Sloping beach with wave breaking and moving shoreline on Romanian Black Sea coast

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Abstract. Purpose of the work: wave breaking and wave run-up on a gently sloping plane beach from Romanian Black Sea Coast. That coast has a length of 244 km and an almost linear configuration with the exception of build-up areas. The paper concentrates on shoaling of regular waves and spilling type of wave breaking running with a simulation on software MIKE 21. Research and methodology: the paper contents the measurements for spilling and plunging type of breakers on a plane sloping beach with a slope of 1/45 starting in depth of 0.23 m to 0.46 m. A moving shoreline is included in the simulations. With respect to the parameters of the breaker model the standard values are applied. An explicit filter is introduced near the still water shoreline to remove short-wave instabilities and to dissipate the wave energy in the model. Results: the obtained values indicate the wave breaking and wave run-up processes, the spatial variation of a number of phase-averaged quantities and the shoreline motion converted intro a vertical and a horizontal displacement.

1. Description of the area studied
Romanian Black Sea coastline length is 244 kilometers, representing 7.65% the length of the border. Seaside is divided into two main sectors: north and south. The northern area (approximately 164 km long) stretches from the Musura Gulf to Cape Midia, including the Danube Delta Biosphere Reserve and Razim-Sinoe Lake. It is characterized by sandy beaches, low altitudes and steep slopes submarine least. The southern area (80 km) lies between Cape Midia and Vama Veche, being covered predominantly limestone cliffs of varying heights, between 3-35 meters shorter sectors sandy beaches to harbours right (Midia, Constanța, Mangalia) and slopes Submarine steeper than in the north. Romanian coastal zone is subject to permanent processes erosion phenomenon emphasizing the last 30 years following the construction of the Iron Gates dam lakes I and II, in this way the amount of sediments from the Danube Black Sea reduced to half and disturbing coastal sediment balance. This case may be added and decreased intake of beach sediment surfaces, general loss of sediment by constructing dams due port, sea walls collapse due to geotechnical instability areas located at the top of the slopes and /or wave action based on the cliffs. The extent of erosion coastal differs from one sector to another. Predominant directions of propagation of waves are in the North East and East. For waves higher than 1.5 m average direction is 68º. Extreme waves (probability of occurrence in 100 years) were estimated by peaks over threshold method. The storm surge (felt $H_s = 3.5$ m). For 46 storms recorded in 11 years were obtained the results listed in table 1.
Table 1. Estimates of amplitude and period of extreme values.

| Period repeatability (year) | Wave height (m) | Wave period (s) |
|----------------------------|-----------------|-----------------|
| 5 years                    | 6.08            | 9.9             |
| 10 years                   | 6.52            | 10.2            |
| 50 years                   | 7.45            | 10.8            |
| 100 years                  | 7.83            | 11.0            |

Measurements made at Gloria Platform showed that the value overall height direction independent of the centennial large waves (with repeatability once every 100 years) is 14.2 m in the direction N and 5.7 m in the direction of SV.

2. Simulation for sloping beach with wave breaking and moving shoreline on Romanian Black Sea coast using MIKE Zero

For this simulation we will choose the south sector of the Romanian Black Sea coast with the bathymetry from the figure 1.

Figure 1. Bathymetry of south sector.

The paper concentrates on shoaling of regular waves and spilling type of wave breaking running with MIKE 21BW (Boussinesq Waves) [4]. In figure 2 we will see the first page of MIKE BW where are presented in the left side the steps for this simulation. We must complete each step to get the desired results.
In this paper we use the measurements for spilling and plunging type of breakers on a plane sloping beach with a slope of 1/45 starting in depth of 0.3 m to 0.46 m [1], [5]. Waves are generated at internal points by source terms, representing the volume flux in progressive waves. The wave period is 1.75 s and the height wave annual average is 0.23 m (on Mangalia) to 0.46 m (Constanta on the isobath to 10 m, theoretical value) and measured height wave annual average value is 1.248 m [5]. The seaward boundary is treated as nonreflective, using sponge layer (100 points).

A moving shoreline is included in the simulations, using a slot width of Ɛ=0.01 and a smoothing parameter of β=100 (default values in MIKE 21). A 50 point wide sponge layer is used in the slot in order to damp the oscillations in the slot. With respect to the parameters of the breaker model the following standard (default) values are applied: initial breaking angle $\phi_b=20^\circ$, final breaking angle $\phi_o=20^\circ$, half-time for cut-off roller $t_{1/2}=T/5=0.4$ and roller form factor $f_\delta=1.5$. An explicit filter is introduced near the still water shoreline to remove short-wave instabilities during uprush and downrush and to dissipate the wave energy in the model where the surface roller cannot be resolved. The main results indicate the wave breaking and wave run-up processes, the spatial variation of a number of phase-averaged quantities and of course the shoreline motion converted into a vertical and a horizontal displacement.

2.1. Basic parameters

First we need to choose the module to work. We choose 1D module (figure 3). The 2DH module (two horizontal space coordinates) solves the enhanced Boussinesq equations by an implicit finite difference techniques with variable defined on a space-staggered rectangular grid. This module is typically selected for calculation of short and long period wave disturbance in ports and harbours. The 1DH module (one horizontal space coordinate) solves the enhanced Boussinesq equations by a standard Galerkin finite element method with mixed interpolation. This module is typically selected for calculation of wave transformation from offshore to the beach for studying surf zone and swash zone dynamics.
2.1.1. Bathymetry. Next we create a suitable model of bathymetry (figure 4). This is essential for obtaining reliable results from our model. Setting up the bathymetry requires more than just specifying a 2D/1D array of accurate water depths covering the area of interest. It also includes the appropriate selection of the area to be modelled, the grid spacing, location and type of boundaries etc.

We can start a simulation as a cold start (figure 5). For this, the flux is initialized to zero. When choosing this option we have to specify a 2D grid for 2DH applications (type 2 data file with extension dfs2 or dt2) or a 1D profile for 1DH applications (type 1 data file with extension dfs1) containing the bathymetry/mesh [3], [4]. When setting up the bathymetry it should be kept in mind that the bathymetry water depths determines which wave conditions that can be modelled. The maximum water depths restrict the minimum wave period that can be modelled and the minimum water depth may restrict the wave height if wave breaking is not included. Further, shallow water results in small wave lengths which imply small grid spacing which again results in increased CPU time. Therefore it can be necessary to modify the bathymetry to reach an acceptable compromise between a correct bathymetry and correct wave conditions.
2.1.2. Type of equation. MIKE 21 BW solves the classical form and an enhanced form of the Boussinesq equations. The enhanced equations are different from the classical formulation as a number of new Boussinesq correction terms (so-called deep water terms) are included (figure 6). The major restriction of the classical form of the Boussinesq equations is the shallow water limitation in terms of the water depth to deep water wave length ratio, $h/L_0$. Celerity errors gradually increase for increasing $h/L_0$, and 5 % is reached for $h/L_0 = 0.22$, which is often taken as the practical deep water limit for these equations. The new form of the Boussinesq equations incorporates a significant improvement of the dispersion relations, which makes it possible to use the new equations to simulate the propagation of irregular wave trains in shallow to deep water up to a depth to deep water wave length ratio, $h/L_0$, of 0.5. For dispersion factor, most practical applications a value of $B = 1/15 = 0.067$ is applied.

\begin{align}
  n \frac{\partial \xi}{\partial t} + \frac{\partial P}{\partial x} &= 0 \\
  n \frac{\partial P}{\partial t} + \frac{\partial}{\partial x} \left( \frac{P^2}{h} \right) + \frac{\partial R_{\alpha\xi}}{\partial x} + n^2 g h \frac{\partial \xi}{\partial x} - n \left( B + \frac{1}{3} \right) d^2 \frac{\partial^3 P}{\partial x \partial \xi \partial t} \\
  - \frac{1}{3} d \frac{\partial^2 d}{\partial x \partial t} - n^2 B g d^2 \frac{\partial w}{\partial x} + n^2 P \left( \alpha + \beta \frac{|P|}{h} \right) + \frac{g P |P|}{h^2 C^2} &= 0
\end{align}

Figure 5. Bathymetry step.

Figure 6. Type of equation.

In this module for solving the equations we use finite element techniques and one of the problems is the presence of higher-order spatial derivatives. To fix this problem we using an approach where the Boussinesq type equations are written in a lower order form by introducing a new auxiliary variable $w$ and an auxiliary algebraic equation. The governing equations (1), (2), (3) then have the following form [4]:
In these equations we have terms with second order derivatives with respect to the spatial coordinates. Recasting these equations into a weak form using the standard Galerkin finite element method and applying the divergence theorem to the dispersive Boussinesq type terms, the equations can be written in a form which only requires the interpolation functions to be continuous [2], [3], [4].

2.1.3. Simulation Period. On the simulation period dialog we specify information on (figure 7):
number of time steps; time step interval and warm-up period.
Further, we must specify date and time for the simulation. The number of time steps is the total simulation time divided by the time step. The total simulation time should allow for waves to reach all model areas and from this time (start-up period) the simulation should continue at least 15-20 min for calculation of statistical parameters such as the significant wave height, $H_{m0}$. If the study includes investigation of e.g. long periodic wave disturbance (e.g. harbour resonance and seiching) or wave-induced currents the simulation time should be longer [2], [5]. For our wave application the simulation time is 50 minutes.

The Courant Number [1] is an expression which describes the number of grid points that wave information will travel in one time step. It is defined as follows (4):

$$Cr = c \frac{\Delta t}{\Delta x},$$

where $c$ is the wave propagation speed (or celerity), $\Delta t$ is the time step, and $\Delta x$ is the spatial resolution. The Courant number should always be equal to, or less than, 1 in 2D applications and less than about 0.5 in 1D applications.

The warm-up period is a period where the forcing functions (boundary conditions) gradually are built up to their prescribed value. Often a warm-up period can be used to avoid blow-ups during the first time steps. In case of application with moving shoreline (1DH and 2DH) a warm-up period is most often required. We consider a warm-up period corresponding to 5-10 characteristic (peak) wave periods. The warm-up period should not be confused with the ‘start-up’ period discussed under wave disturbance calculation.

![Simulation Period](image)

**Figure 7.** Simulation period.
2.1.4. Boundary. In most cases the boundary positions as detected by the model may be used. But in special cases we might want to define the positions explicitly. This can be due to internal boundaries, a boundary stretching over a series of small islands etc. The model requires to specify either the surface elevation or the flux at all open boundaries. For our simulation we exclude boundary [2], [3].

2.2. Calibration

2.2.1. Bottom friction. Usually the effects of bottom friction are relatively unimportant in simulation of short waves in ports and harbours. This is because the area covered by most short wave models is relatively small (typically less than a few square km's), and with the exception of high waves and/or very shallow water there is usually not a sufficient distance for the bed resistance to attain any significant effect on short wave propagation. In our application the bed resistance can be excluded (figure 8), without the need for detailed evaluations.

![Figure 8. Bottom friction.](image)

2.2.2. Filter. An explicit numerical lowpass filter is introduced to remove high-frequency instabilities during uprush and downrush and to dissipate the wave energy in the area where the surface roller can not be resolved. Because we have included wave breaking and moving shoreline in our simulation we also have to specify a data file including filter coefficients. Near the still water shoreline it is recommended to use a filter coefficient between 0 and 1, eg. 0.25 or 0.5. Outside this area the filter coefficient will be zero (no filtering) (figure 9).

![Figure 9. Filter.](image)
The wave breaking is assumed initiated if the slope of the local water surface exceeds a certain angle, in which case the geometry of the surface roller is determined. The roller is considered as a passive bulk of water isolated from the rest of the wave motion, while being transported with the wave celerity. The influence of the roller is taken into account through an additional convective momentum term arising from the non-uniform vertical distribution of the horizontal velocity.

- **Roller form factor.** The roller thickness is determined as the water above the tangent of slope and the resulting thickness is multiplied by a form or shape factor. The default value is 1.5.
- **Type of roller celerity.** The roller celerity is assumed to be proportional to the linear shallow water celerity. The roller direction can either be determined interactively from the instantaneous wave field (type 1) or set to a prescribed wave direction (type 3). The first procedure (type 1) may sometime cause stability problems why the second type is usually recommended.
- **Roller celerity factor.** For the type 1 of roller celerity the default factor is 1.3.
- **Initial breaking angle.** Breaking is predicted to occur when the local slope of the surface elevation exceeds the initial breaking angle. The default value is 20°.
- **Final breaking angle.** During the transition from the initial breaking to a bore-like stage in the inner surf zone, the critical angle is assumed to change gradually from the initial breaking angle to a smaller terminal angle, the final breaking angle. The default value is 10 degrees.
- **Half-time for cut-off roller.** This time defines the transition between the two breaker. The default value is $T_p/5$, where $T_p$ is the wave period of the most energetic wave components.
- **Wave direction.** This direction is the main or characteristic wave propagation direction of the breaking waves relative to true North. Our direction is 45° corresponding to waves from North East (figure 10).

![Wave Breaking](image)

**Figure 10.** Wave breaking.

2.2.3. **Moving shoreline.** The incorporation of a moving shoreline in MIKE 21 BW is based on the following approach: the computation domain is extended artificially by replacing the solid beach by a permeable beach characterised by a very small porosity. Near the moving shoreline the water surface will insect with the sea bed and continue into the porous beach. Hence the instantaneous position of the shoreline is simply determined by this intersection.

- **Slot depth.** In practice the slot depth is normally chosen as the datum of the toe of the slope. It is important to keep slot so deep that it is not dried out during a downrush.
- **Slot width.** In principle the slot width (or the minimum porosity) should be as small as possible in order to avoid a distortion of the mass balance and a disturbance of the flow in the
physical domain. On the other hand, the numerical solution becomes unstable for extreme values of the slot width. In practice, it turns out that the slot width should be chosen in the interval of 0.01 to 0.001. For steep slopes an even higher slot width is sometimes required. Too high values of the slot width may results in an underestimation of the run-up.

- **Slot smoothing parameter.** In principle the slot smoothing parameter should be as large as possible in order to avoid a distortion of the mass balance and a disturbance of the flow in the physical domain. On the other hand, the numerical solution becomes unstable for extreme values of the slot smoothing parameter. In practice, it turns out that the parameter should be order of 100. For steep slopes a small slot smoothing parameter is sometimes required. Too small values of the parameter width may results in an underestimation of the run-up.

- **Slot friction coefficient.** We set this parameter to zero. Non-zero values may damp out high-frequency noise, but may also end up in an underestimation of the run-up (figure 11).

*Figure 11. Moving shoreline.*

2.2.4. **Porosity.** Porosity values are used to model either partial reflection and/or transmission through structures. If porosity values are backed up by land, partial reflection will take place. Conversely, (partial) transmission will also take place if the porosity values are not backed up by land points. The porosity values at open water grid points should be set to unity (i.e. porosity = 1.0). The porosity should only be set to less than unity along structures where you want to include the dissipation effect of porous flow. When determining the porosities to be used in your simulation, the values of the porous flow parameters are not that important (figure 12).
2.2.5. **Sponge.** Sponge (or absorbing) layers can be used as numerical wave absorbers in Boussinesq wave simulations. These may e.g. be set up along model boundaries to provide radiation boundary conditions, which absorb wave energy propagating out of the model area. In connection with modelling of nonlinear wave transformation on coastal profiles sponge layers are usually applied at the two model domain extremes. As for 2D applications the sponge layers at $j = 0$ are used for absorption of wave energy propagation out of the model domain (figure 13).

![Figure 12. Porosity.](image)

The purpose of having sponge layers at the other extreme (i.e. at $j = j_{\text{extr}}$) is to either absorb incoming waves in areas where no computation is requested (see left-hand side figure 13 below) or to reduce oscillations in the slot [3], [4].

2.3. **Simulation and Results**

Figure 14 shows a line series of the simulated surface elevation on top of the bathymetry. The wave breaking and wave run-up processes are clearly seen on the figure.
In the next figures (figure 15, 16) we also see the spatial variation of the crest and trough elevation and of the mean water level. Here we can observe that the mean water level increases in the surf zone in order to balance the decrease in momentum due to the wave height decay.
We also obtain the moving shoreline model results. Temporal variation of the vertical and horizontal run-up height (figure 16, figure 17, figure 18, figure 19).

**Figure 15.** Moving shoreline $x = 5m$.

**Figure 16.** Moving shoreline $x = 10m$. 
Figure 17. Moving shoreline x = 15m.

Figure 18. Moving shoreline x = 20m.
For this application we obtained a final moving shoreline where we can save time series of the horizontal, vertical and total run-up and subsequently perform statistical analysis of these data [4], [5] (figure 20).

**Figure 19.** Moving shoreline x = 22m.
3. Conclusions
The main results indicate the wave breaking and wave run-up processes, the spatial variation of a number of phase-averaged quantities and of course the shoreline motion converted into a vertical and a horizontal displacement.

We have obtained the spatial variation of the crest and trough elevation and of the mean water level which increases in the surf zone in order to balance the decrease in momentum due to the wave height decay.

We also obtain the moving shoreline model results: moving shoreline x=5m, x=10m, x=15m, x=20m, x=22m.

We obtained a final moving shoreline through perform statistical analysis of data.

References
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Figure 20. Moving shoreline final results.