ALS – A COASTAL ENGINEERING MODEL FOR WAVE PROPAGATION, WAVE-STRUCTURE INTERACTION AND BED MORPHOLOGY EVOLUTION

Th. V. Karambas\textsuperscript{1}, E. Koutandos\textsuperscript{2}, N. Kampanis\textsuperscript{2}

\textsuperscript{1} Dept. of Marine Sciences, University of the Aegean, Mytilene, Lesbos, 81 100, GREECE
tel: +30 22510 36840, fax: +30 22510 36809, email: karambas@marine.aegean.gr
\textsuperscript{2} Foundation for Research and Technology-Hellas, Institute of Applied and Computational Mathematics, P.O. Box 1385, 71110, Heraklion, Crete, GREECE
e-mails: ekoutant@iacm.forth.gr, kampanis@iacm.forth.gr

ABSTRACT
In the present work the integrated coastal engineering numerical model ALS is presented (the name ALS becomes from the ancient Greek word \(\alpha\lambda\zeta\) which means sea). The model simulates the linear wave propagation, wave induced circulation, sediment transport and bed morphology evolution. The model consists of three main modules: WAVE-LS, WAVE-L and COAST. The Large Scale module WAVE-LS is based on the numerical solution of the directional wave energy balance equation. The nearshore wave transformation module WAVE-L is based on the hyperbolic type mild slope equation and is valid for a compound wave field near coastal structures where the waves are subjected to the combined effects of shoaling, refraction, diffraction, reflection (total and partial) and breaking. Radiation stress components (estimated from the Large Scale module as well as from the hyperbolic wave module) drive the depth averaged circulation module COAST for the description of the nearshore currents and sediment transport in the surf and swash zone. The module COAST is coupled with a 3D bed evolution module to predict coastal bathymetry changes.

Keywords: Waves, coastal structures, sediment transport, morphology evolution, numerical model.

1. INTRODUCTION
Accurate numerical modelling of water wave propagation from offshore to coastal regions is of paramount importance to coastal, port and environmental engineers. Such models can greatly simplify and expedite the design of coastal structures and the evaluation of their influence on the surrounding environment. An integrated approach includes also the estimation of the wave induced current field, the sediment transport and the bottom topography changes in the coastal areas due to the action of the waves. Basic to the description of these processes is the incorporation of the wave breaking (into the wave model) and the formulation of the driving forces (radiation stress) from the wave model results.

On the other hand simple shoreline change models are widely used as tools in coastal engineering projects to predict shoreline changes associated with coastal structures or storm effects over the long term. These models are based on the single line theory and they have the advantage of being very fast. However, they cannot predict bed level changes and also the impact of morphological changes in the vicinity of coastal structures that are due to short-term storms. An integrated approach has to involve the modeling of the whole suite of elementary processes responsible for the local morphological changes in a given area, Leont’yev (1999).
An integrated coastal engineering model consists of several modules describing the wave field, the spatial distribution of wave-induced currents, the associated sediment transport fluxes, and finally the resulting spatial and temporal changes of the bed level.

In the present work the integrated coastal engineering numerical model ALS is presented (the name ALS becomes from the ancient Greek word αλς which means sea). The model consists of three main modules: WAVE-LS, WAVE-L and COAST. The Large Scale module WAVE-LS is based on the numerical solution of the directional wave energy balance equation. The nearshore wave propagation module WAVE-L is based on the hyperbolic type mild slope equation and it is valid for a compound wave field. The model, after the incorporation of breaking and the evaluation of the radiation stress, drives the depth-averaged circulation and sediment transport module COAST for the description of the nearshore currents and beach deformation.

2. MODELS DESCRIPTION
2.1. LARGE SCALE MODULE WAVE-LS
The proposed Large Scale wave propagation module is used to estimate wave conditions in large coastal regions with horizontal scales 20–30 km and water depth less than 50-60 m. The module is based on the directional wave energy balance equation (Booij et al, 1999, Holthuijn et al, 2003):

\[
\frac{\partial E}{\partial t} + \frac{\partial c_x E}{\partial x} + \frac{\partial c_y E}{\partial y} + \frac{\partial c_\theta E}{\partial \theta} = -D
\]  

where \( E(f,\theta;x,y;t) \) is the spectral density of frequency \( f \) and direction \( \theta \), at a point \((x,y)\) and time \( t \), \( c_x, c_y \) and \( c_\theta \) are the \( x, y \) and \( \theta \) components of group velocity \( c_g \) \((c_x = c_g \sin \theta, c_y = c_g \cos \theta, c_\theta = c_g \)) , 
\[ c_\theta = -\frac{c_g}{c} \left( \cos \theta \frac{\partial c}{\partial x} - \sin \theta \frac{\partial c}{\partial y} \right), \]
where \( c \) is the wave celerity and \( D \) the wave energy dissipation due to wave breaking: 
\[ D = \frac{1}{4} Q_b \rho g H_m^2, \]

The numerical solution is based on implicit finite difference scheme according to:

\[
\n
\]
\[ \frac{E^n_{i,j,m} - E^{n-1}_{i,j,m}}{\Delta t} + \frac{\Delta x}{\Delta y} \left( c_x E^n_{i-1,j,m} - c_x E^n_{i,j,m} \right) + \frac{\Delta y}{\Delta y} \left( c_y E^n_{i,j,m} - c_y E^n_{i,j-1,m} \right) + \frac{0.5 \left[ c_{\theta} E^n_{i,j,m+1} + c_{\theta} E^n_{i,j,m-1} \right] - 1.5 \left[ c_{\theta} E^n_{i,j,m-1} \right]}{2 \Delta \theta} = -D^n_{i,j,m} \]

where \(i,j\) and \(m\) are the grid counters, \(n\) represents the values at the current time step and \(\Delta t\), \(\Delta x\), \(\Delta y\) are the time, space and directional discretisation steps, respectively.

The above backward differences are applied for positive values of \(c_x\), \(c_y\) and \(c_{\theta}\). For negative values of \(c_x\), \(c_y\) and \(c_{\theta}\) forward differences are used.

The linear system of equations is solved using an iterative procedure. The predicted values of \(E\) are obtained from:

\[ \frac{E^n_{i,j,m} - E^{n-1}_{i,j,m}}{\Delta t} + \frac{\Delta x}{\Delta y} \left( c_x E^n_{i-1,j,m} - c_x E^n_{i,j,m} \right) + \frac{\Delta y}{\Delta y} \left( c_y E^n_{i,j,m} - c_y E^n_{i,j-1,m} \right) + \frac{0.5 \left[ c_{\theta} E^n_{i,j,m+1} + c_{\theta} E^n_{i,j,m-1} \right] - 1.5 \left[ c_{\theta} E^n_{i,j,m-1} \right]}{2 \Delta \theta} = -D^n_{i,j,m} \]

The iterative procedure is considered complete when the relative differences in \(E\) between two iterations \(k\) and \(k+1\) are \(<10^{-6}\). The relative difference is defined as \(\sum_{i,j} \left| E_{i,j}^{k+1} - E_{i,j}^k \right| / \sum_{i,j} \left| E_{i,j}^{k+1} \right|\). After the first time steps only one iteration is usually required.

The results of the WAVE-LS module are used as input for the nearshore wave transformation module WAVE-L described in the next paragraph.

### 2.2 NEARSHORE WAVE TRANSFORMATION MODULE WAVE-L

Although diffraction effects have been incorporated in the above module (WAVE-LS), much better results are expected from the application of mild-slope models (Copeland, 1985a, Watanabe and Maruyama, 1986), since their equations have been derived without the assumption of progressive waves (as in the case of equation 1). In addition mild-slope models are able to describe (partial and total) wave reflection from coastal structures.

The present module is based on the hyperbolic type mild slope equation and is valid for a compound wave field near coastal structures where the waves are subjected to the combined effects of shoaling, refraction, diffraction, reflection (total and partial) and breaking. The module consists of the following pair of equations (Copeland, 1985a, Watanabe and Maruyama, 1986):

\[ \frac{\partial \eta}{\partial t} + \frac{c}{c_g} \nabla \cdot Q_w = 0 \]

\[ \frac{\partial U_w}{\partial t} + \frac{c^2}{d} \nabla \eta = 0 \]  

(6)

where \(\eta\) is the surface elevation, \(U_w\) the mean velocity vector \(U_w = (U_w, V_w)\), \(d\) the depth, \(Q_w = U_w h_w = (Q_{w1}, P_w)\), \(h_w\) the total depth \((h_w = d + \eta)\), \(c\) the celerity and \(c_g\) the group velocity.

The model is extended in the surf zone in order to include breaking effects providing the equations with a suitable dissipation mechanism by the introduction of a dispersion term in the right-hand side of momentum equation (6):

\[ \nu_h = \nabla^2 U_w \]  

(7)
where $v_h$ is an horizontal eddy viscosity coefficient estimated from Battjes (1975):

$$v_h = 2d(D/\rho)^{1/3} \text{ (with } D = \frac{I}{4}Q_s f \rho g H_m^2).$$

The mean square wave height $H_{rms}$ in equation (2) is estimated from $H_{rms} = 2 \langle \zeta_w^2 \rangle^{1/2}$ and the brackets $\langle \rangle$ denote a time mean quantity.

The numerical model is adapted for engineering applications:

1. The input wave is introduced in a line inside the computational domain according to Larsen and Dancy (1983) and Lee and Suh (1998).
2. A sponge layer boundary condition is used to absorb the outgoing waves in the four sides of the domain (Larsen and Dancy, 1983).
3. Total reflection boundary condition ($U_w$ or $V_w = 0$) due to the existence of vertical structures is incorporated in the model.
4. Partial reflection is also simulated by introducing an artificial eddy viscosity coefficient $v_h$. The values of $v_h$ are estimated from the method developed by Karambas and Bowers (1996), using the values of the reflection coefficients proposed by Bruun (1985).
5. Submerged structures are incorporated as in Karambas and Kriezi (1997).
6. Floating structures are incorporated as in Koutandos et al. (2002, 2004).

For the numerical solution a simple classical, well documented, explicit 2nd order finite difference staggered scheme and a mid-time method is adopted (Watanabe and Maruyama, 1986, Koutitas, 1988).

### 2.3 WAVE-INDUCED CIRCULATION (MODULE COAST)

The depth and shortwave-averaged 2D continuity and momentum equations are used for simulating nearshore currents in the coastal zone:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (Uh)}{\partial x} + \frac{\partial (Vh)}{\partial y} = 0$$

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + g \frac{\partial \zeta}{\partial x} = - \frac{1}{\rho h} \left( \frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \right) + \frac{1}{\rho h} \left( v_h \frac{\partial U}{\partial x} \right) + \frac{1}{\rho h} \left( v_h \frac{\partial U}{\partial y} \right) - \frac{\tau_{hx}}{\rho h}$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + g \frac{\partial \zeta}{\partial y} = - \frac{1}{\rho h} \left( \frac{\partial S_{yy}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \right) + \frac{1}{\rho h} \left( v_h \frac{\partial V}{\partial x} \right) + \frac{1}{\rho h} \left( v_h \frac{\partial V}{\partial y} \right) - \frac{\tau_{hy}}{\rho h}$$

where $S_{xx}, S_{yy}$ and $S_{xy}$ are the radiation stresses, $\zeta$ is the mean water surface elevation, $h$ is the total depth $h=d+\zeta$, $U$, $V$ are the current horizontal velocities and $\tau_{hx}$ and $\tau_{hy}$ are the bottom shear stresses.

Using linear wave theory, (Copeland, 1985b) derived the expressions for radiation stresses $S_{ij}$ without the assumption of progressive waves:

$$\frac{S_{xx}}{\rho} = d^2 < U_{w}^2 >A_d - d^2 \left( \frac{\partial U_{w}}{\partial x} + \frac{\partial V_{w}}{\partial y} \right)^2 > B_d + \frac{\partial}{\partial x} \left[ U_{w} \left( \frac{\partial U_{w}}{\partial x} + \frac{\partial V_{w}}{\partial y} \right) \right] > D_d + 1 \frac{g}{2} < \eta^2 >$$
\[
\frac{S_{xy}}{\rho} = d^2 \left< V_w^2 \right> - A_i - d^2 \left< \left( \frac{\partial U_w}{\partial x} + \frac{\partial V_w}{\partial y} \right)^2 \right> B_i + d^2 \cdot \frac{\partial}{\partial y} \left[ V_w \left( \frac{\partial U_w}{\partial x} + \frac{\partial V_w}{\partial y} \right) \right] \left< V_w \right> = D_i + \frac{1}{2} \xi^2 \left< \eta^2 \right>
\]

\[
\frac{S_{xy}}{\rho} = d^2 \left< V_w^2 \right> > A_i
\]

\[
A_i = \frac{k}{4 \sinh^2 kd} (\sinh 2kd + 2kd)
\]

\[
B_i = \frac{1}{4k \sinh kd} (\sinh 2kd - 2kd)
\]

\[
D_i = \frac{d}{4 \sinh^2 kd} \left( \frac{1}{2kd} \sinh 2kd - \cosh 2kd \right)
\] (9)

When the module WAVE-LS is applied radiation stresses are calculated by the classical well known expressions valid for progressive waves in terms of the wave height, the wave number and the wave propagation direction (Leont’yev, 1999).

In a current model the treatment of the bottom stress is critical. The general expression for the time-average bottom shear stress in the current model is written:

\[
\tau_{bx} = \rho C_f \left< (U + u_b) \sqrt{(U + u_b)^2 + (V + v_b)^2} \right>
\]

\[
\tau_{by} = \rho C_f \left< (V + v_b) \sqrt{(U + u_b)^2 + (V + v_b)^2} \right>
\] (10)

where \( C_f \) is the friction coefficient which depends on the bottom roughness and on the orbital amplitude at the bed, and \( u_b \) and \( v_b \) are the wave velocities at the bottom (Leont’yev, 1999).

Inside surf zone the existence of the undertow current that is directed offshore cannot predicted by a depth averaged model. However, representing the cross-shore flow is essential for a realistic description of the sediment transport processes. In the present model Quasi-3D effects are introduced by considering the analytical expression for the vertical distribution of the cross-shore flow below wave trough level proposed by Stive and Wind (1986):

\[
v_u = \frac{1}{2} \left[ (\xi - 1)^2 - \frac{1}{3} \right] \frac{h - \zeta}{\rho v_r} \frac{dR}{dy} + \left( \frac{h - \zeta}{2} \right) \frac{h - \zeta}{\rho v_r} \frac{dR}{dy} - \frac{M \cos \Theta}{h - \zeta}
\] (11)

where \( v_u \) is the undertow velocity in the y (shore-normal) direction, \( \xi = z/(h - \zeta) \). \( \zeta \) is the wave trough level, \( dR/dy = 0.14 \rho g dh/dy \). \( \tau_r \) is the shear stress at the wave trough level (Stive and Wind, 1986), \( M \) is the wave mass flux above trough level (including surface roller effects), \( \Theta \) is the direction of the wave propagation and \( v_r \) the eddy viscosity coefficient according to De Vried and Stive (1987): \( v_r = 0.025h(D/\rho)^{1/3} \). The direction of the wave propagation \( \Theta \) is given by: \( \Theta = \arctan \left[ (\langle Q_w^2 \rangle / \langle P_w^2 \rangle)^{1/2} \right] \).

For the numerical solution again the above mentioned explicit finite difference scheme is used (Watanabe and Maruyama, 1986, Koutitas, 1988).

2.4. SEDIMENT TRANSPORT SUBMODEL COAST

The prediction of the sediment transport is based on the energetics approach, in which the submerged weight transport rates, \( i_{xt} \) in the x direction and \( i_{yt} \) in the y direction, are given by Karambas (2002):
where \( w \) is the sediment fall velocity, \( \phi \) is the angle of internal friction, \( \varepsilon_b \) and \( \varepsilon_s \) are the bed and suspended load efficiency factors respectively (\( \varepsilon_b = 0.13 \), \( \varepsilon_s = 0.01 \)), \( u_{ot} = \sqrt{u_o^2 + v_o^2} \) (\( u_o, v_o \) are the total flow velocities at the bottom), \( d_s \) and \( d_x \) are the bottom slopes \( \omega_b = C_f \rho u_{ot}^3 \), and \( \omega_i \) is the total rate of energy dissipation given by Leont’yev (1996):

\[
\omega_i = \omega_b + D e^{3/2(1-b/H)}
\]

in which \( H \) is the wave height (\( H = H_{rms} \)), \( D \) is the mean rate of breaking wave energy dissipation per unit area.

In equation (13) the first term express the power expenditures due to bed friction while the second due to excess turbulence penetrating into bottom layer from breaking waves.

The total flow velocity at the bottom is considered as a sum of the steady \( U, V, v_{ub} \) and the oscillatory \( u_b, v_b \) components which include two harmonics:

\[
u_o = U + u_{bm} \cos(\omega t) + u_{b2m} \cos(2\omega t)
\]
\[
v_o = V + v_{ub} + v_{bm} \cos(\omega t) + v_{b2m} \cos(2\omega t + a)
\]

in which \( v_{ub} \) is the near bottom undertow velocity (equation 11 with \( z = -d \)), \( \omega \) is the wave frequency, \( a \) is the phase shift and \( u_{bm}, u_{b2m}, v_{bm}, v_{b2m} \) are the velocity amplitudes given by Leont’yev (1996, 1999).

Adopting the procedure proposed by Leont’yev (1996) the submerged weight transport rates \( i_{ys} \) near the shoreline, in the \( y \) (shore-normal) direction, is given by:

\[
i_{ys} = f R \left( \frac{\tan \phi}{2\tan^2 \phi} \right) u_R^3 \tan \beta_{eq} - \tan \beta \)
\]

where \( f_R \) is the run-up friction coefficient (of order \( 10^{-1}-10^{-3} \)), \( u_R \) is the flow velocity in the swash zone, \( \tan \beta \) is the actual slope gradient and \( \tan \beta_{eq} \) is the slope under equilibrium state approximated by (Yamamoto et al., 1996):

\[
\tan \beta_{eq} = \left( \frac{0.0864 s d_{50} T^2}{H_b^2} \right)^{2/3}
\]

where \( s \) is the specific gravity of sediment in water, \( d_{50} \) is the median grain size, \( H_b \) is the breaker height and \( T \) the wave period.

The flow velocity in the swash zone \( u_R \) is parameterized in terms of the run-up height \( R \) according to Leont’yev (1996): \( u_R = (2g (R - z_e)) \), where \( z_e \) is the height of water mass above the water level which increases proportionally to the distance from the upper run-up boundary. If the bottom gradient exceeds the equilibrium value then \( i_{ys} < 0 \) (erosion). In opposite case \( i_{ys} > 0 \) (accretion).

The longshore \( (x) \) direction total swash sediment transport \( i_{xs} \) is calculated by the global expression proposed by Briad and Kamphuis (1993).
3. BED EVOLUTION SUBMODEL
The model COAST is coupled with a 3D bed evolution model or with a one-line model to provide bathymetry or shoreline changes.

The nearshore morphological changes are calculated by solving the conservation of sediment transport equation (Leont’yev, 1996):

\[
\frac{\partial z_b}{\partial t} = -\frac{\partial}{\partial x} \left( q_x - 2q_x \frac{\partial z_b}{\partial x} \right) - \frac{\partial}{\partial y} \left( q_y - 2q_y \frac{\partial z_b}{\partial y} \right)
\]

(17)

where \(z_b\) is the local bottom elevation and \(q_x, q_y\) are the volumetric longshore and cross-shore sediment transport rates, related to the immersed weight sediment transport through:

\[
q_{x,y} = \frac{i_{x,y}}{(\rho_s - \rho)gN}
\]

(18)
in which \(N\) is the volume concentration of solids of the sediment (\(N = 0.6\)) and \(\rho_s\) and \(\rho\) are the sediment and fluid densities.

4. APPLICATIONS
The wave and the wave-induced circulation modules had been tested against experimental data for diffraction, refraction, reflection, shoaling, breaking, dissipation after breaking of regular waves, as well as for the breaking wave induced current in previous works (Karambas and Bowers, 1996, Karambas and Koutitas, 1996, Karambas and Kriezi, 1997).

In order to verify the bed morphology evolution submodel (coupled with the submodels WAVE-L and COAST), we try to simulate the beach evolution at Rethymno Eastern coast (N. Crete, Greece). After the construction and the extension of the breakwater (Figure 1) shoreline changes (erosion and accretion) had been recorded.

Since wave data were not available, a hindcast procedure is used. The main incident wind directions are: N, NE and NW. The equivalent wave height \(H_e\) on an annual basis are set according to Borah and Balloffet, (1985) as following:
\[ H_e^2 T = \frac{\sum H_i^2 T_i f_i}{\sum f_i} \]  

(19)

where \( T \) is the equivalent wave period, \( H_i, T_i, f_i \) are the height, the period and the frequency of the waves that correspond on the various levels of wind intensity from each incident direction.

Figure 2. A snapshot of the computed free surface elevation of obliquely incident waves (NW direction, \( H_e=2.1 \text{m}, T=6.77 \text{ s} \)) in Rethymno Eastern coast area.

Figure 3. Breaking wave induced current field due to NW waves.

The equivalent wave is actually the wave that appears with the frequency \( \sum f_i \) and includes the same wave energy with the series of the waves of various intensity of the specific direction. Using the wind data from the specific area from the Greek Metereological Service and applying the JONSWAP wave prediction method the significant wave heights \( H_e \), the periods \( T \) and the frequencies of the equivalent open sea waves were deduced.
Large scale module WAVE-LS is applied to calculate wave height and direction in deep and intermediate waters. The results are used as input to the nearshore module WAVE-L.

Figure 2 shows the computed free surface elevation (module WAVE-L) of obliquely incident waves (NW direction, $H_s=2.1\,\text{m}$, $T=6.77\,\text{s}$). Wave refraction, diffraction, partial reflection, breaking and dissipation after breaking are shown.

In Figure 3 breaking wave induced current field is shown (module COAST). Figure 4 shows the comparison between shoreline field measurements and model results, 5 years after the extension of the breakwater. The shoreline changes are well predicted by the model.

![Figure 4. Shoreline change in Rethymno Eastern coast: comparison between model results and field measurements 5 years after the extension of the breakwater.](image)

5. CONCLUSIONS

A coastal engineering model for the description of wave propagation, wave induced circulation and bed morphology evolution has been proposed. The proposed model ALS can be applied in complex bathymetries and topographies in the vicinity of coastal structures. Based on the results of the wave and the wave-induced circulation modules bed level changes are simulated using a three-dimensional morphodynamical model. The ALS model was successfully applied to the Rethymno Eastern coast area, where significant shoreline changes has been recorder last 5 years. When compared with the field measurements, the model results are considered to be good. It is deduced that the model can be used as a design tool for coastal engineering structures (harbours, marinas, coastal protection structures) and the evaluation of their influence on the surrounding environment as far as morphological changes are concerned.

ACKNOWLEDGEMENTS

The authors acknowledges the financial support of EU through the INTERREG IIIC program “Beachmed-e”.

REFERENCES


