CHAPTER 159

Numerical Modelling of Bed Evolution Behind a Detached Breakwater

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Abstract

The sedimentological impact of waves on a sandy beach with a detached breakwater is simulated using a compound system of models. The results are satisfying since a salient could be generated behind the structure. They are in agreement with bed evolutions surveyed in experimental facilities and in nature. A quantitative analysis of the results performed in the framework of the working group 'Coastal Area Modelling' of the project MAST G8M shows that the volume of accretion computed here is in good agreement with the volumes obtained by other models and empirical formula.

Introduction

A numerical system has been developed for simulating bed evolution due to breaking waves. Wave, current, sediment, transport and bed evolution are computed successively. Since the wave field is affected by sea bed changes, hydrodynamic phenomena are up-dated when bed evolution is significant. The system of models is illustrated on figure 1.

The three numerical models belong to the library TELEMAC based on finite element technic. They are coupled within an automatic procedure.

Comparisons of the numerical results with measurements in flume cases were carried out in the past. They gave satisfying results (Broker Hedegaard et al 1992, Péchon 1994), undertow as well as bed evolution were well predicted. Standard parameters were used for these simulations except for the sediment transport formula where the suspended load was increased in the surf zone to account for breaking effect.

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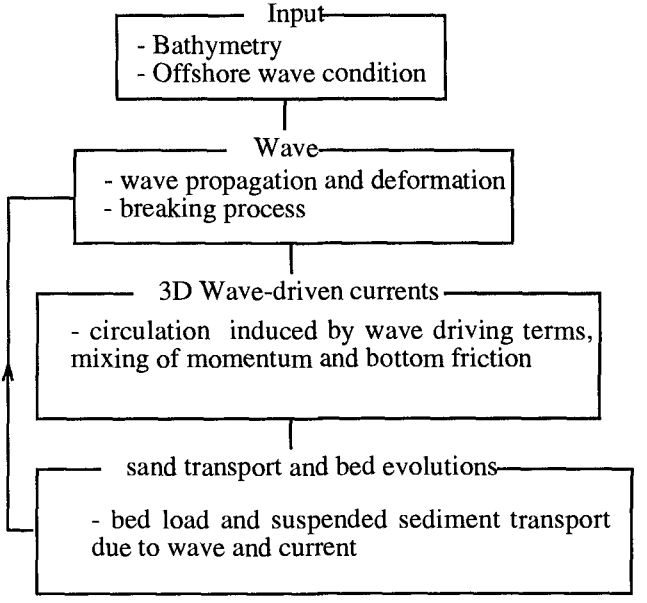

Fig.1 Structure of models

The present article deals with the application of the models on a three-dimensional case ; the impact of a detached breakwater built along a rectilinear beach is investigated. In a previous study (Péchon et al., 1995) the good agreement of computed currents with measurements collected in a basin (Mory and Hamm, 1995) was exhibited on the same but reduced scaled structure. Accurate data of seabed movement and wave climate are not available for the present full scaled test. However the effect of breakwaters is qualitatively known according to surveys in coastal zones, and the ability of models to reproduce realistic morphological changes can be checked. Moreover an intercomparison exercise with other modellers was performed (Nicholson et al 1995) in the framework of the European program MAST2 G8M.

The numerical models

The wave model

The model ARTEMIS V1.0 solves the complete mild-slope equations :

$$div\,(C\,C_G\,\overrightarrow{grad}\varphi) + \omega\frac{C_G}{C}\,\varphi = 0$$

with $C = w/k$ C: phase celerity

$C_G = \frac{1}{2}(1 + \frac{2\,kh}{sh\,2\,kh})\,C$ C_G: wave group celerity

φ : complex horizontal part of the potential

$$\Phi(x, y, z, t) = Z(z)\,\varphi(x, y)\,e^{-i\omega t}$$

where $Z(z) = \dfrac{ch\,(k\,(h+z))}{ch\,(kh)}$

According to the rather schematise bathymetry tested here, the wave height decay in the surf-zone is given by the formula $H_b = 0.8\ h$ where H_b is the breaking wave height and h the still water depth.

The radiation stress can be calculated knowing the wave potential. However this leads to a very irregular radiation stress field which has to be smoothen. So it is prefered here to express the driving terms in function of the dissipation of breaking waves.

The computed instantaneous wave velocity follows an ellipse, therefore there is not a simple incidence. In the following current and transport models, the required incidence is supposed to be given by the large axis of the ellipse.

The time-averaged current model

The model TELEMAC-3D V3.0 solves the time-averaged three-dimensional equations accounting for the vertical variability of the forces due to breaking waves and especially roller effect (Péchon 1994). They read, in the case of a flume for clarity :

$$\frac{\partial U^2}{\partial x} + \frac{\partial UW}{\partial z} + \frac{\partial(\overline{u_w^2} - \overline{w_w^2})}{\partial x} + \frac{\partial \overline{u_w w_w}}{\partial z} = - g \frac{\partial \bar{\xi}}{\partial x} - \frac{\partial \overline{u'w'}}{\partial z} + t$$

$$\frac{\partial U}{\partial x} + \frac{\partial W}{\partial z} = 0$$

with U, W :time-averaged current due to breaking waves
u_w, w_w: instantaneous wave velocity
u', w' : turbulent fluctuations of velocity
x : free surface level
t : contribution of the roller of breaking waves

The overbar indicates time-averaged quantities.

The following closures are taken :

$$\frac{\partial (\overline{u_w^2} - \overline{w_w^2})}{\partial x} = \frac{1}{\rho h} \frac{D}{C}$$

$$\frac{\partial \overline{u_w w_w}}{\partial z} = \frac{1}{2\rho h} \frac{D}{C}$$

with
D : energy dissipation
C : wave celerity
h : mean water depth

$$\overline{u'w'} = -\nu_t \frac{\partial U}{\partial z}$$

$$\nu_t = Mh \left(\frac{D}{\rho}\right)^{1/3}, \text{ constant } M = 0.4$$

$$t = \frac{14}{\rho g} \frac{D}{HT}$$

T : wave period
H : wave height

The sediment transport model

The sediment transport is calculated by a satellite version of the numerical model TSEF V3.0 using Bailard formula (1981) in terms of the near-bed velocity field resulting from the previous model. The bed load and suspended load transport rates are expressed as :

$$\vec{q}_b = \frac{f_{cw}\,\varepsilon_b}{\Delta\, g\, tg\,\phi}\left[<|\vec{u}|^2 \vec{u}> - \frac{tg\,\theta}{tg\,\phi} <|\vec{u}|^3> \vec{i} \right]$$

$$\vec{q}_s = \frac{f_{cw}\,\varepsilon_s}{\Delta\, g\, W_s}\left[<|\vec{u}|^3 \vec{u}> - \frac{\varepsilon_s}{W_s} tg\theta <|\vec{u}|^5> \vec{i} \right]$$

in which

$\vec{q}_b$ bed-load transport rate m^2/s

$\vec{q}_s$ suspended load transport rate

f_{cw} friction factor wave+current

ε_b efficiency factor for bed-load transport $\varepsilon_b = 0.13$

ε_s efficiency factor for suspended load transport $\varepsilon_s = 0.024$

$\vec{i}$ unit vector directed downslope

ϕ internal angle of friction of the sediment

W_s fall velocity

Δ apparent density

$\vec{u}$ instantaneous nearbed velocity vector

$tg\,\theta$ bed slope

<.> time-averaged quantity

This formula is expected to give the transport rate inside and outside the surf-zone. The friction factor is adopted for the wave alone :

$$f_w = exp\,(-6.+5.2\,(\frac{A_w}{k_s})^{-0.19})$$

with $A_w = \frac{H}{2\,sin\,kh}$ orbital excursion

$k_w = 3\,D_s$ roughness coefficient

D_s grain size diameter

In the present model the velocity $\vec{u}$ is the summation of the time-averaged velocity and the instantaneous orbital wave velocity near the bed.

At the present state of knowledge, sediment transport formulae have broad correlation between predicted and observed values. Soulsby et al (1995) compared Bailard formula with data and they showed that only 57% of the predicted transport rate lay within a factor of 5 of the data. In the following application, it has been observed that the original formula overestimates the transport rate. So it is divided by 10 here, which is equivalent to increase the time scale.

Bed evolution model

The mass conservation of sand is also computed by the previous model which solves the equation for mass conservation of sediment.

Wave and current fields are updated when the bed evolution is greater than 0.5 time the water depth at 3 nodes of the mesh or 0.3 time at 10 nodes. In the following application this criteria occurs about every 30 hours.

Application

Description of the case

The domain of computation is presented on figure 2. At the initial time the bottom slope is 1:50 nearshore and the bed is horizontal offshore where the bottom level is -7.4 m.

The four lateral boundaries are closed for current and sediment transport. Only the offshore boundary is open for waves.

The generated wave at the offshore boundary is perpendicular to the shoreline. In the present model the wave is supposed to be regular, with a period of 8.0 s. The wave height is 1.2 m. The median grain size is 250 μ.

The mesh grid for wave computation contains 10500 nodes. It is refined in order to have at least 10 nodes per wave length. The horizontal mesh grid for current and sediment transport (fig 3) has 1450 nodes and each vertical profile has 9 nodes in the three-dimensional computation of currents.

Results

For the initial bottom, along a current cross-shore profile the wave height increases and reaches 1.6 m at the distance of the structure y = -110 m where the still water depth is -2.0 m (fig. 4), then it breaks. Wave pattern diffracts behind the structure.

In spite of the account for three-dimensional effects, the velocity field is nearly homogeneous over the water depth. In fact in this case the currents are mainly generated by alongshore gradient of surface elevation because the wave direction is nearly normal to the shoreline, and this gradient is constant over the vertical. The 3D effect would be stronger with oblique wave direction because the current would be also generated directly by driving terms with non-uniform vertical profile.

The near-bed velocity field displays a large eddy behind the breakwater (fig. 5). In the shallower part the intensity reaches 1.0 m/s whereas it is less along the structure in deeper part. In the open area the velocity field is very irregular because of variations of wave height. A cell takes place in the right hand side of the beach because of the closed boundaries at this corner. 2DV undertows are not

generated. The irregularities of the velocity field near the breaking line are due to the variation of the wave height in the longshore direction (fig. 4).

The resulting sand transport pattern displays very strong rate of 0.013 m^2/s behind the breakwater in shallower water (fig. 6). Out of this area, the transport rate is very small except locally such as on the right hand side of the beach.

After 10 days of cumulative wave action, the accretion behind the breakwater is very strong, often greater than 2.0 m, creating a salient (fig. 7). The thickness of erosion in the bordering area is generally smaller, less than 1.5 m .

The wave, current and sediment transport patterns calculated with this new bathymetry are modified (fig. 8, 9 and 10). The wave field is more irregular. The velocities and transport rates behind the breakwater are more intense because of the reduction of the water depth. The cell seen initially on the right hand side of the beach creates disturbances which extends along the beach. The choice of constant wave conditions is probably responsible for this situation ; in prototype situation the variation of wave incidence for instance contributes to smooth bathymetry and avoid extension of such phenomenum.

Comparison with other models and available data

In a literature review reported by Moreno (1995), a similar case was mentioned. The shoreline evolution behind a detached breakwater with a normal wave was investigated in a wave tank (Rosen and Vajda 1982). The beach was built of coarse bakelite. In the computation, the offshore steepness H_0/L_0 is equal to 0.012 which is close to the experimental condition 0.015. The ratio of structure length on the distance from shoreline is 1.4 in the computation, 1.0 and 2.0 in tests 6 and 7 of the experiments.

In the experiments a salient is created behind the breakwater with one prominence in test 6 and two symmetrical prominences in test 7. Regarding the computed bed evolution after 10 days (fig. 7), the numerical modelling leads to formation of two salients (or one in the half-domain) as in test 7. However the immersed area was not measured in the basin, so it is not possible to go further in the comparison. Moreover the numerical modelling does not reproduce the stirring up of sand in the emerged part.

Watanabe et al (1986) also tested a detached breakwater in a experimental basin with movable bed. The beach was made of sand of 0.2 mm. In this test the wave breaks in deeper water than in the numerical simulation, roughly at the same distance offshore than the breakwater. According to the different conditions the numerical and experimental results cannot be superimposed. However it is seen that in intermediate water, the contourlines -3.0 m in the field case (fig. 7) and -6 cm in the basin for instance have the same curvature. In shallow water a prominence is created in both tests but the shoreline moves offshore just out of the lee of the structure in the basin whereas it is eroded in the same area in the field test.

After 15 days the volume of accretion behind the structure is equal to 23 000 m^3 according to the readjusted transport formula. This value is in good

agreement with other models of DHI, Uni. Liverpool, HR and STCPMVN developed in the project MAST2 G8M where it ranges from 21 000 to 29 000 m^3 (Nicholson et al 1995).

It is noted that these two tests in experimental basins were not chosen for the present simulation because on one hand the transport formula of Bailard was elaborated for real life conditions and would not be appropriate for a reduced scale simulation. On the other hand the hydrodynamic results of the present simulation was already validated in a wave tank with fixed bed (Péchon et al 1995).

Conclusion

A compound system of models of the library TELEMAC have been developed in order to reproduce the refined evolution of the sea-bed in the surf-zone. In order to facilitate its use in practical applications, the codes have been coupled in an automatic procedure.

The sedimentological impact of waves on a sandy beach with a detached breakwater have been reproduced. The results are qualitatively satisfying since a salient have been generated behind the structure. They are in agreement with bed evolutions surveyed in experimental facilities and in nature. A quantitative analysis of the results performed in the framework of the working group 'Coastal Area Modelling' of the project MAST G8M shows that the volume of accretion computed here was in good agreement with the values obtained by other models.

Improvement of the models can be expected in the future by calculating instantaneous wave velocity field solving Boussinesq equations which include non-linear effects. Moreover Soulsby et al (1995) showed deficiencies of the transport formula compared with measurements. So further work is required for having a more reliable one.

Additional applications have to be done with this system of models in order to get experience and to appraise its limitations. More complex situations have to be investigated, for instance by accounting for tidal range.

Acknowledgement

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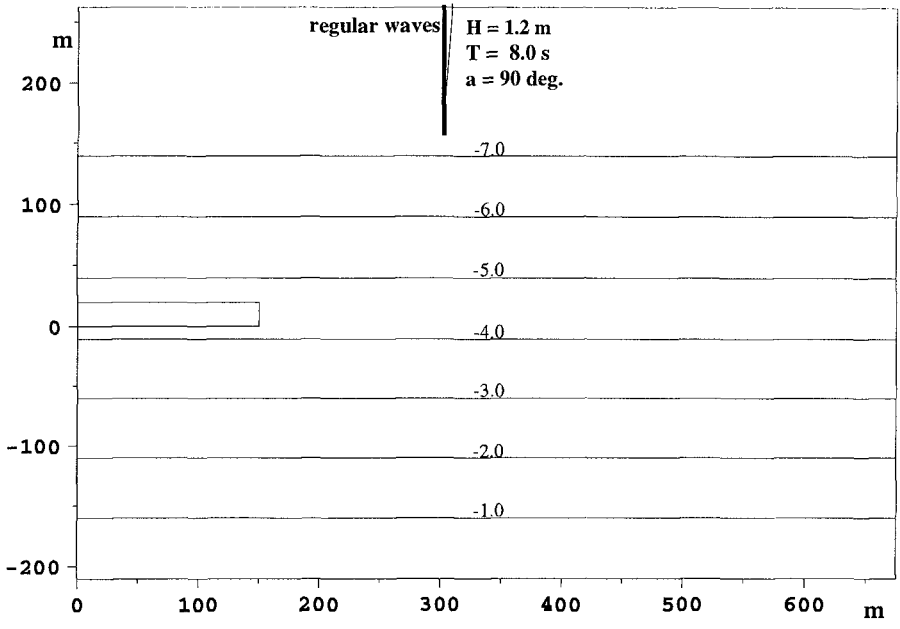

Figure 2 Bathymetry, initial time

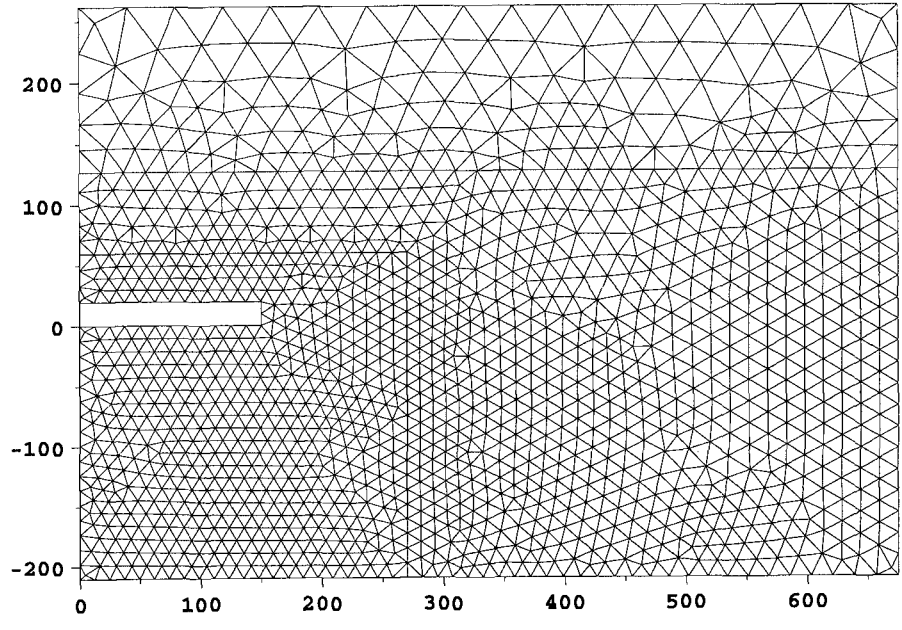

Figure 3 The mesh grid for computation of current and sediment transport

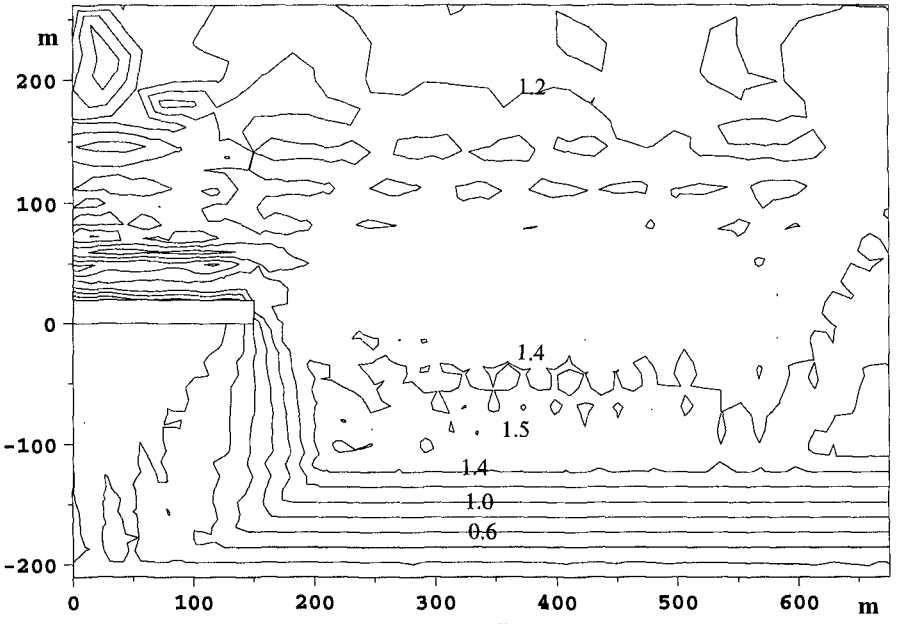

Figure 4 Wave field, initial time

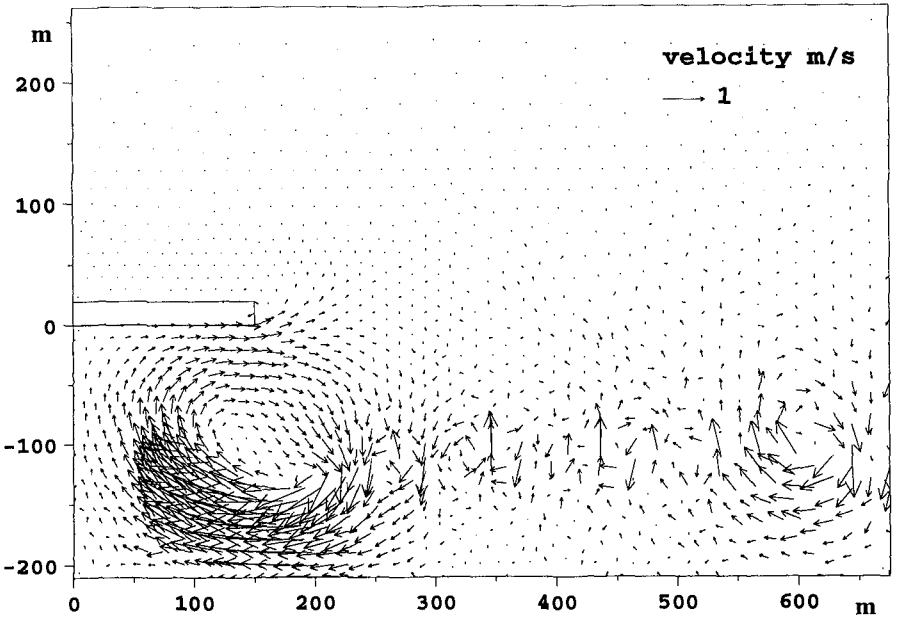

Figure 5 Velocity field near the bed, initial time

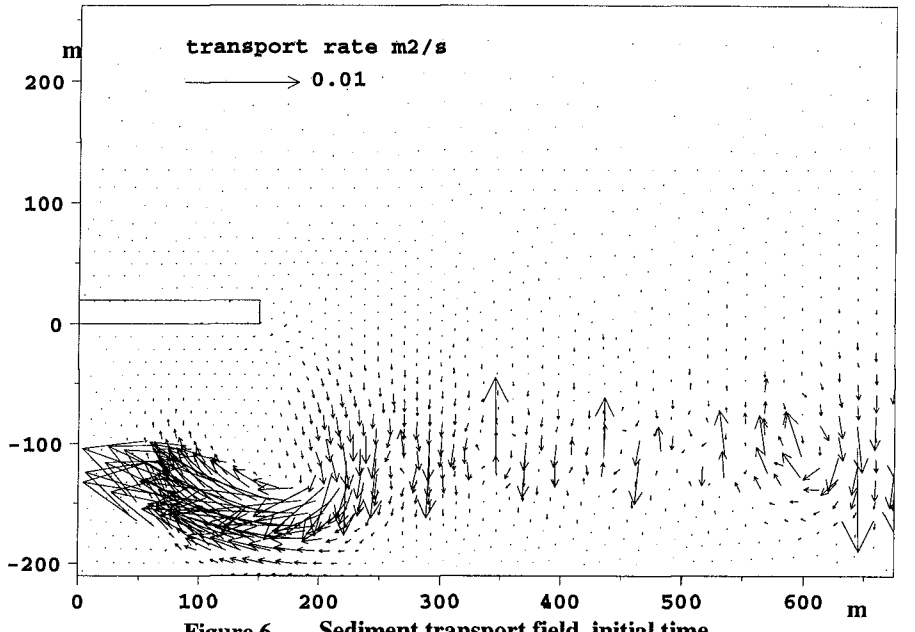

Figure 6 Sediment transport field, initial time

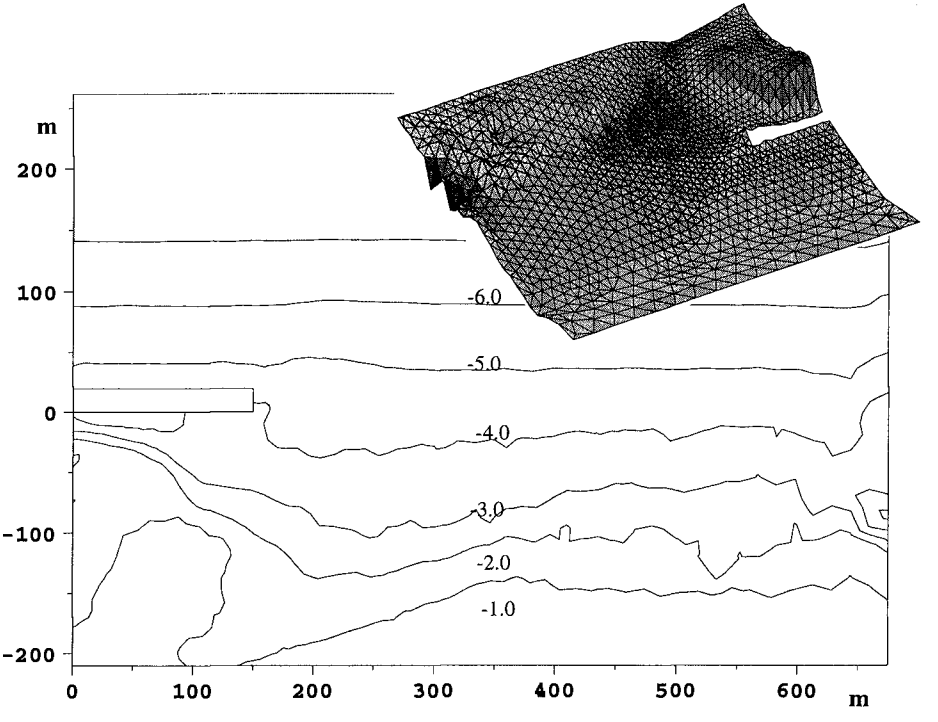

Figure 7 Bathymetry, t = 10 days

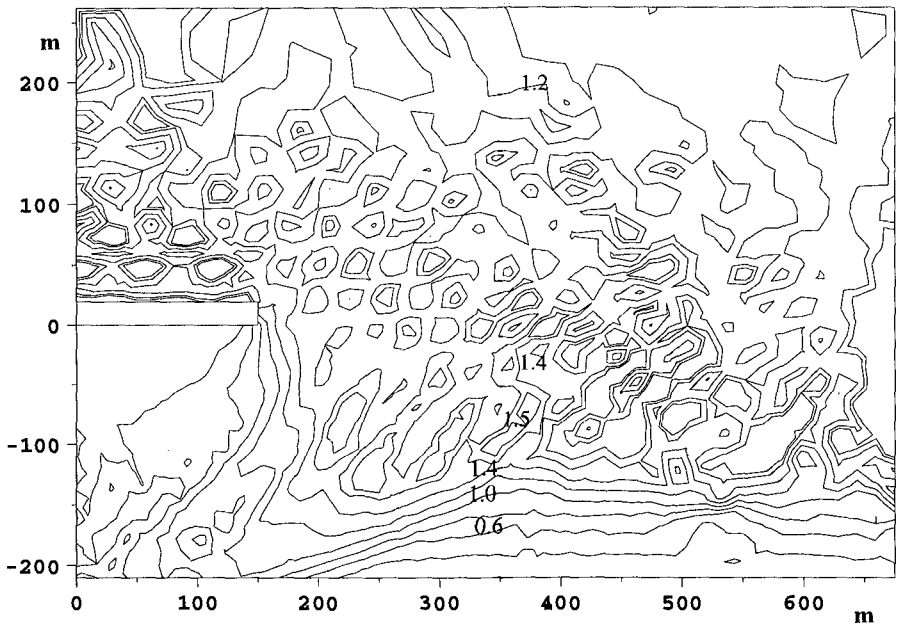

Figure 8 Wave field, time = 10 days

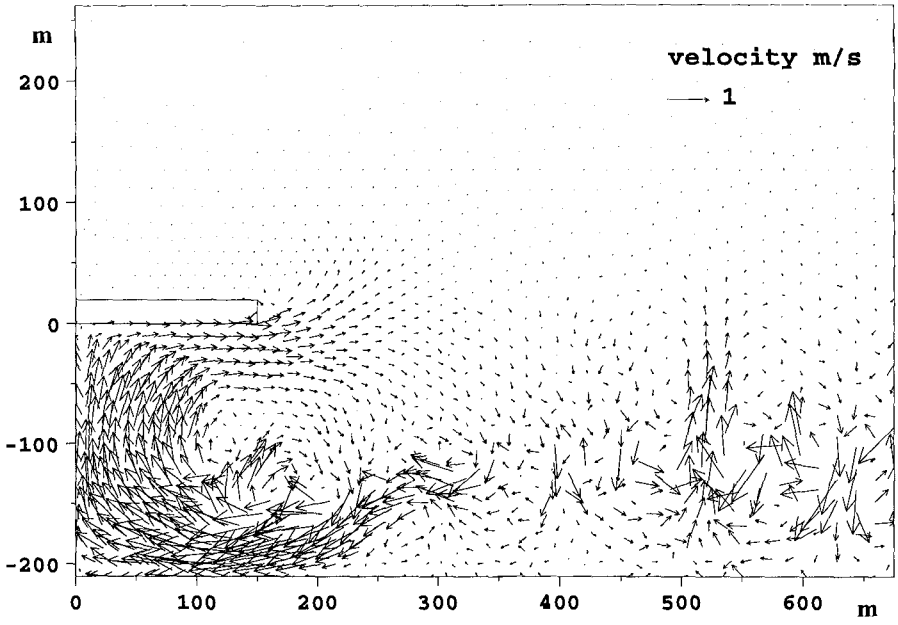

Figure 9 Velocity field near the bed, time = 10 days

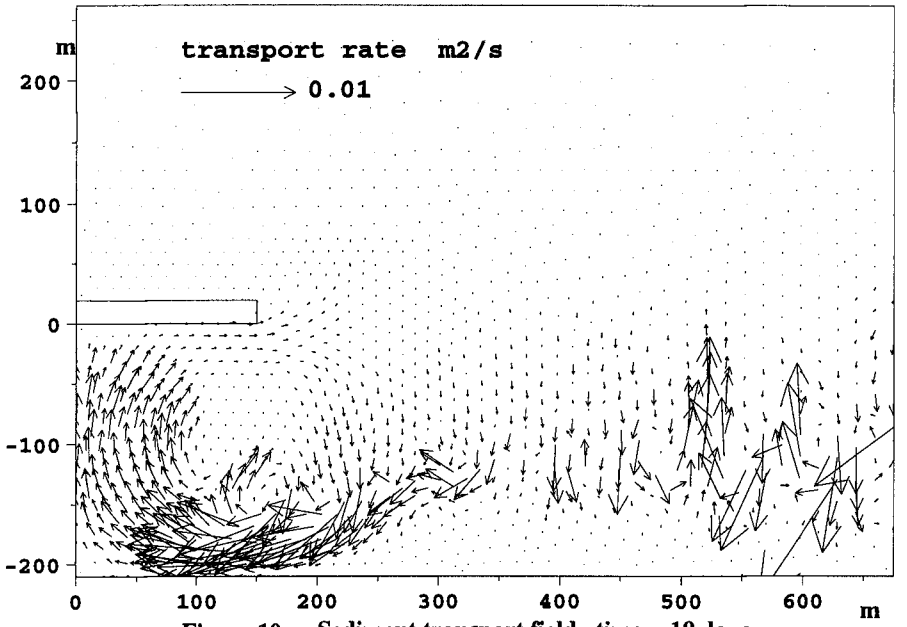

Figure 10 Sediment transport field, time = 10 days