HARBOUR DESIGN INCLUDING SEDIMENTOLOGICAL PROBLEMS USING MAINLY NUMERICAL TECHNICS

by
B. LATTEUX+

ABSTRACT

For most of the needed studies for the design of Calais harbour enlargement works, the "Laboratoire National d'Hydraulique" chose to use numerical models. This approach includes the determination of currents around and inside the new outer-harbour, just as the evaluation of the project sedimentologic impact and of the long-term evolution of a bank named "le Riden de la Rade", edging the access channel.

Current studies were performed using four nested bidimensionnal computer models fitted on field data and supplying in each point the depth-averaged velocity and the total water height. These four models are based on an implicite finite difference fractionnal step method. Besides for the very near field model the method is especially elaborated to enable the detailed reproduction of eddies and flow separations.

The sedimentological numerical study is based upon current models results : the bed-load transport is computed from the depth-averaged velocity and the water height previously determined using an empirical formula, and the continuity equation applied to this load transport gives then the bed evolution. As soon as the depth variation is significant enough to react on the flow pattern, current fields are readjusted by a simple method based on flow continuity equation.

This numerical model, applied to the near field, has given an evaluation of the sedimentological impact of the harbour enlargement project :

- strong erosion in front of the new harbour due to current strengthening ;
- accretion on each side of this erosion area, especially in the channel ;
- bar formation at the harbour entrance.

1. INTRODUCTION

Due to the increase of the passengers traffic between Calais and the United Kingdom, Calais Harbour is going to be equiped with supplementary car-ferry berths ; this development required an enlargement of the outer-harbour which will enable in a second stage the harbour spreading towards East (fig. 1).

+ Division Hydraulique Maritime. Laboratoire National d'Hydraulique. Electricité de France. Chatou. France.

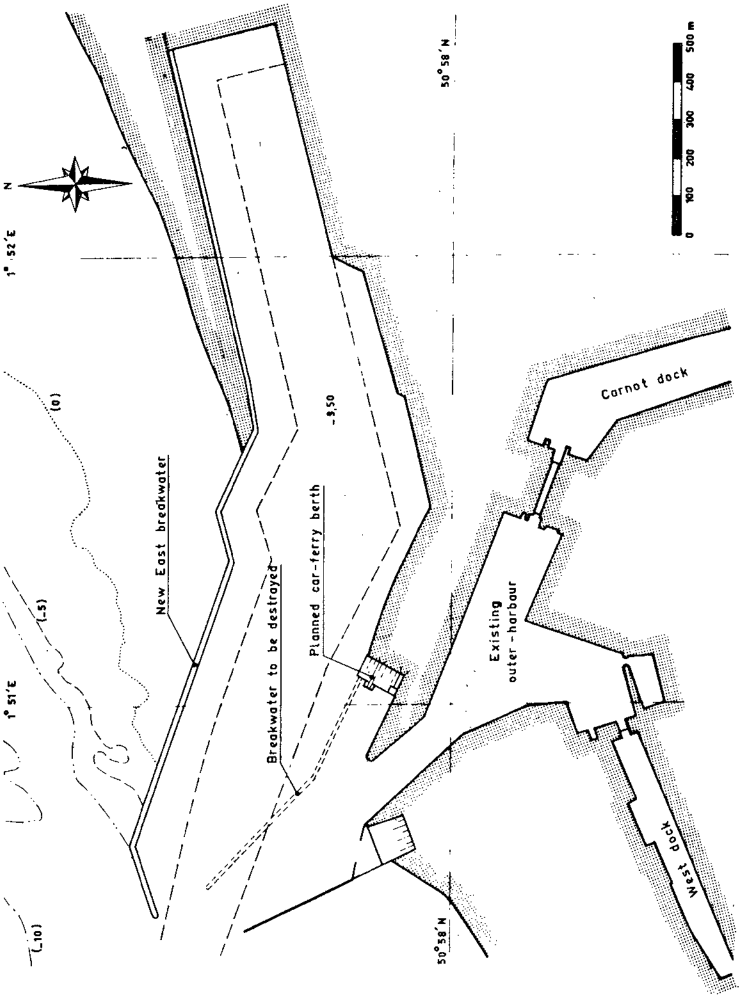


Fig.1 - CALAIS HARBOUR : NEW OUTER-HARBOUR LAYOUT

Hydraulic and sedimentological studies required by this development have been performed using mainly computer models : wave refraction off the harbour and diffraction inside were thus numerically studied by the "Service Central Technique des Ponts et Chaussées" ; the determination of tidal currents around and inside the new outer-harbour, just as the evaluation of the project sedimentological impact on bed-load transport, both presented here, were carried out in the same way by the "Laboratoire National d'Hydraulique". Only breakwater structure adjusting and final tests of wave agitation inside the harbour have required physical modelling.

2. NOTATION

C = Chezy's bottom friction factor ;
C_s = Strickler's bottom friction factor ;
d_m = mean particle diameter ;
g = gravitational acceleration ;
h = water height ;
K = dispersion coefficient reckoning velocities vertical heterogeneity in ;
K_s = porosity coefficient ;
t = time variable ;
T = bed-load transport rate ;
U, V = components of flow discharge per unit width ;
v = depth-averaged velocity ;
x, y = space variables ;
Z_o = bottom elevation related to the horizontal reference level ;
λ = mean latitude in the model's field ;
ϖ = water specific weight ;
ϖ_s = particle specific weight ;
τ = bottom shear stress ;
τ_c = critical bottom shear stress ;
Ω = angular rotational velocity of the Earth.

3. STUDY OF THE CURRENTS

3.1. Presentation

Tidal stream and level distribution have been computed on mean spring tide conditions by means of four nested bidimensional numerical models (fig. 2 and 3) fitted on field data :

- a global model of the Southern part of the North Sea (5 kilometers mesh-grid) ;
- a regional model of the Dover Strait (one kilometer mesh-grid) ;
- a local model of Calais region (250 meters mesh-grid) ;
- a very near field model representing outer and inner parts of the harbour (variable mesh down to 30 m).

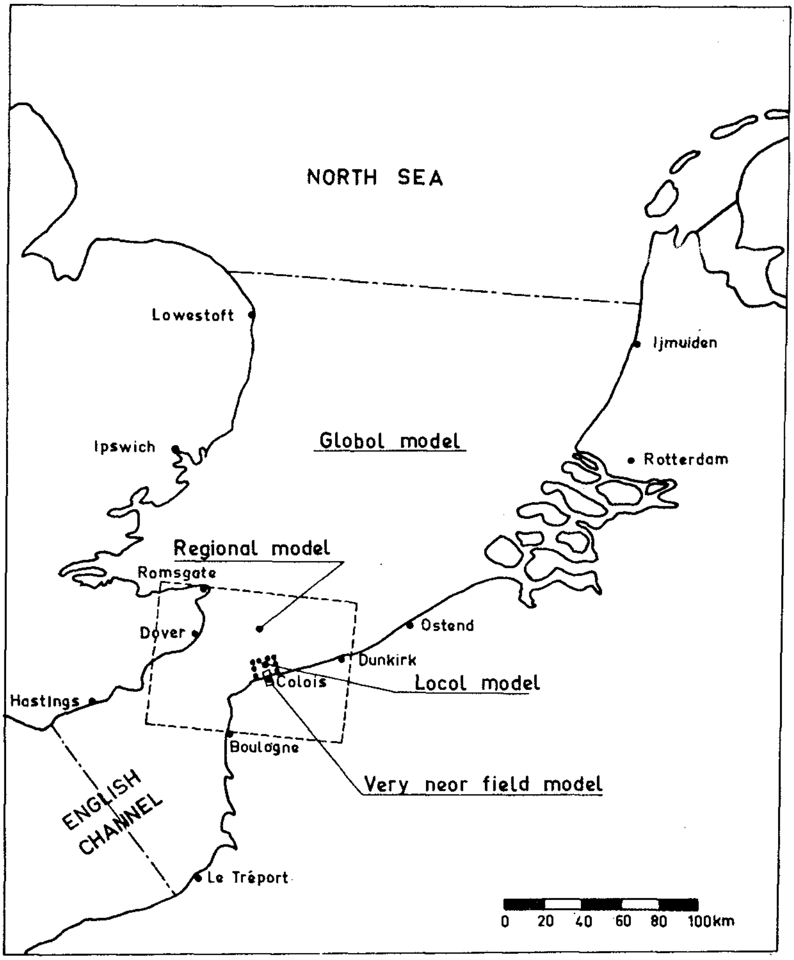


Fig.2 – AREA COVERED BY THE DIFFERENT NUMERICAL MODELS

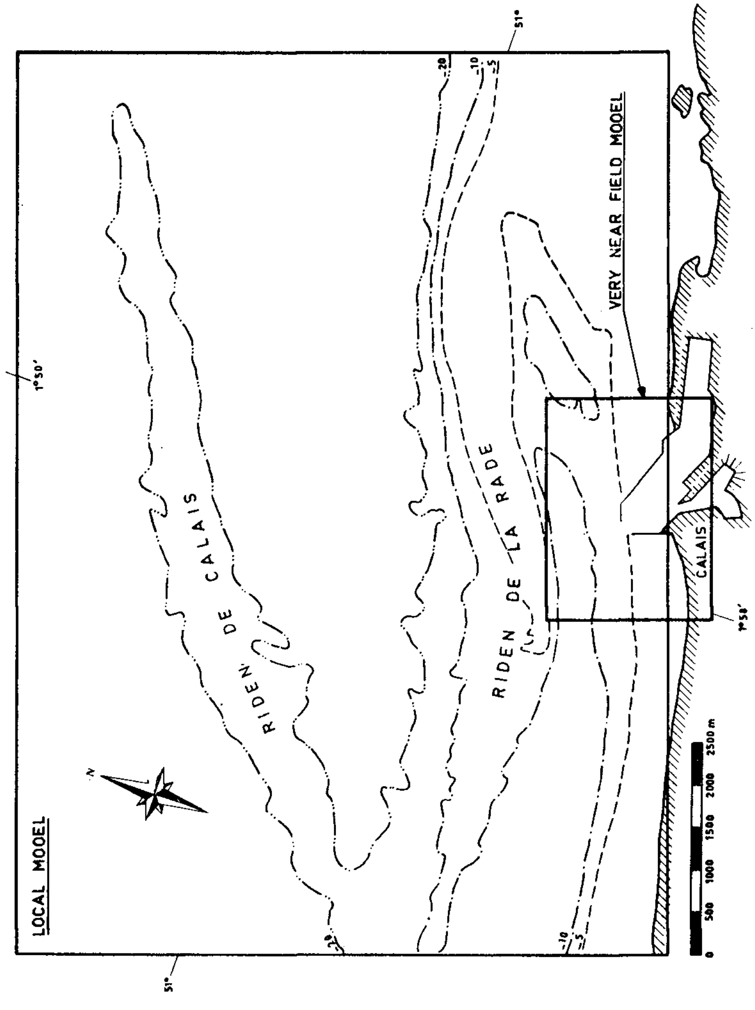
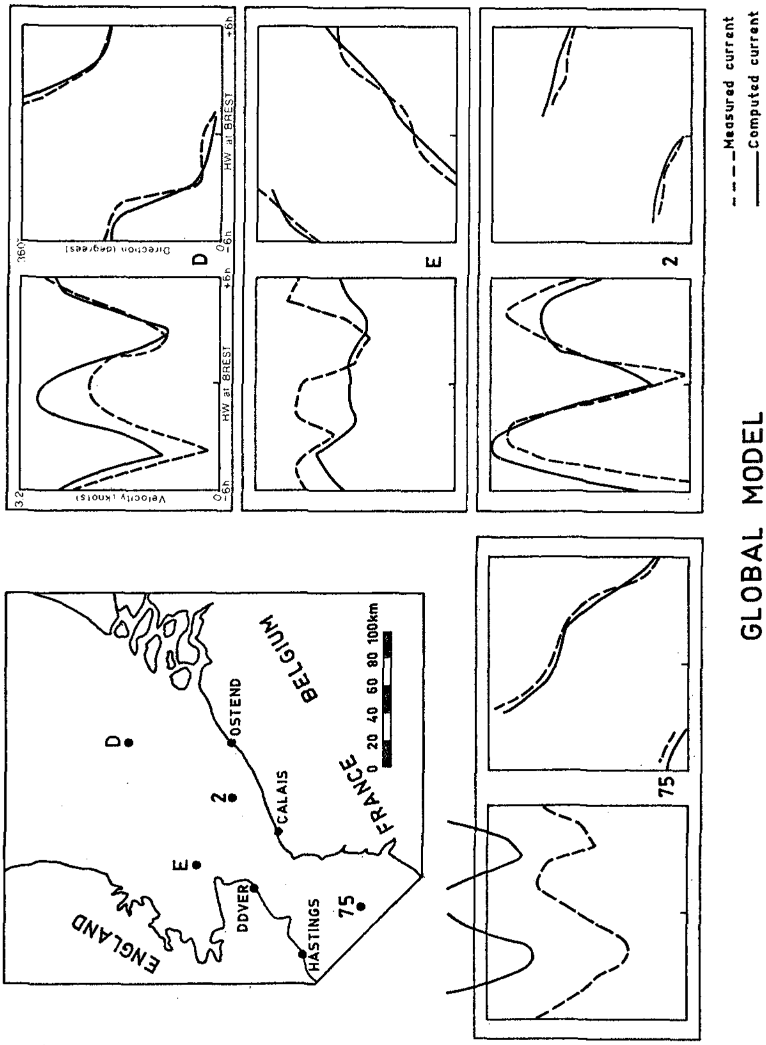


Fig.3_AREA COVERED BY THE LOCAL AND VERY NEAR FIELD MODELS



GLOBAL MODEL

Fig.4 – COMPARISON BETWEEN COMPUTED AND MEASURED CURRENTS

Only the last two models are directly within the goal of the study, allowing the evaluation of the project nautical conditions and serving as input to the sedimentological investigation ; the first two models, extending very far off the studied area, are only used to solve the problem of the boundary conditions : the few field measurements near Calais are not sufficient to give by interpolation adequate conditions ; limits must then be pushed away so far as computed current near the harbour depends on the well-known bed and coast topography and on the global boundary conditions rather than on the distribution of these conditions.

3.2. Model principle

The model is based upon the assumptions of an hydrostatic pressure, slight curvature of the bottom and the free surface and a vertical quasi-homogeneity of the current. Sun and moon attractive forces are neglected in the model's field (they are included only in the boundary conditions). The model computes then the depth-averaged velocity and the total water height using the classical Saint-Venant equations including bottom friction and Coriolis force :

$$\frac{\partial h}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \qquad (1)$$

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x}(V^2/h) + \frac{\partial}{\partial y}(UV/h) + g\,h\,\frac{\partial h}{\partial x} = -\,g\,h\,\frac{\partial Zb}{\partial x}$$

$$-\,g\,\frac{U\sqrt{U^2+V^2}}{C^2\,h^2} + 2\,\Omega\,V\sin\lambda + K\,\Delta\,U \qquad (2)$$

$$\frac{\partial V}{\partial t} + \frac{\partial}{\partial x}(U\,V/h) + \frac{\partial}{\partial y}(V^2/h) + g\,h\,\frac{\partial h}{\partial y} = -\,g\,h\,\frac{\partial Zb}{\partial y}$$

$$-\,g\,\frac{V\sqrt{U^2+V^2}}{C^2\,h^2} - 2\,\Omega\,U\sin\lambda + K\,\Delta\,V \qquad (3)$$

The solving metnod is an implicite finite difference fractional step scheme using an orthogonal grid. Boundary conditions (water height, flow discharge or tidal wave) are coming partly from field date, partly from the results of another global model in the case of the largest one. The finer models are successively feeded with boundary conditions interpolated from the results of the preceding one.

3.3. Results

3.3.1. Global model

This model includes the Southern part of the North Sea and the Eastern part of the English Channel from Great - Yarmouth - Ijmuiden to Hastings - Le Tréport with a 5 kilometers mesh. On

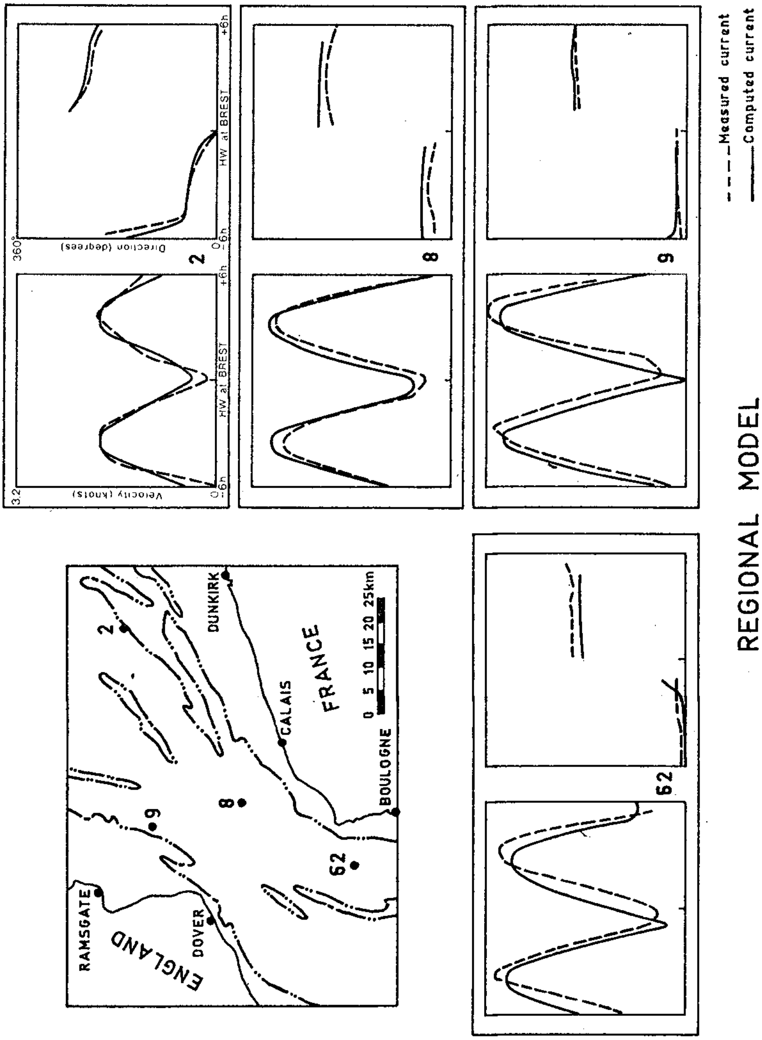


Fig.5 _ COMPARISON BETWEEN COMPUTED AND MEASURED CURRENTS the northern boundary, crossing an amphidromic point, surface level and flow discharge were fixed basing on field data ; on the southern boundary were imposed both components of flow discharge, supplied by the results of another preexisting numerical model, covering the whole English Channel.

The complex tidal range distribution due to the superposition of two tidal waves, one coming from the English Channel, the other from the North Sea, is generally well reproduced except near the Dover Strait, too narrow compared with the mesh to be correctly described. Figure 4 shows the comparison between measured and computed current for some of the calibration points ; it reveals a rather good agreement concerning flow direction, even when his value is continually changing (points E and 75), and a less accurate simulation of the velocities.

3.3.2. Regional model

Dover Strait is considered in more details in the regional one kilometer mesh model. Boundary conditions, supplied by the global model, are the two components of flow discharge.

Tide law is rather improved ; as displayed on figure 5 for some calibration points, velocity, direction and phase of the tidal stream are accurately reproduced, except on narrow banks, badly described in the grid system, where velocities are often overrated.

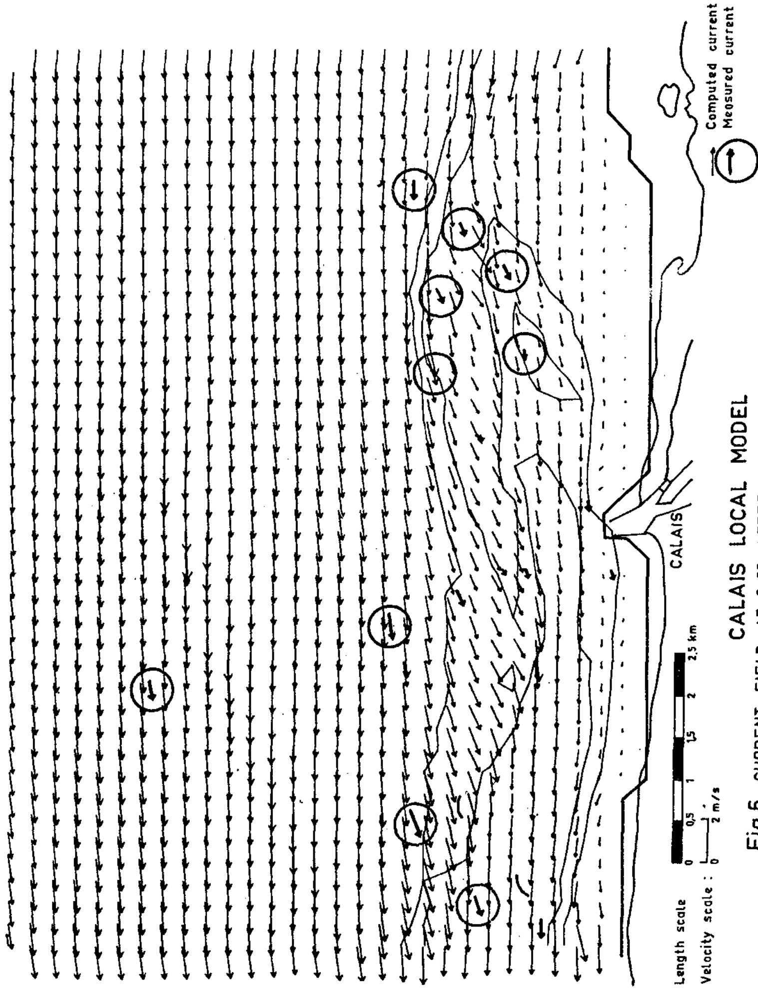
3.3.3. Local model

This 250 meters mesh model covers the whole "Riden de la Rade" (fig. 3), a sand bank edging the access channel to Calais Harbour, whose evolution has to be computed with and without the influence of the new outer-harbour.

The flow pattern pecularities involved by this bank are effectively achieved by the model in spite of the two-dimensional representation of the actually three-dimensional flow configuration. Figure 6 gives the computed stream distribution 6 hours after high water, compared with current measured in a few points : natural current deflection on the bank induced by the feeding of the southern channel, just as the ebb flow reducing in this channel are rather well reproduced.

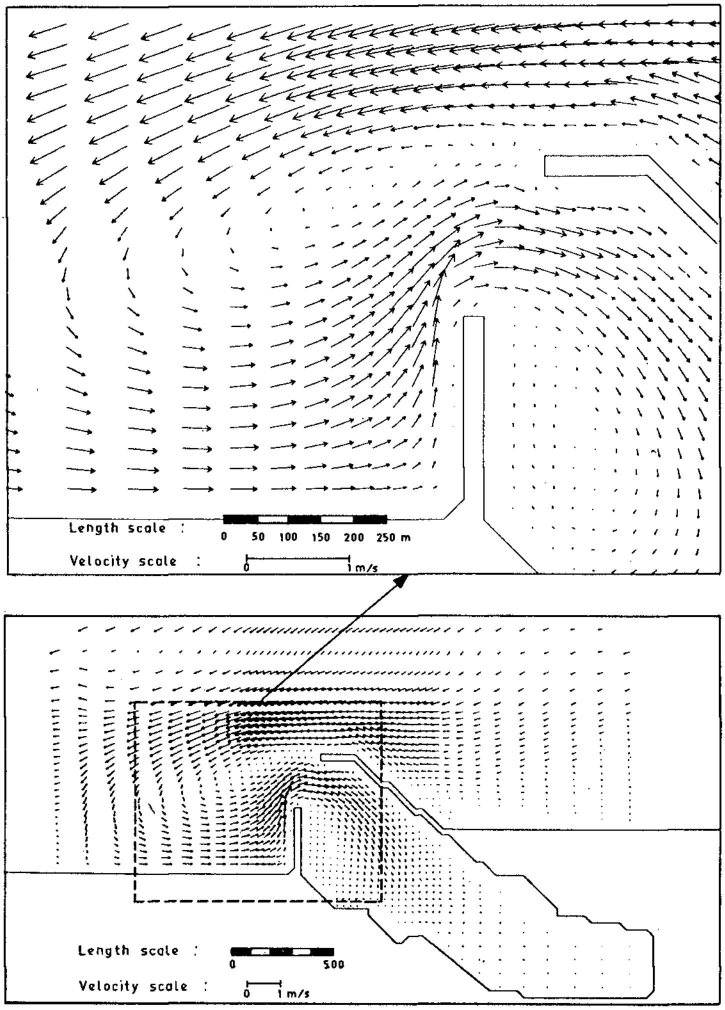
3.3.4. Very near field model

The last model, representing the enlarged outer-harbour and its close vicinity, uses a variable mesh grid (down to 30 m), allowing an accurate representation of the harbour entrance and inner parts while having at the same time boundaries far enough to get there a flow pattern not disturbed by the harbour enlargement. The solving method is especially suited to enable the detailed reproduction of eddies and flow separations ; these flow configurations can be reproduced



CALAIS LOCAL MODEL

Fig.5 – CURRENT FIELD AT 6:00 AFTER HIGH WATER AT CALAIS



CALAIS HARBOUR VERY NEAR FIELD MODEL

Fig. 7 - CURRENT FIELD AT 3:00 BEFORE HIGH WATER

owing to the zero velocity assigned on solid boundaries, whose effect is carried inside the model field by the diffusion terms. Both components of flow discharge are imposed on eastern and westerns fluid boundaries ; on the northern one, rather near to the harbour, it has proved better to impose water level and tangential component of flow discharge, thus allowing contingent flow lines deflection by the new breakwater even on the boundary.

Flow pattern has been computed for two stages of the harbour development and for two different considerations of the west breakwater one being permeable. The model results show a significant flow strengthening and deflection northward of the harbour during flood, slighter during ebb, and the development of two eddies, the largest one occuring to the west of the harbour at the end of ebb (fig. 7). In the harbour entrance velocities do not exceed 30 cm/s ; inside, the flow is rather slow, slightly vortical at the end of filling.

These results yield an estimate of the nautical conditions, which seem rather better that the present ones, point out the most propitious time for the harbour access and give precious informations concerning the access handling.

4. SEDIMENTOLOGICAL STUDY

Current results are used to compute by means of a two-dimensional bed-load transport model the sedimentological effect of the harbour enlargement.

4.1. Model presentation

Besides assumptions considered for current determination, following ones are made :
- flow and bottom evolutions are slow ;
- bed-load transport has the same direction as the depth-averaged velocity.

Bed-load transport induced by tidal current is computed using Meyer-Peter's formula :

$$T = 8\ Kv\sqrt{\frac{g}{\varpi}}\ \frac{1}{\varpi_s - \varpi}\ (\tau - \tau_c)^{3/2} \qquad \text{pour } \tau > \tau_c \tag{4}$$

$$T = 0 \qquad \text{pour } \tau < \tau_c$$

Where τ is given by Strickler's law :

$$= \frac{\varpi \quad V^2}{C_s^2\ h^{1/3}} \tag{5}$$

and τ_c by Shield's law :

$$\tau_c = A\ (\varpi_s - \varpi)\ d_m \qquad (6)$$

where A is a coefficient between 0,02 and 0,06 (0,047 according to Meyer-Peter).

Continuity equation applied to the bed-load transport provides then the bed evolution :

$$\frac{\partial Z_b}{\partial t} + \text{div}\ \vec{T} = 0$$

Numerical solving is based upon an explicite finite difference method using an orthogonal grid. Boundary conditions have to be imposed only when flowing in ; sea bed is then kept fixed on the bound mesh.

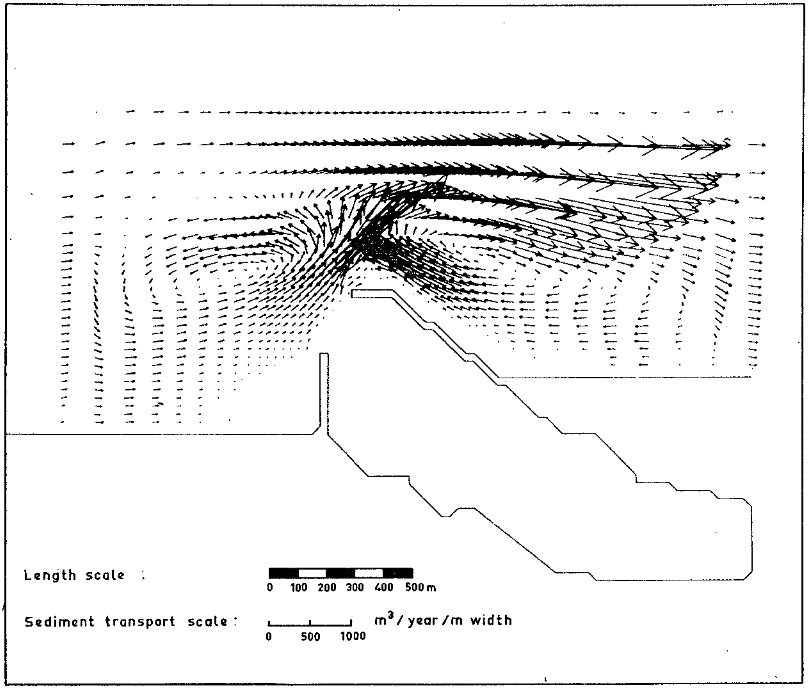
In order to avoid a prohibitive number of computation steps, tide is filtered by expanding sedimentological time step with respect to hydraulic one (so a lengthened tide represents several tides, in the same way as it is made on scale models). At every step velocity is readjusted according to the new water depth assuming that the initial flow discharge remains the same at the same time of the tide.

This model has already been applied in a similar case, related to the sea bed evolution induced in the building of the new outer-harbour of Dunkirk, about 40 kilometers away from Calais : mathematical model results turned out to be close to those achieved on the physical movable bed model operated for the study, themselves well corroborated afterwards by the natural bed evolution.

4.2. Results

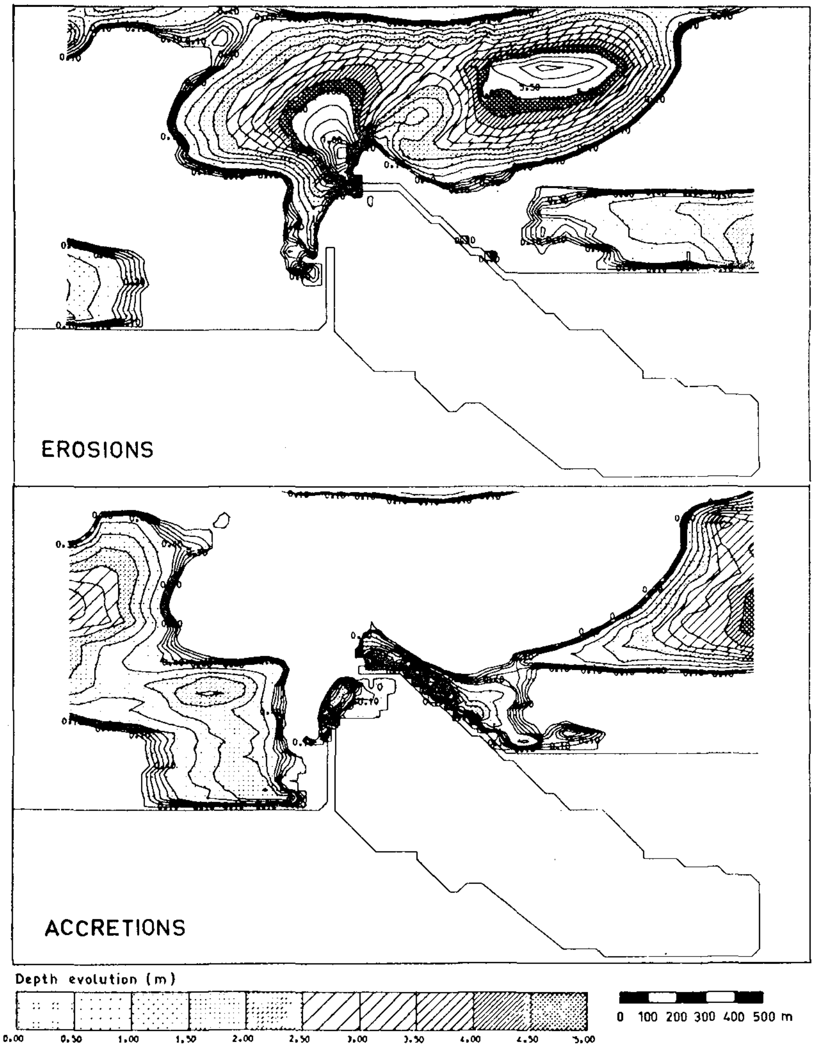
Based on the results of the very near field current model, the bed-load transport model, using the same grid as the current one, has supplied an evaluation of the sedimentological impact of the final enlargement project.

Figure 8 displays, in the initial state, the computed distribution of tidal-averaged sediment transport rate : it points out predominance of flood action, especially northward of the harbour where current strengthening inferred from the new breakwater building is then much more significant than during ebb ; in this area sediment transport rate reaches 1 500 m^3/year/m width, i.e. ten times as much as on the eastern and western bounds. On each side of the harbour occurs a sediment transport "eddy" caused by unequal distribution of both ebb and flood current downstream the harbour, strengthened in the north and reduced in the south in the lie of the breakwaters. As time elapses maximum transport rates decrease gradually because of mutual adjustment of flow distribution and bottom topography.



CALAIS NEW OUTER-HARBOUR

Fig.8 - COMPUTED PATTERN OF NET SEDIMENT TRANSPORT (INITIAL STATE)



CALAIS NEW OUTER-HARBOUR

Fig.9 _ COMPUTED EVOLUTION AFTER 5456 TIDES (8 YEARS)

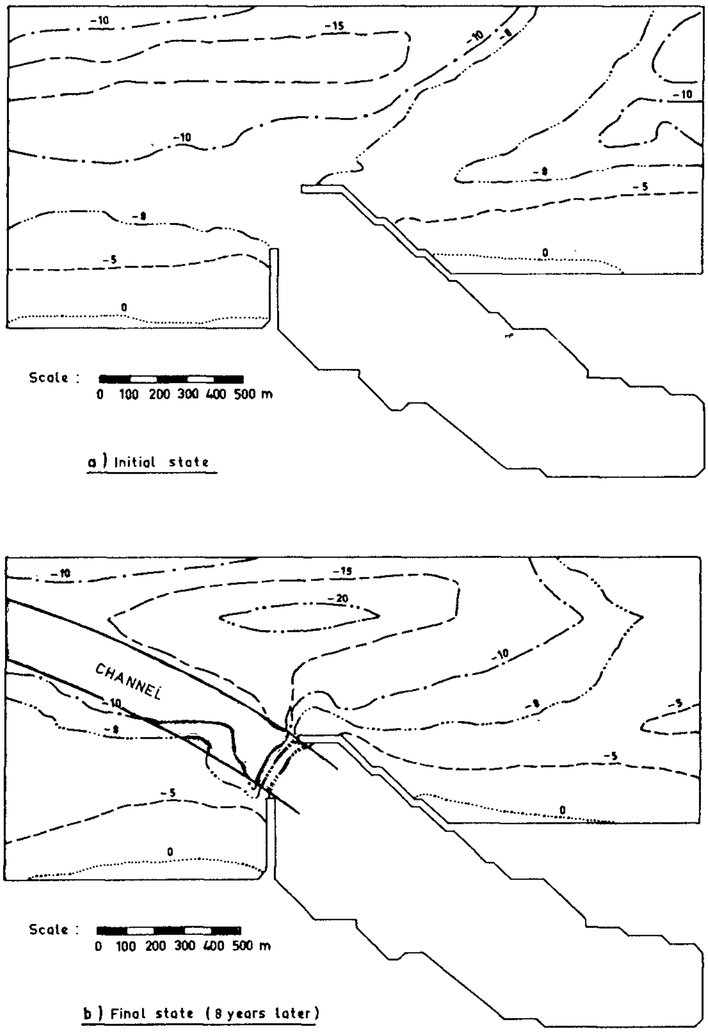


Fig.10- CALAIS - COMPUTED BED EVOLUTION NEAR THE NEW OUTER-HARBOUR

Figure 9 presents the bed evolution computed after 8 years of tidal current action ; it shows a large area of erosion from the nort-west to the north-east of the harbour with deepening exceeding 8 m near to the new breakwater head ; slighter accretion occurs on each side, especially at the edge of the access channel ; in the harbour entrance the current velocity gradient brings out the development of a bar of rather limited size.

Figure 10 yields the comparison between present and final bottom topography, showing up the necessity of maintenance dredging in the harbour entrance and in the south of the outer channel.

The results of this bed-load transport study show that a bed protection has to be placed at the toe of the new breakwater ; they also give an estimate of the sand volume to be dredged to maintain the harbour access.

Bed evolution owing to suspended sediment, notably prevailing inside the harbour, will be separately examined using a method of balance calibrated from the present state data.

5. CONCLUSION

Among hydraulic studies needed by the enlargement of Calais Harbour, both stream distribution and sedimentological impact of the project have been dealt by means of numerical technics : current computer simulation, involving four bidimensional nested models, has enabled the detailed determination of nautical conditions in relation with the design of the new outer-harbour, pointing out the most propitious time for the harbour access and giving information for access handling ; current results have then been used to compute from a bidimensional bed-load transport model, validated on a similar study, the effect of the harbour extension on the bed evolution, yielding definitions of bed protection and forecast of channel dredging rates. This computer model will be used afterwards to study the evolution of a bank named "Riden de la Rade" (fig. 3) which could threaten in a very distant future the harbour access.

Physical modelling was required only for items needing little equipment and able to be quickly dealt with : final tests of wave agitation and breakwater structure adjusting.

This procedure of comprehensive numerical harbour design study is of moderate cost, of great flexibility and rather fast compared with scale modelling.