Sediment Transport Near Groynes in the Nearshore Zone

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ABSTRACT ∎

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A bathymetric evolution model has been developed for predicting bottom changes in the nearshore zone where structures are present. The model is made up of a wave sub-model, based on a hyperbolic approximation to the Mild Slope Equation, a depth-averaged Navier Stokes solution for the nearshore currents, which employs a two equation (k-ε) turbulence model, and a sediment sub-model which uses the predicted turbulence levels to solve the suspended sediment equation. The individual submodels have been tested extensively using field and laboratory data. The total model has been used to predict the effect of varying the length of groynes on their behaviour as a means of beach stabilization.

ADDITIONAL INDEX WORDS: *Bathymetric evolution model, Mild Slope Equation, nearshore numerical model, suspended sediment transport, k-ε turbulence model.*

INTRODUCTION

A structure built in the nearshore zone will alter not only the local wave and current climate but also the transport of sediment in the area. An element of the structure design will include an estimation of this effect on the local bathymetry. In some cases the aim will be for the structure to have a negligible effect. This might be the case where a harbour breakwater is being constructed or where land reclamation is being considered. There are also numerous examples where structures such as groynes or offshore breakwaters are built specifically to bring about some beneficial changes in the nearshore zone. Strategies of beach replenishment also rely on being able to place sediment optimally. In all cases it is necessary to be able to predict accurately the changes that will be caused by the structure. Until recently this meant physical model studies, which were costly and in the case of movable bed models unreliable, due mainly to sediment scaling effects. Recent advances in numerical model-

ling have enabled numerical models to be used with more confidence.[1]

Early attempts at numerical models consisted of simple one or two line models which could predict the effect that groynes would have on a plane beach. The models were shown to be adequate if the groyne trapped virtually all of the longshore sediment transport, but were not suitable if this was not the case or if the geometry was complicated or the area influenced by tidal or other currents.

A more general approach, first demonstrated by FLEMING and HUNT (1976), considered the problem over a two dimensional grid of points and solved it using a number of sub-models where the wave field, nearshore currents and the resulting sediment transport were each solved in turn.

The wave field can now be solved including the combined effects of wave refraction, diffraction and reflection as well as the effects of wave-current interactions. The solution of the mean

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current field is achieved taking into account not only the non-linear convective accelerations in the governing differential equations but also the effects of turbulence. The modelling of the sediment allows for the suspended sediment to be treated in some detail. Finally a bathymetric model is introduced to predict changes in the nearshore region. The present model ignores any tidal effects.

The model is demonstrated by investigating the effect of changing the relative length of groynes on a sandy beach.

WAVE MODEL

The wave model solves the Mild Slope Equation derived by BERKHOFF (1972). The solution however is not of the full elliptic equation but of a hyperbolic approximation as derived by COPELAND (1985). The advantage of the hyperbolic approximation over the full elliptic solution is that it generally requires significantly less operations for the solution. The approximation includes the effects of wave-current interaction added to the formulation by DONG (1987). The Mild Slope Equation, including the effects of wave-current interactions, can be written after KIRBY (1984):

$$-g\left(\frac{; pt\eta}{\partial t} + \nabla\ (U\eta)\right) - \nabla\ (cc_g\ \nabla\ \phi)$$
$$+ (\sigma^2 - k^2cc_g)\phi = 0 \quad (1)$$

where ϕ is the surface potential, U is the mean current, ∇ the horizontal gradient operator and the other terms are defined as:

$$\sigma^2 = gk\ \tanh(kh) \quad (2)$$
$$\omega = \sigma + k.U \quad (3)$$
$$c = \sigma/k \quad (4)$$
$$c_g = \frac{\partial\sigma}{\partial k} \quad (5)$$

where c is the wave celerity, c_g the group velocity, k the wave number, σ the intrinsic frequency and ω the absolute frequency. By assuming a harmonic surface potential, small wave amplitude modulation and employing the linearized free surface boundary condition Equation 1 can be split into two first order equations which can be solved using an explicit finite difference technique.

The equations can be written:

$$\nabla Q + \nabla\ (U\eta) - \lambda\frac{\partial\eta}{\partial t} = 0 \quad (6)$$

$$\frac{\partial Q}{\partial t} + \omega cc_g\nabla\left(\frac{\eta}{\sigma}\right) = 0 \quad (7)$$

where η is the free surface elevation. Q is a function defined as:

$$Q = -icc_g\nabla\left(\frac{\eta}{\sigma}\right) \quad (8)$$

where $i = \sqrt{-1}$ and λ is defined as:

$$\lambda = \frac{\sigma^2 - k^2cc_g}{\omega\sigma} - 1 \quad (9)$$

The solution is carried out over a regular grid of points using finite differences where η, the surface elevation is evaluated a half time step ahead of the x and y components of Q. The scheme is therefore similar to a leap-frog technique and is centered in time and space. To begin, an initial wave field is assumed, and the solution proceeds until steady conditions are obtained. Generally this will occur after the initially assumed wave field conditions have propagated out of the solution area. Special care is taken at the boundaries to allow reflections to propagate out of the area without generating spurious waves.

Although it is recognized that wave breaking is vital in the solution of the nearshore zone equations a simple breaking criterion has been used in this work. The authors would see this as one of the areas where improvement could be made with the use of a more realistic formulation.

Given finite computing resources the physical area that can be modelled is determined to a large extent by the frequency of the incoming waves. Since η must represent the wave surface accurately, at least 10 and preferably 20 points per wavelength should be used. Modelling of short period waves therefore involves a large number of grid points if a large area is to be solved. Once set up the solution proceeds forward in time. The time step used is determined by the wave period and by the space step since there is a Courant stability criteria that must be satisfied. In a typical test of a nearshore zone with waves of 6 second period, a grid spacing of 1.50 metres could be used giving 12 points per wavelength in 1.0 metres of water and a timestep of 0.20 seconds would give 30 time steps per wave period. A computational grid 200 by 200

points would cover an area of 300 metres square. If the wave period were 20 seconds an area of some 1000 metres square could be considered for the same number of grid points.

The model has been tested against analytical solutions for pure refraction and diffraction. In all cases the agreement between the predicted and measured solutions was good. The model predictions were also compared with the results of a laboratory study of combined refraction-diffraction carried out by BERKHOFF et al. (1982). Figure 1 shows the layout of the laboratory test bed and a comparison of measured and computed wave heights along one of the defined section lines is shown in Figure 2. The agreement is good and typical of the results for this particular test.

CURRENT MODEL

The wave model allows not only the nearshore wave heights and directions to be calculated but also the radiation stress components which are evaluated in terms of the η and Q functions. These are required by the second model which solves the depth-averaged Navier-Stokes equations. The equations are solved using an alternating direction implicit (ADI) finite difference scheme. Also solved as part of the scheme is a two equation (k-ϵ) turbulence

model. The accurate representation of turbulence is important not only in the solution of the nearshore current field but also later in the suspended sediment model. In the past simple zero equation turbulence models have been used for the solutions of the nearshore currents, for example LONGUET-HIGGINS (1970). It has been shown by FLOKSTRA (1977) that if recirculation is to be modelled correctly a higher order turbulence model should be employed. Recirculation in the lee of structures such as groynes or offshore breakwaters could be expected to occur in the nearshore zone.

The equations to be solved for the flow can be written (in tensor notation)

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x_i}(U_iD) = 0 \qquad (10)$$

$$\frac{\partial U_i}{\partial t} + U_j\frac{\partial U_i}{\partial x_j} + g\frac{\partial \eta}{\partial x_i} + \frac{1}{\rho D}\tau_{bi}$$
$$+ \frac{1}{\rho D}\left(\frac{\partial S_{ij}}{\partial x_j}\right) - \frac{1}{\rho}\left(\frac{\partial DT_{ij}}{\partial x_j}\right) = 0 \qquad (11)$$

where U, represents the x and y velocities, D is the total depth and η the water surface elevation. S_{ij} are the radiation stress components and T_{ij} the effective stresses. τ_{bi} are the bottom friction components.

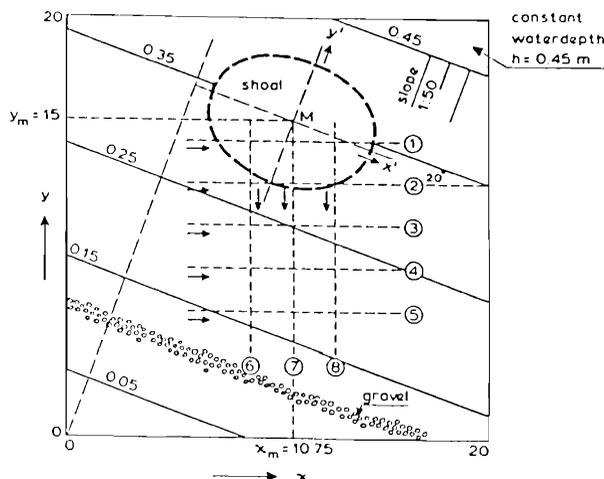In the nearshore zone the effective stresses are related mainly to the turbulence in the flow.

Figure 1.   Test bed for submerged elliptic shoal used by Berkhoff et al. (1982). The numbers in circles refer to section lines used for comparison.
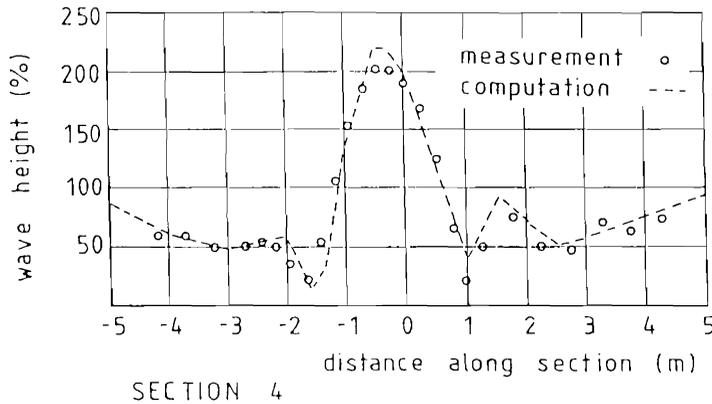
Figure 2. Comparison of measured and computed wave heights along section 4 for submerged elliptic shoal of Berkhoff *et al.* (1982).

Using the Boussinesq eddy viscosity approximation the stresses are written in terms of a velocity gradient and an eddy viscosity. The importance of the turbulence in the mean flow and sediment calculations warrants the use of a two equation turbulence model for the calculation of the eddy viscosity. This allows the turbulence at a point to be calculated in terms of both local effects and those due to convection by the mean flow.

The turbulence model, which is formulated in terms of k, the turbulent kinetic energy and ϵ its rate of dissipation, can be written, after DONG (1987):

$$\frac{\partial Dk}{\partial t} + U_i \frac{\partial Dk}{\partial x_i} - \frac{\partial}{\partial x_i}\left(\frac{\nu_t}{\sigma_k} D \frac{\partial k}{\partial x_i}\right)$$
$$= P_h D + D_t - D\epsilon \quad (12)$$

$$\frac{\partial D\epsilon}{\partial t} + U_i \frac{\partial D\epsilon}{\partial x_i} - \frac{\partial}{\partial x_i}\left(\frac{\nu_t}{\sigma_e} D \frac{\partial k}{\partial x_i}\right)$$
$$= c_{1\epsilon} P_h D \frac{\epsilon}{k} - c_{2\epsilon} \frac{\epsilon^2 D}{k} + D_t c_p \frac{c}{D} \quad (13)$$

where D_t is the production term due to wave breaking.

$$D_t = -\frac{\partial}{\partial x}\left(\frac{E c_{gx}}{\rho}\right) - \frac{\partial}{\partial y}\left(\frac{E c_{gy}}{\rho}\right) \quad (14)$$

P_h is the production term due to shear as defined by RODI (1980). σ_k, σ_ϵ, $c_{1\epsilon}$, $c_{2\epsilon}$ are constants determined empirically and reported by RODI (1980), and others. The coefficient c_p is a constant defined by DONG (1987) and is of the

order of 0.20. ν_t is the eddy viscosity and defined as:

$$\nu_t = c_\mu \frac{k^2}{\epsilon} \quad (15)$$

Based on laboratory work by VISSER (1984) the coefficient $C\mu$ should be of the order of 2.5, in the case of the nearshore zone, rather than the standard value of 0.09 as quoted by RODI (1980). Although the higher value gives reasonable estimates of the nearshore currents, it will be seen that work on sediment modelling suggests that the standard value may be a better choice.

The nearshore current model has been verified by comparison with other numerical model studies and the field data of THORNTON and GUZA (1986). Figure 3 shows the results of one such test.

The area that is difficult to verify is the predicted turbulence values. Although there have been a number of laboratory studies measuring turbulence in a wave flume there have been none, to the authors' knowledge, measuring depth-averaged values over a two dimensional grid. It is hoped that some studies in the future may provide valuable proving data in this regard.

Although the correct representation of turbulence is important in that it provides a closed set of equations, the resulting flow is relatively insensitive to the actual values of turbulence,
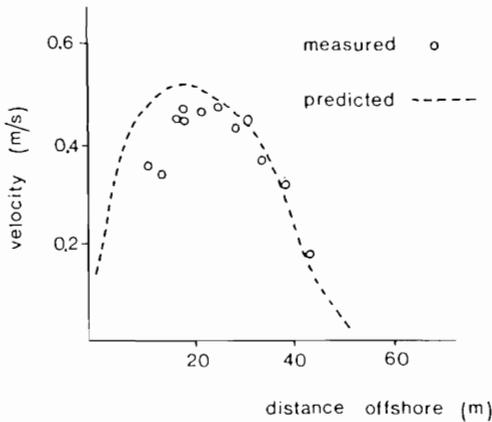
Figure 3. Comparison of measured and predicted longshore velocity profile (Feb. 4, 1980) (from field experiment by Thornton and Guza, 1986).

and depends more on the bottom friction. The early numerical model of LONGUET-HIGGINS (1970) for a plane beach used a simple relationship for turbulence based on the distance from the shore and the water depth. The resulting prediction gave values for turbulence that increased steadily in the offshore direction. The model was criticized on the grounds that the turbulence was known to vanish offshore of the breaker zone, whereas the assumption was for turbulence that continued to grow. The actual differences in the velocity profile calculated by a simple zero equation model and the present two equation model vary only slightly with the greatest difference being at the breaker line. This of course for a simple plane beach. In more complicated situations larger differences are evident.

Whereas the depth-averaged velocity profile can be relatively insensitive to the distribution of turbulence, the behaviour of the suspended sediment depends critically on the general level of turbulence and can provide some measure of testing the accuracy of the turbulence model.

SEDIMENT MODEL

Sediment is transported in the nearshore zone as a combination of bed load and suspended load. Although opinion is divided, it has been recognized that suspended sediment transport will, in many cases, be the major

cause of transport in the nearshore region. Studies carried out by STERNBERG et al. (1984) and KANA and WARD (1980) for example, found that under storm conditions the suspended transport could account for the total transport predicted by the CERC formula.

The derivation of the sediment model assumes high water particle velocities at the bed and under these circumstances it is assumed that suspended sediment load will account for the majority of the transport. It is further assumed that the oscillatory velocities at the bed will be strong enough to wash out any ripples. This will occur when the Shields Number is of the order of 1.0. This latter assumption is used in determining bed level sediment concentrations.

When dealing with suspended transport the turbulence has a major effect, as it is the turbulence, by definition, that supports the grains in the fluid. The suspended sediment equation can be written, after DEIGAARD et al. (1986):

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z}\left(\epsilon \frac{\partial c}{\partial z} + cw\right) \qquad (16)$$

where c is the sediment concentration, w the fall velocity, ϵ the eddy viscosity and z the vertical dimension.

The depth averaged current model gives no details about the vertical distribution of turbulence. Work by DEIGAARD et al. (1986) in deriving the vertical distribution indicates that, in the case of spilling breakers, it is not unreasonable to assume a constant value of turbulence for the top 80% of the flow and a parabolic distribution for the bottom 20% over the vertical. This has been assumed in the present work.

The steady state sediment equation, derived by taking out the time dependency from Equation 16 can be written:

$$\frac{\partial c}{\partial z} = \frac{-wc}{\epsilon} \qquad (17)$$

It is evident from this that if the general magnitude of the eddy viscosity is incorrect the slope of the sediment concentration curve plotted over the depth will also be incorrect. It is therefore possible to gain some confidence in the turbulence figures by using predicted turbulence values in the sediment model. This has been done over a number of data sets collected in the field by NIELSEN (1984). Figure 4 illus-
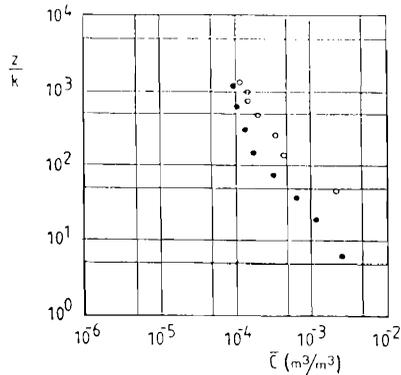
Figure 4. Comparison of predicted (●) and measured (o) sediment concentrations (from Nielsen, 1984). z is the distance from the bed and k, the bed roughness.

trates one such result. In the plot the vertical dimension has been normalized by dividing z, the distance from the bed by k, the bed roughness. In the calculation of these profiles the standard value for C_μ of 0.09 was found to give better agreement than the value of 2.5 proposed following the work of VISSER (1984). The comparison for this and other tests is generally good, especially in sediment modelling terms where agreement within a factor of two is considered good.

The wave-current-sediment model was further verified by comparison with a field study carried out in the North Sea by the DANISH HYDRAULIC INSTITUTE (1984). Figure 5 shows the predicted and measured longshore transport across a section of coastline where natural backfilling of a trench was monitored. The agreement on total longshore transport was good, although there was some variation in the distribution with part of the inaccuracy due, probably, to the simple wave breaking assumptions used in the wave model.

Figure 6 shows how the model predictions of longshore current, eddy viscosity and sediment transport vary across the surfzone for a plane beach. It can be seen that turbulence and longshore current have a maximum near the breaker line. This is important because it suggests that if for any reason the flow is diverted towards the break point region there is likely to be an increase in the volume of sediment transported since the potential to transport sediment is greatest at this point.
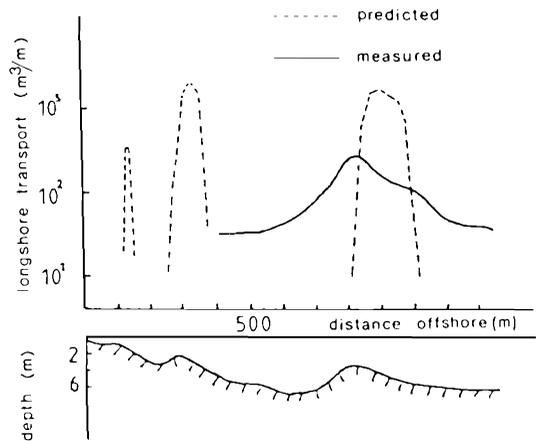

Figure 5. Comparison of predicted and measured longshore transport (from Danish Hydraulics Institute (1984) Investigation).

BATHYMETRIC EVOLUTION MODEL

The bathymetric evolution model assumes that a balance exists between the net sediment transported in and out of a finite area and the change in the bottom elevation of that area. It can be written:

$$\frac{\partial z}{\partial t} + \left(\frac{1}{1-\lambda}\right)\left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y}\right) = 0 \qquad (18)$$

where q_x and q_y are the transports in the x and
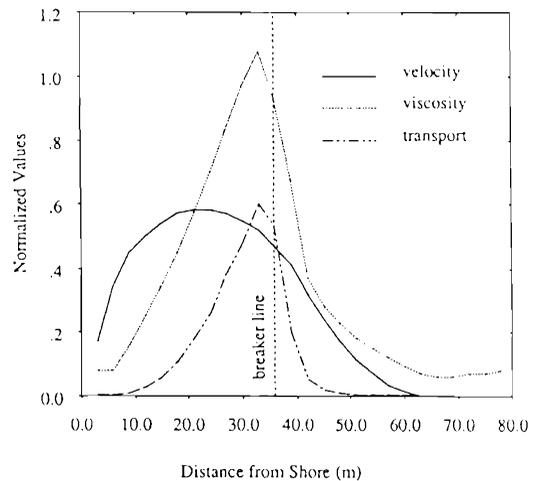

Figure 6. Predicted variations in velocity, eddy viscosity and transport across the surf zone for a plane beach.
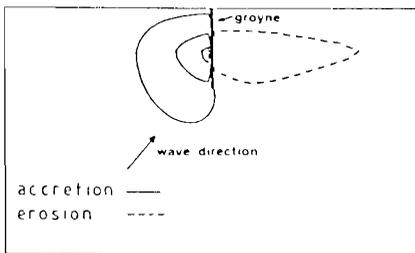
Figure 7. Accretion/erosion zones for X_{br} = 0.5L where X_{br} is the breaker zone width and L, the groyne length.

y direction respectively and λ is the bed porosity, typically between 0.3 and 0.4.

The calculations assume that the sediment will respond quickly to changes in the capacity of the flow to transport sediment resulting in local equilibrium. This question has been considered by O'CONNOR et al. (1981) and it was concluded that with sand in the marine environment this was a reasonable assumption.

Like WATANABE (1982) the total solution shown in Figures 7-9, which are taken from WALKER (1987), has not been iterated after changes have been predicted in the bathymetry.
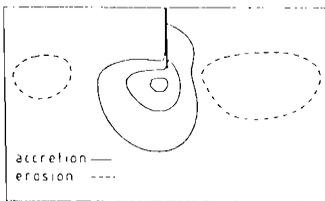

Figure 8. Accretion/erosion Zones for X_{br} = 1.0L where X_{br} is the breaker zone width and L, the groyne length.
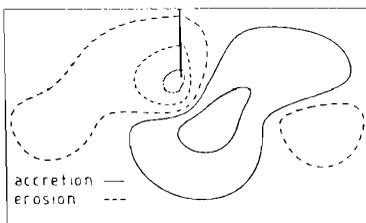

Figure 9. Accretion/erosion zones for X_{br} = 1.5L where X_{br} is the breaker zone width and L, the groyne length.

This is not ideal, and it is planned to incorporate this feature into future runs of the model.

The bathymetric evolution model was run on a number of simulated groyne field situations as part of a study carried out in the U.K. Unfortunately there was no field data with which to compare the predictions. Such data is extremely difficult and expensive to collect. It would be possible to compare the predictions with the results of physical model studies, however, such comparisons must be made with caution since movable bed physical models are notoriously difficult to scale.

The parameter varied in the series of groyne tests was the breaker zone width (X_{br}), which was set as a fraction of the groyne length. Figure 7 shows the accretion and erosion patterns in the case of a relatively narrow breaker zone. It can be seen that the pattern is similar to the typical groyne pattern with a build up of material on the updrift side of the groyne. As the width of the breaker zone is increased the pattern begins to change dramatically. This is illustrated in Figures 8 and 9. There comes a stage where the groyne tends to deflect the nearshore currents to the area where there is higher concentrations of suspended sediment and therefore greater potential for transport. In this case there is increased erosion off the end of the groyne tip leading to accretion downstream of the groyne rather than upstream as would normally be predicted. This sort of behaviour has been observed in physical model studies carried out by HULSBERGEN et al. (1976) although it is not known whether this was caused by this particular effect. The pattern of nearshore currents for the final groyne length are illustrated in Figure 10. In this case the groyne tip is at two thirds the breaker zone width from the shore. The diversion of the flow towards the breaker line is evident.

SUMMARY AND CONCLUSIONS

A numerical model has been presented which allows the effects that a groyne will have on the nearshore bathymetry to be estimated. The model employs sophisticated finite difference models of the wave and nearshore current climate and uses the information provided by these to predict the behaviour of sediment in the region near the structure. The separate submodels have been tested as thoroughly as pos-
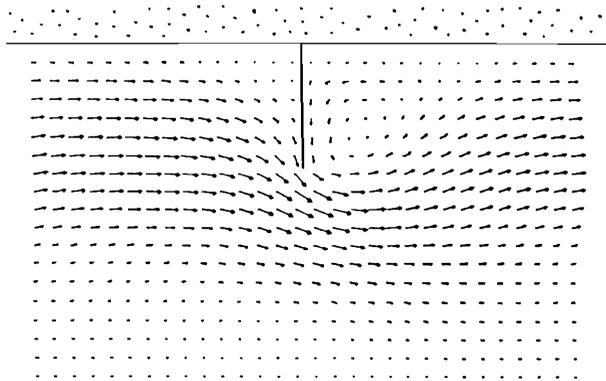
Figure 10. Nearshore currents for $X_{br} = 1.5L$ where X_{br} is the breaker zone width and L, the groyne length.

sible individually. It has not been possible to test the total model against reliable field data where structures were present. Further work is planned on verifying the model with field and laboratory experiments as data become available.

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□ RÉSUMÉ □

On a développé un modèle de l'évolution bathymétrique pour prédire les modifications des fonds dans une zone prélittorale comportant des structures. Ce modèle relève d'un sous-modèle de la houle ayant pour base une approximation hyperbolique de l'équation de la pente douce et, pour les courants prélittoraux, une solution de Navier Stokes avec profondeurs moyennées. Cette solution emploie une double équation (k − ε) du modèle de turbulence, et un sous-modèle qui utilise les niveaux de turbulence prédite pour résoudre l'équation des sédiments en suspension. Les sous-modèles individuels ont été testés sur le terrain et en laboratoire de manière extensive. Le modèle d'ensemble a servi à prédire les effets de la longueur des jetées et leur comportement comme moyen de stabilisation des plages.—*Catherine Bousquet-Bressolier, Géomorphologie EPHE, Montrouge, France.*

□ ZUSAMMENFASSUNG □

Es wurde ein Modell zur Vorhersage der veränderlichen Wassertiefe im strandnahen Bereich unter Einfluß von Küstenbauwerken entwickelt. Das Modell besteht aus einem Hilfsmodell für den Wellengang, basierend auf einer hyperbolischen Annäherung an eine Gleichung für sehr sanfte Böschungen, eine Navier-Stokes-Lösung für die strandnahen Strömungen bei mittlerer Wassertiefe, die auf einem Turbulenzmodell mit zwei Unbekannten (k − ε) beruht, und einem Teilmodell für das Sediment, welches die vorausgesagten Turbulenzniveaus benutzt, um die Gleichung für das Suspensions-material zu lösen. Die einzelnen Teilmodelle wurden ausgiebig unter Benutzung von Feld- und Laboradaten getestet. Das Gesamtmodell wurde benutzt, um den Effekt unterschiedlich langer Buhnen auf die Strandstabilisierung vorherzusagen.—*Dieter Kelletat, Essen, Germany.*

□ RESUMEN □

Se ha desarrollado un modelo de evolución de la batimetría para predecir los cambios del fondo en las zonas próximas a la costa, donde se sitúan las estructuras. El modelo está compuesto por un sub-modelo de oleaje, basado en una aproximación hiperbólica de la mild-slope, una solución de Navier-Stokes integrada en profundidad para corrientes longitudinales, que emplea el modelo de turbulencia de dos ecuaciones (K-ε) y un sub-modelo que usa los niveles de turbulencia predichos para resolver la ecuación que profundidad para corrientes longitudinales, que emplea el modelo de turbulencia de dos ecuaciones (K-ε) y un sub-modelo que usa los niveles de turbulencia predichos para resolver la ecuación que gobierna el sedimento en suspensión. Cada submodelo ha sido chequeado intensivamente usando datos de campo y de laboratorio. El modelo global se ha usado para predecir el efecto de la variación de la longitud de espigones y su comportamiento como método de estabilización de playas.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*