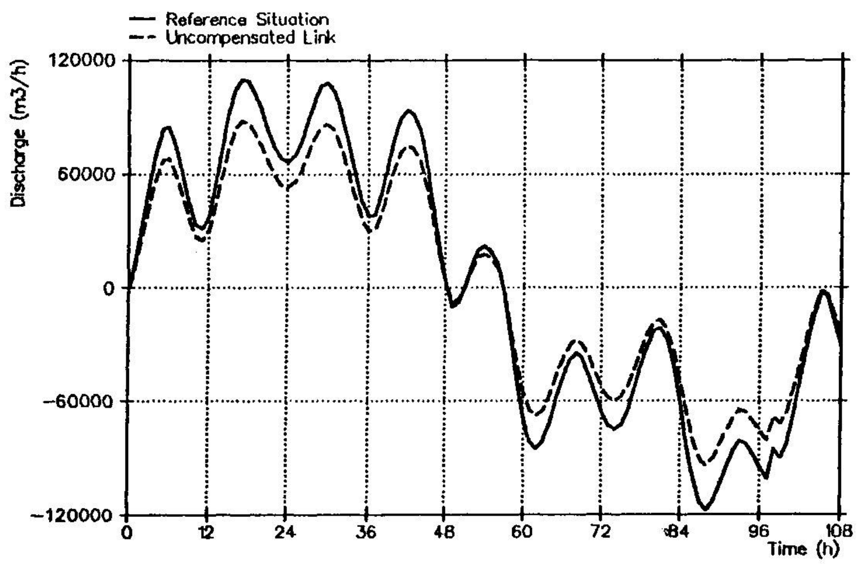

Fig. 3 Sketch showing effect of the Link on the flow. (Principle).

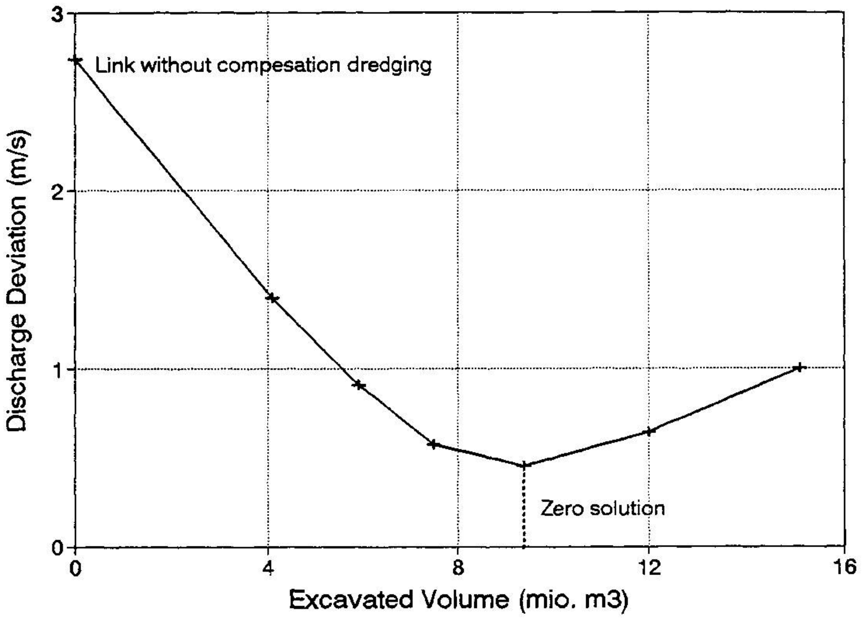

Fig. 4 Discharge deviation as function of the excavated volume. (Principle).

The flux for a combination of bridge design and compensation dredging design is compared to the reference situation, see Fig. 3. The area between the curves is representing the deviation of the flux. The deviation Δq_i is expressed by

$$\Delta q_i = \frac{\int_T |Q_i - Q_{ref}| \, dt}{\int_T |Q_{ref}| \, dt}$$

Q is the flux through the link section. Index "ref" is denoting refererence situation and "i" design i.

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. By repeating the calculation of deviation for different dredging volumes the deviation is minimized. Zero solution is reached for minimum deviation, see Fig. 4.

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

3. HYDROGRAPHY OF THE GREAT BELT

To perform reliable numerical modelling it is necessary to understand the hydrographic conditions. The water exchange through the Great Belt is governed by the following mechanisms:

1. Tidal forces.
2. Fresh water surplus from the Baltic Sea.
3. Meteorological forces.

The tidal forces are generating an oscillating current of well known periods. The fresh water surplus is generating a current varying over the year, the mean flow being $9{,}5 \cdot 10^3$ m³/s, Belt Project (1980). The meterological forces are less predictable. These forces are generating an oscillating current with varying period and amplitude. It is thus concluded that the flow is more complicated than just a monotone flow of brackish water from the Baltic Sea into the North Sea.

When the current is north bound brackish water from the Baltic Sea is flowing across the Darss Sill (Fig. 1). Since the brackish water is buoyant compared to the saline water from the North Sea, a stratified flow is generated in the Great Belt. The upper layer of brackish water moving towards north tends to increase its salinity due to turbulent mixing with the saline bottom water.

When the flow is south bound the now saline upper layer is moved across the Darss Sill. Even more saline water from the bottom layer is also being pulled over the sill. These saline water masses plunges down the slopes of the Darss Sill and eventually feeds the bottom water of the Baltic with salt and oxygen.

Modelling the stratified flow of the Great Belt requires in principle a three-dimensional hydrodynamic model. Such a model suitable for engineering purposes does not exist. It was therefore decided to analyse the flow further in order to investigate if it was possible to use a 2-layer model for documentation of the compensation dredging design. When stratified flow is simplified and assumed two layered, one has to distinguish three flow regimes:

- Subcritical two-layer flow
- Supercritical two-layer flow
- Well mixed flow

Subcritical flow exist when the stratification together with the dynamic condition (the speeds of the layers) is stable and long internal waves in the interface between the brackish upper layer and the saline bottom layer can move freely in all directions.

Supercritical flow exist when the long interval waves are arrested by the mean current, the waves cannot move freely against the current.

Well mixed (or continously stratified) flow exist when the two-layer assumption is unstable and internal waves break. In this last case the two-layer assumption is invalid.

Based on the theory of dynamic stability outlined in Abbot and Torbe (1963) field data from Storebælt (DHI/LIC, 1990) have been analysed and a histogram of the frequency of the flow regimes is shown in Fig. 5. It is seen that the most frequent flow regime is the subcritical regime. This supports the choise of a two-layer model as an appropriate design tool.

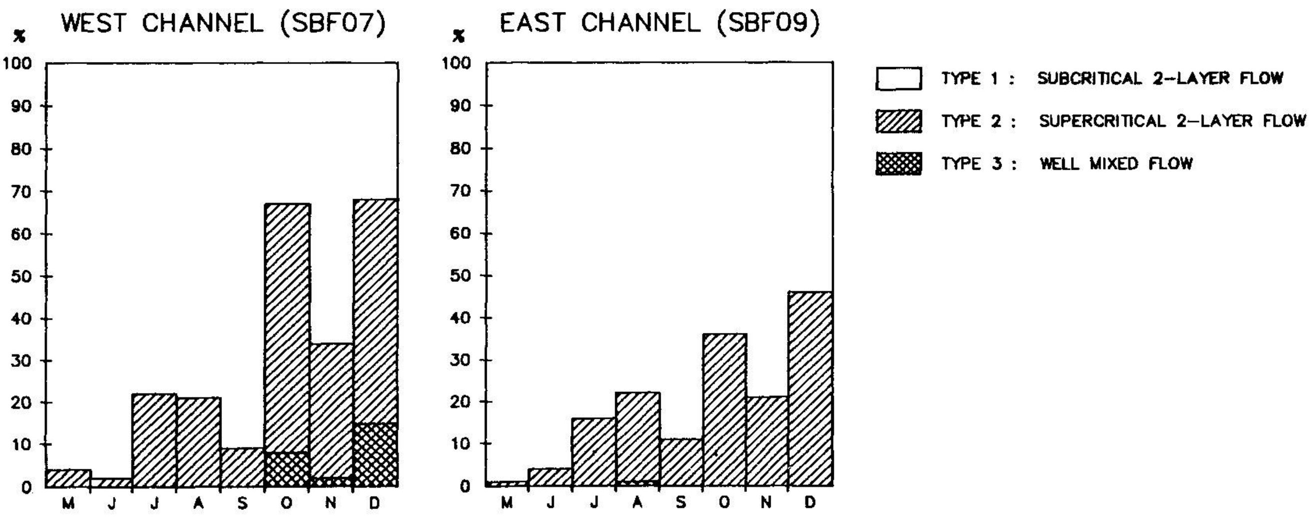

Fig. 5 Frequency of flow regimes in the Great Belt based on measurements from West Channel (SBF07) and East Channel (SBF09) see Fig. 7. Data from the period May to December 1989 are included.

4. NUMERICAL MODELLING

From the hydrographic description it is seen that a layered model should be chosen. Also the model must be able to calculate the effect of bridge piers and causeways on the flow.

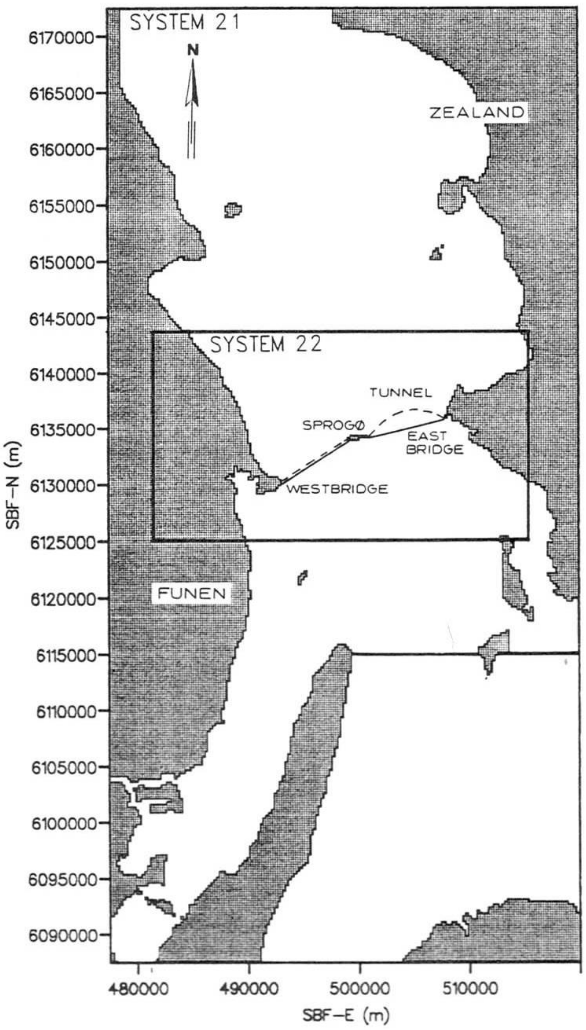

Fig. 6 Model Area.

The model requirements are:
- Two-layer model
- Subcritical and supercritical flow regime
- Flow resistance of bridge piers
- Flow resistance of causeways
- Turbulence description (mixing between layers)

Also it is required that the model is verified by field measurements, see below.

The task of setting up a numerical model for producing multiple simulations is a compromise between model performance and the limits due to computer capacity. For the determination of the zero solution an approach including two models was chosen.

A main model was set up for a large area of $43 \cdot 85$ km². Inside this area a submodel of $34 \cdot 19$ km² was employed on basis of boundary data calculated by the main model. The grid size was chosen to be 250 x 250 m².

The main model is an one-layer model set up in the DHI modelling system 21. The submodel is a two-layer model set up in the DHI modelling system 22. See Fig. 6.

The surface elevation along the submodel boundary is extracted from the main model results. The level of the interface is found on the basis of measurements carried out on a few locations corresponding to the model boundary.

The tilt of the interface along the boundaries is found from surface elevations considering hydrostatic pressure distributions.

The models are based on the coupled equation for conservation of mass and momentum in two directions. By solving this set of equations numerically the elevation and two velocity components are found for each grid point and each layer.

In the equations of momentum the following terms are included:

- non linear convective and cross momentum,
- coriolis force,
- turbulent momentum dispersion,
- wind shear stress, and bottom shear stress,

and for the two-layer model:

- interface shear stress.

To model the bridge piers properly a subgrid module has been developed. The drag forces on the piers are calculated and equivalent drag forces are added to the momentum equations.

The calculations are performed using a design period representative for the varying current conditions in the Belt. The final compensation dredging is controlled by a sensitivity analysis in which design period and model parameters are varied within a physically reasonable range. Sensitivity tests show that the uncertainty of the method is comparable to the practical uncertainty of dredging.

5. VERIFICATION

The verification of the model includes comparison of measured and model simulated parameters such as water level, interface position and current. The measurement programme is described in Mogensen (1991). An outline of the measurement programme is shown in Fig. 7.

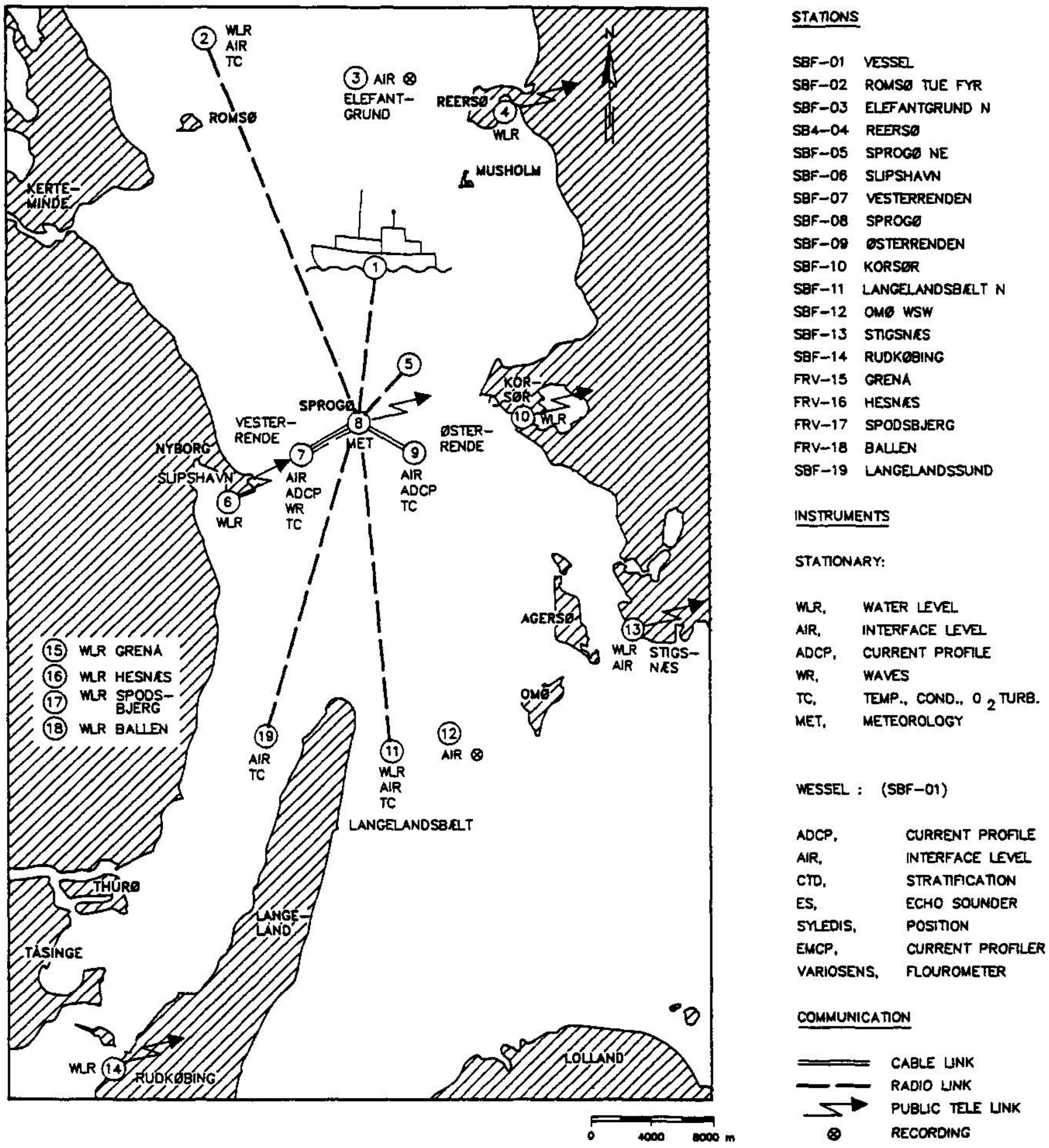

Fig. 7 The Great Belt Link Monitoring Programme.

Model verification was carried out for all three flow regimes and the overall conclusion is that the model verification was successful and that the model is a suitable tool for the compensation dredging design.

Examples from the verification period 2. to 8. September 1989 are shown in the figures. The flow regime of the period is mainly subcritical, except at the end of the period where the flow becomes supercritical.

In Fig. 8 is shown the measured and calculated time series of the current in station SBF07 and SBF09.

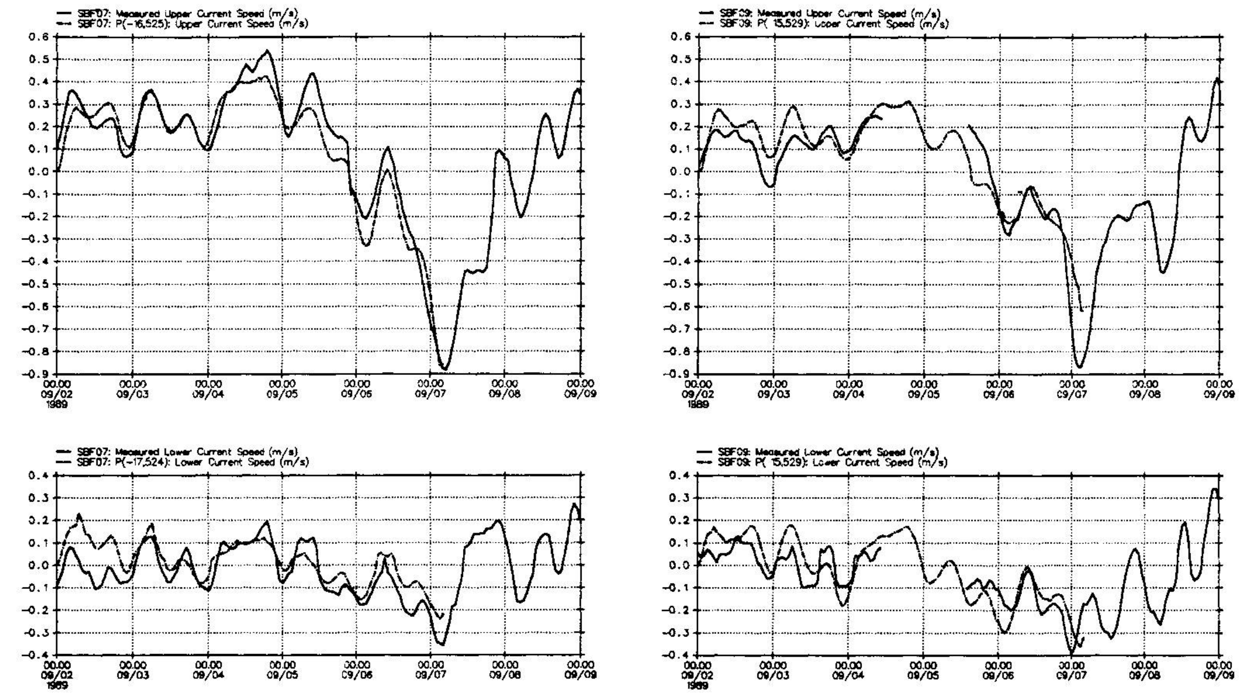

Fig. 8 Current time series. Measured and calculated (SYSTEM 22) for upper and lower layer in SBF07 and SBF09.

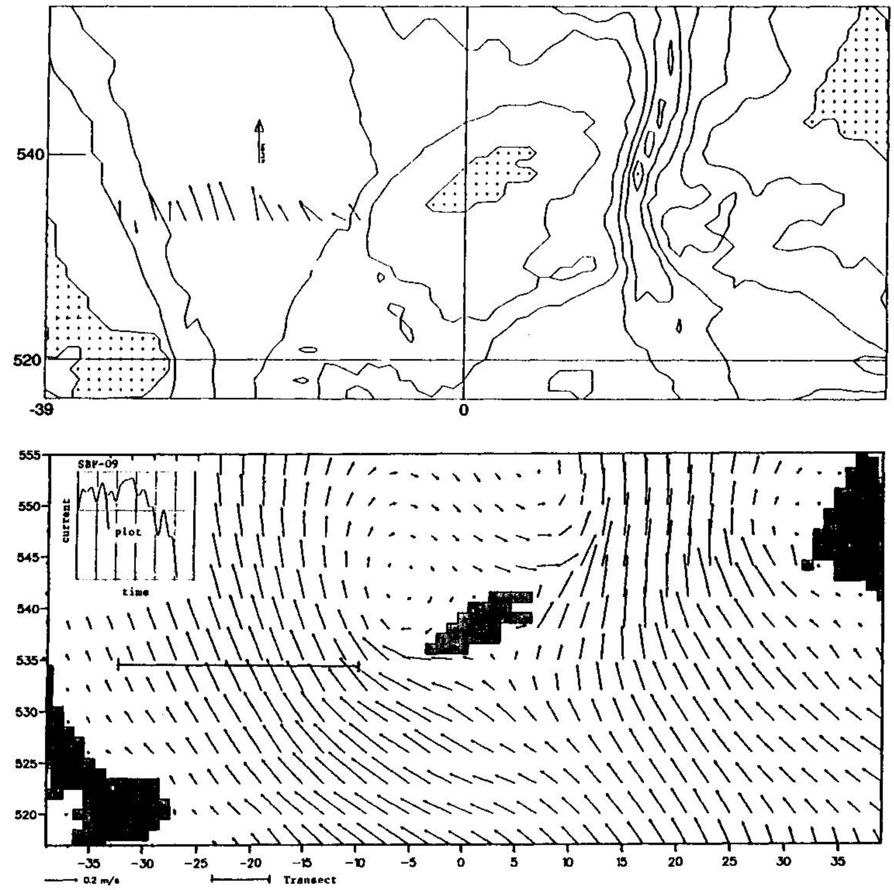

Fig. 9 Example of measured (vessel mounted ADCP current meter) and calculated (SYSTEM 22) current vectors, upper layer. (03/09/89, 10:00)

Good agreement is obtained for both upper and lower layer. Some discrepancies are observed for SBF09 when the flow is strong towards south. SBF09 is located at the transition between the jet and the lee water whereas the current signal is unstable.

An example of synoptic plots of measured and calculated current vectors are shown in fig. 9. When the vector plots are inspected it should be noted that calculated vectors only are plotted for every second grid point in the east-west direction, and for every third grid point in the north-south direction.

In Fig. 10 is shown the measured and calculated time series of water levels. The water levels show very good agreement between measured and calculated values.

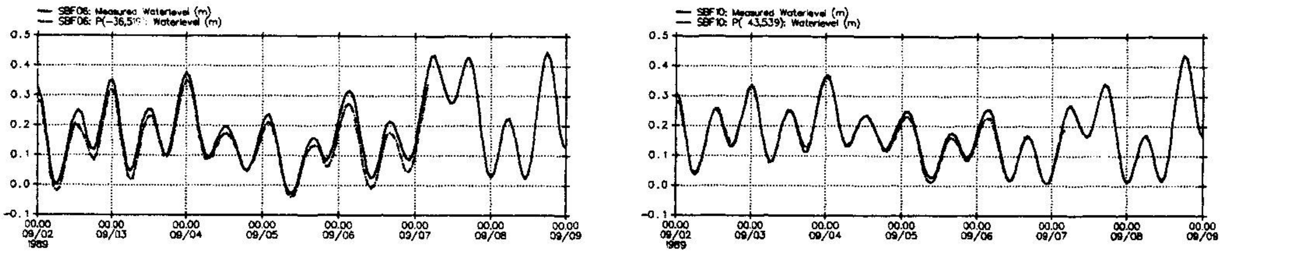

Fig. 10 Measured and calculated water levels for SBF07 and SBF09.

In Fig. 11 is shown the measured and calculated time series of interface levels. It is seen that in SBF07 the agreement is good considering the uncertainty in measurement of the interface. It is nice that the sharp change in level on 5 September is simulated by the model. The same trend is seen in the comparison for the SBF09. An example of synoptic plot of interface level is shown in fig. 12.

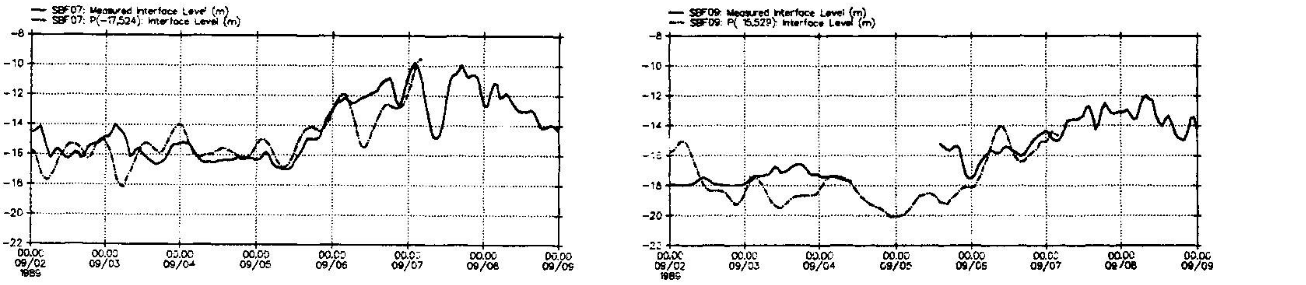

Fig. 11 Measured (TC-chain) and calculated interface level (SYSTEM 22) for SBF07 and SBF09.

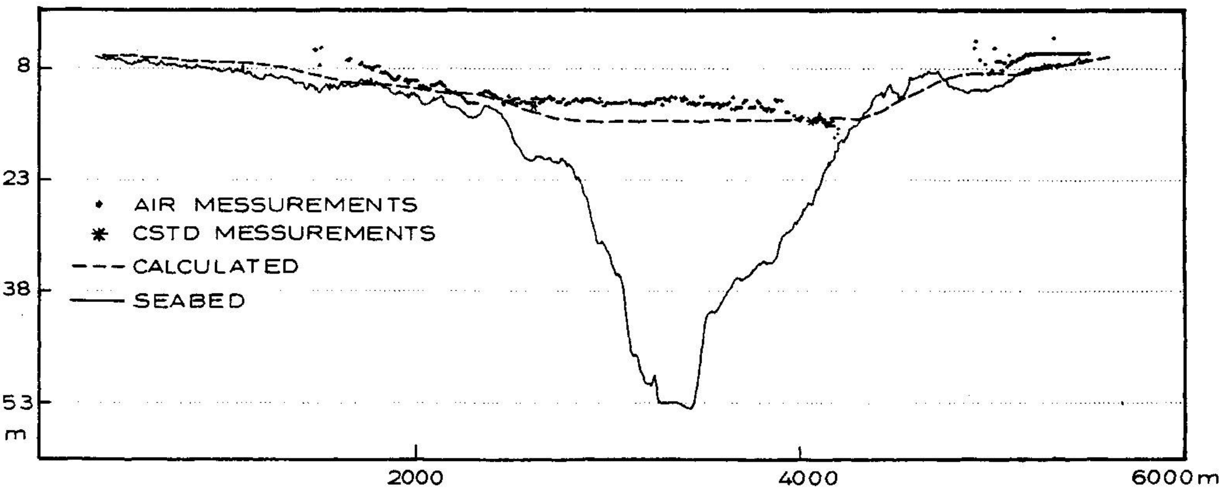

Fig. 12 Measured (vessel mounted AIR and CSTD) and calculated (SYSTEM 22) interface. (06/09/89, 10:00). Section across East channel.

A measure of the flow regime is the densimetric Fronde number number G^2, Pedersen (1986). G^2 is defined by:

$$G^2 = \frac{V_1^2}{\Delta g y_1} + \frac{V_2^2}{\Delta g y_2}$$

Where V is speeds, y is layer depth, Δ is $(\rho_2-\rho_1)/\rho_2$, (ρ is density) and g is accelleration of gravity. Index 1 and 2 is denoting upper and lower layer. In fig. 13 is shown the calculated densimetric Fronde number. It is seen that in the vicinity of the link, the flow can become supercritical. Outside the supercritical area the flow gradually adjust to the subcritical flow regime. This flow adjustment was observed by measurements carried out during the verification period.

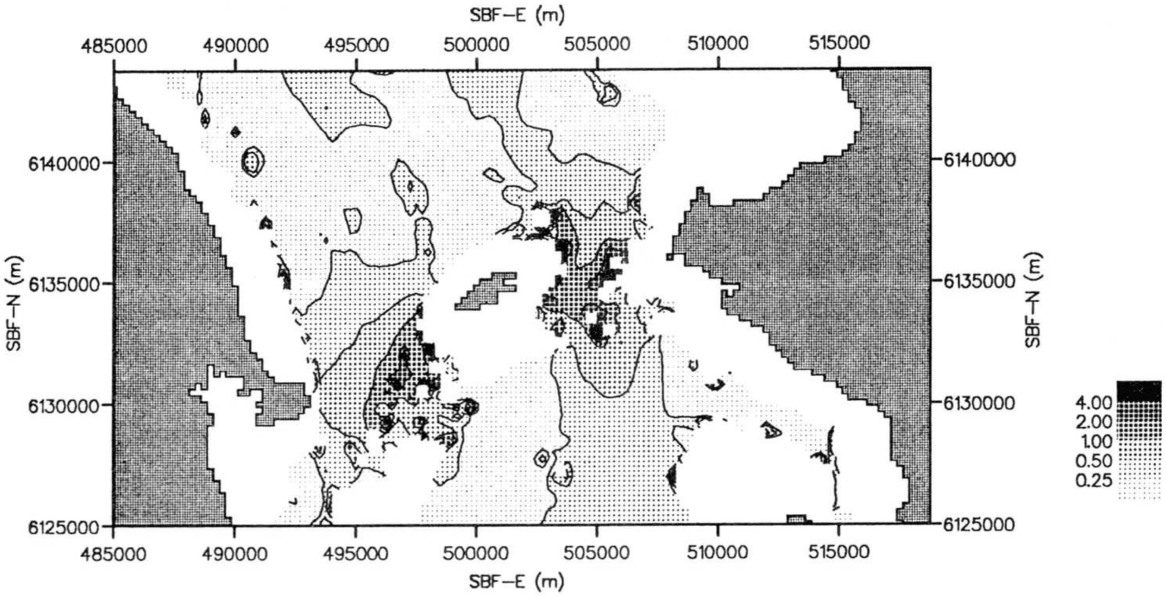

Fig. 13 Contour plot of Fronde number (07/09/89, 02:00). In blank areas one layer flow is present due to shallow water depth.

The verification is considered successful and the model is accepted as the design tool when compensation volumes are calculated.

6. COMPENSATION DREDGING

The final compensation dredging is shown in fig. 2. The dredging is described in Ottesen-Hansen (1991). The total volume is $6 \cdot 10^6$ m³ on the East Reef of Sprogø. The major part of the dredged material is used in the ramps and anchor block construction.

The dredging influences the near field because of significant sediment spill to the environment. The near field effects are described in Randløv and Jensen (1991).

7. ACKNOWLEDGEMENTS

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