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NUMERICAL MODELING OF WAVE TRANSFORMATION AND SEDIMENT TRANSPORT IN YSTAD BAY

Vågor, strömmar och sedimenttransport i Ystadbukten

by S. ABBAS HOSSEINI SADABADI and MAGNUS LARSON
Water Resources Engineering, Lund University, Box 118, SE-22100 Lund, Sweden


Abstract

The main objective of the present study was to apply a numerical modelling system to determine the wave transformation and sediment transport patterns in the Ystad Bay, Skåne, Sweden. This work was performed with emphasis on different time scales and various types of wave conditions. For this purpose, a preliminary study of background data for the Ystad Bay was first performed. A wave transformation model, known as the EBED model, was modified and implemented to calculate the wave field in the bay for the wave conditions from 2004 to 2010 for both extreme situations and for long-term representative conditions. Furthermore, the EBED-modified model was applied to derive two-dimensional current fields. The numerical model developed by Nam (2010) was subsequently implemented to calculate the sediment transport fields with focus on the longshore transport. The simulation results from the application of the numerical models show that waves from south and southwest, which have the long fetches for Ystad Bay, will cause erosion in the western parts of the bay and accretion along the lower southern parts of the bay. These results are qualitatively in good agreement with observations.

Key words – Numerical Model, EBED, Ystad Bay, Wave, Currents, Sediment transport

Sammanfattning

Syftet med föreliggande studie var att bestämma den storskaliga transporten av sediment i Ystadbukten till följd av vind-genererade vågor och de kustnära strömmar, som induceras av sådana vågor. Den kustnära sedimenttransporten är primärt en följd av dess vågor och strömmar, medan resulterande strandförändringar bestäms av hur transporten varierar längs kusten. Ett system av kopplade numeriska modeller användes för att sekventiellt bestämma vågor, strömmar och sedimenttransport. En existerande vågutbredningsmodell (EBED) modifierades för att bättre beskriva brytande vågor på grunt vatten och ett schematiserat vågklimat användes som indata för att simulera typiska vågförhållanden över längre tidsperioder. Baserat på de beräknade vågorna simulerades kustnära strömmar genom att lösa de vertikal-integrerade rörelsemängdsekvationerna i två dimensioner tillsammans med kontinuitetsekvationen (Nam, 2010). Med kännedom om våg- och strömförhållandena kunde sedimenttransporten beräknas med fokus på den kustparallella transporten som huvudsakligen orsakar den erosion som förekommer i Ystadbukten. Det representativa sedimenttransportmönster som erhölls från schematiseringen av vågklimatet indikerade en strandutveckling i överensstämmelse med fältobservationer, med erosion förekommande i den västra delen av bukten och ackumulation i den östra delen av bukten över längre perioder.

1 Introduction

Different natural hydrodynamic processes such as wind-induced waves, currents, and tides, as well as man-made structures and activities, including breakwaters, sea walls and beach nourishments (a soft structure), have significant influences on the sediment transport in the near-shore zones. They change the sediment balance and the beach topography resulting in erosion and accretion within the beach area. Therefore, finding methods to mathematically calculate shoreline changes and beach evolution are of great importance both to residents and

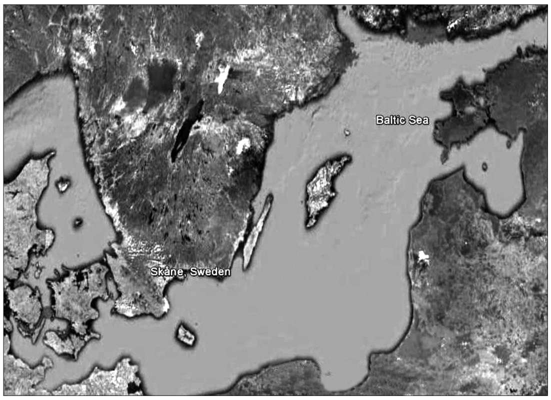

Figure 1. *The Baltic sea with Ystad Bay located on the south coast of Skåne, Sweden.*

coastal municipalities. Thus, a common approach is to apply numerical models in order to understand and predict the beach evolution. Using models is highly useful and helpful in achieving an evolution that is desirable with regard to human activities at the coast. Recently, several such models have been developed and applied in different coastal engineering projects. The main objective of this study was to calculate the wave and current generation and ultimately, the sediment transport pattern in Ystad Bay. For this purpose, a wave transformation model (Nam et al., 2009), known as EBED, was modified and implemented for the Ystad Bay. The wave field in the bay was determined for different offshore wave conditions derived by Street (2011), either for extreme situations or for long-term representative conditions. Furthermore, the calculated waves from the EBED-modified model were used to derive the two-dimensional current field (Nam et al., 2009) and the simulation results are presented. From the wave and current field, the nearshore sediment transport field was computed (Nam et al., 2009). Finally, the sediment transport field was analyzed to obtain transport gradients and the resulting topographic changes in Ystad Bay. These calculated changes were qualitatively compared to observed changes.

2 Ystad Bay Study Area

2.1 Geographic and Geological Characteristics

Ystad Bay is located in the southern part of Sweden called Skåne. On the western part of Ystad Bay, the Ystad City is positioned and it is the largest coastal city on the Swedish South coast (Figure 1). The Ystad coast includes a number of small towns and it also has one of the main beaches in Sweden with substantial economic benefits for the tourist industry. In general, the coastal areas surrounding Sweden mainly consist of rocky shorelines (Bird, 1985; Bird and Schwartz 1985). In the southern part of Sweden, the county of Skåne where Ystad is located, and also part of the Halland County, the coastal areas are largely covered in sand and the size varies from very fine sand to boulder. These beaches are the result of glacial deposits (Larson and Hanson, 2010).

2.2 Hydrodynamic and Sediment Transport Conditions

In order to derive the sediment transport pattern, the hydrodynamic conditions of Ystad Bay have to be studied. This was performed through an analysis of the water level variations and the wave generating conditions.

2.2.1 Water Level Variation

Recent investigations by Hanson and Larson (2010) of the hydrodynamic conditions showed that the main causes of water level variations in Ystad are the wind distribution at the water surface over the the Baltic Sea and the air pressure variation. These factors induce water level variations by moving the water mass in the Baltic Sea, which may be hydrodynamically characterized as an enclosed basin. The investigation of water level and wind direction demonstrated that high water levels in Skåne are due to winds blowing from N to NE, when the water is transported towards the southern parts of the Baltic Sea, whereas winds generated from SW to W lead to low water levels in Skåne (Figure 1). With regard to an expected climate change, simulations for a 100-year period indicate two scenarios for the change in relative mean sea level. The first scenario for the best case shows a decrease of 0.05 m, whereas the second scenario for the worst case results in an increase by 0.85 m. However, the mean scenario results show an increase of 0.38 m in the water level by 2100 (Larson and Hanson, 2010).

2.2.2 Wave Heights

The highest significant wave height in the Baltic Sea was recorded to be 7.7 m (Street, 2011) near Åland on December 22nd in 2004 (SMHI, 2010) However, the occurrence of large wave heights is not common and is an exception due to the hydrodynamic nature of Baltic Sea as an enclosed basin with limited fetches (Street, 2011) The wave conditions in the Baltic Sea where Ystad is located, is in general fetch-limited. The mean significant wave height for the South Swedish coast was calculated to be 0.4 m and the maximum wave height to be 4.5 m based on a 16-year time series (Larson and

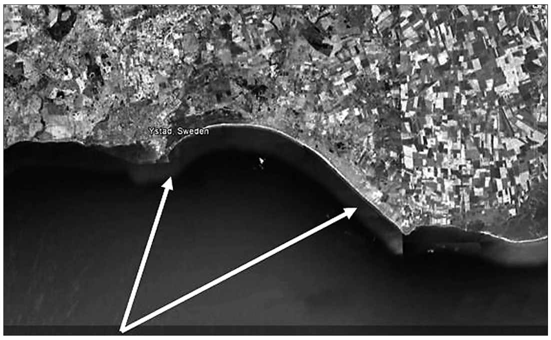

Figure 2. *Different incident wave directions are important for the western and eastern side of the bay.*

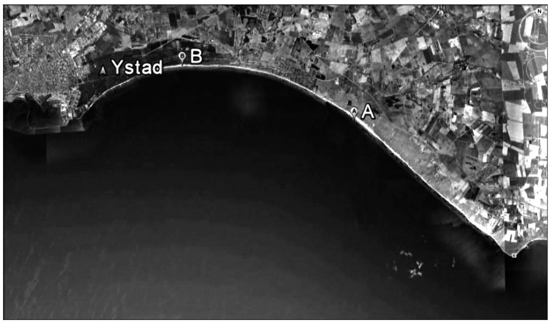

Figure 3. *Point A with zero transport and point B with no shoreline changes in Ystad Bay.*

Hanson, 1992). It has also been shown that waves traveling from southwest towards the eastern side of Ystad Bay mainly determine its shape here, whereas the opposite is true for the western side (Larson and Hanson, 2010) (Figure 2).

2.3 Sediment Transport Processes

The sediment transport processes were also investigated by Larson and Hanson (2010). Their study indicated that most of the erosion takes place in the western part of Ystad Bay, whereas the eastern part of the bay remains rather stable with minor gradients in sediment transport. The calculations results also revealed that the sediment transport direction in the eastern part of the bay is towards the west, whereas the opposite is true in the western part of the bay (Larson and Hanson, 2010). This implies a zero transport in the centre of the bay around 8 kilometers from the eastern end of the bay close to the mouth of Kabusa River (Point A, Figure 3). This study also suggested that there is a point in which no shoreline change occurs and it is located about three kilometers toward the east (Point B, Figure 3). Therefore, at a large scale erosion takes place at Y < 3 km and accretion is expected to occur at Y > 3 km, where Y is a coordinate starting at the western end of the bay, pointing East (Figure 3).

3 The EBED-Modified Wave Model

3.1 Model Background

Numerical models are useful tools for investigating the hydrodynamic processes in the coastal areas. EBED is a model for calculating wave transformation in the nearshore, including a detailed description of processes such as shoaling, refraction, breaking, and diffraction. The model was developed by Mase (2001) and is based on the conservation of wave energy flux (Equation 1). Nam et al. (2010) modified EBED to better quantify energy dissipation due to wave breaking (EBED modified). In this study the modified version of EBED was applied to calculate the wave field and associated mean currents for Ystad Bay. The offshore wave conditions for Ystad Bay (input to the EBED model) were selected based on the study by Street (2011). The results from this study were classified into 18 scenarios with different wave heights and directions in the offshore.

The energy balance equation with diffraction and energy dissipation is written,

$$\frac{\partial(v_x S)}{\partial x} + \frac{\partial(v_y S)}{\partial y} + \frac{\partial(v_\theta S)}{\partial \theta} = \frac{\kappa}{2\omega}\left\{(CC_g \cos^2\theta\, S_y)_y - \frac{1}{2}\, CC_g \cos^2\theta\, S_{yy}\right\} - \varepsilon_b S \tag{1}$$

where S is the angular-frequency spectrum density, (x ,y) are the coordinates, where x points in the longshore direction and y in the cross-shore direction, θ is the angle measured counterclockwise from x axis; v_x, v_y, and v_θ are propagation velocities in respective coordinate direction, ω is the angular frequency, C, C_g are the phase speed and group speed respectively, κ is defined as an independent variable number applied to change the diffraction impact, and ε_b is a dissipation coefficient.

3.2 Simulation Results

To provide a general overview of the simulation results for the wave generation in Ystad Bay, the dominant scenario (denoted as 15) with the highest significant wave heights, has been selected to illustrate the wave transformation for the foremost direction. This represents the one for which the highest number of incident waves

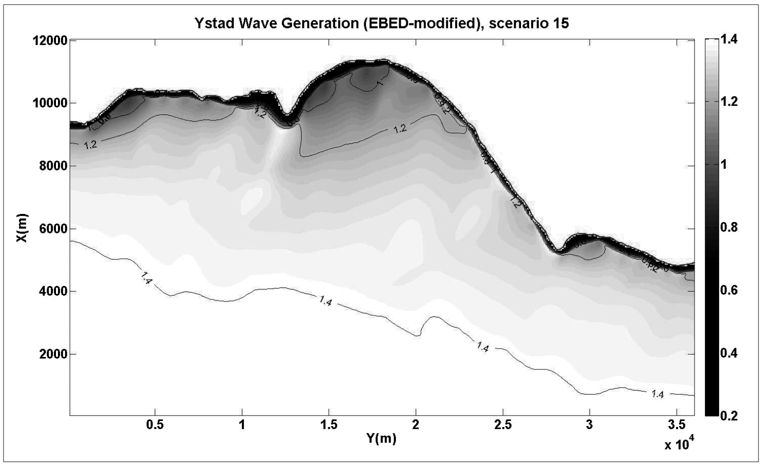

Figure 4a. *Contour plots for significant wave height (Hs), Scenario 15 with Hs = 1.4 m at offshore boundary.*

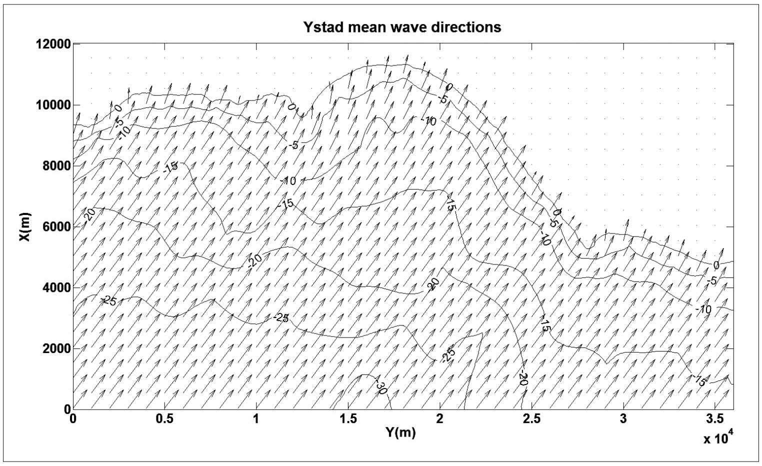

Figure 4b. *Wave directions for Ystad Bay, Scenario 15 with the incident wave direction θ = 35° at offshore boundary.*

occur, as well as the highest value on the offshore significant height, being 1.42 m and traveling in the NE direction.

Figure 4a shows the wave field from deep water towards shallow water in the entire modeling area (greater than Ystad Bay). In Figure 4b, the wave direction and the wave transformation pattern are illustrated with vector plots. This also clearly shows how the waves are refracted over the bathymetry as they approach the coast, implying that the direction changes when the waves reach shallow water and they start becoming perpendicular towards the coastline. In order to illustrate the wave height variation from deep water to shallow water a straight line from the middle of the bay has been selected and the changes in the wave heights for the this scenario along the line is shown in Figure 5.

The simulation results from EBED indicate that in scenario 15 with *Hs* = 1.42 m there is a small, continuous decrease in the wave height until the waves start interacting with the bottom and a sudden increase in *Hs* is observed due to the shoaling. Then, as wave breaking occurs at a depth of about 2.4m, the significant height starts to decrease and at it approaches zero at the shoreline (Figure 5).

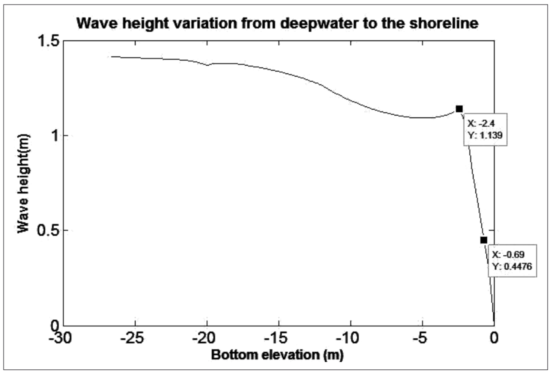

Figure 5. *The wave height variation for scenario 15 across a selected profile line in the center of Ystad Bay.*

4 Current Modeling

Wave-generated mean currents are the main cause for longshore sediment transport emerging in coastal areas. Using the wave output from the EBED-modified model together with the radiation stresses, Nam (2010) developed a two-dimensional, vertically integrated nearshore current model, to calculate the current generation along the shoreline, expressed as,

$$\frac{\partial(h+\eta)}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=0 \qquad (2)$$

$$\frac{\partial q_x}{\partial t}+\frac{\partial u q_x}{\partial x}+\frac{\partial v q_x}{\partial y}+g(h+\eta)\frac{\partial \eta}{\partial x}= \frac{\partial}{\partial x}D_x\frac{\partial q_x}{\partial x}+\frac{\partial}{\partial y}D_y\frac{\partial q_x}{\partial y}+fq_y-\tau_{bx}+\tau_{Sx} \qquad (3)$$

$$\frac{\partial q_y}{\partial t}+\frac{\partial u q_y}{\partial x}+\frac{\partial v q_y}{\partial y}+g(h+\eta)\frac{\partial \eta}{\partial y}= \frac{\partial}{\partial x}D_x\frac{\partial q_y}{\partial x}+\frac{\partial}{\partial y}D_y\frac{\partial q_y}{\partial y}-fq_x-\tau_{by}+\tau_{Sy} \qquad (4)$$

where η is the water elevation, t is the time, q_x q_y are the flow per unit width in the x and y direction, respectively, u, v is the depth-averaged velocity in the x and y directions, respectively, f is the Coriolis factor, D_x and D_y are the eddy viscosity coefficients, τ_{bx} and τ_{by} are the bottom stresses and τ_{Sx} and τ_{Sy} are the wave stresses in the x and y directions, respectively (Nam, et al., 2009), and (Larson, et al., 2010). For the individual expressions on the various quantities in the above equations, see Nam (2010).

The calculated current field in Ystad Bay for the dominant scenario are shown in Figure 6.

The wave-induced currents for Scenario 15 are mostly from west to east, parallel to the shoreline. In Figure 6, there are a few velocity vectors with the opposite directions compared to the main current direction. The main reason is the occurrence of recirculation zones, where the coastline changes orientation abruptly.

5 Sediment Transport Model

The complex hydrodynamics of the nearshore makes it difficult to carry out sediment transport modeling. Many investigations and studies on sediment transport have been performed through years resulting in a variety of models. In the recent years Camenen and Larson (2005, 2007, and 2008) have proposed and validated expressions for the sediment transport applicable both for the longshore and cross-shore directions. Nam (2010) employed these expressions and numerically developed a model for sediment transport which is used in this study to compute the sediment transport rates (see Figures 7 and 8). The transport rate was calculated for all scenarios yielding representative annual rates in Ystad Bay.

Figures 7 and 8 show the results from the calculations of the total sediment transport rate (bed load and suspended load), including the general transport pattern and the local directions of the sediment transport. It is deduced from Figure 7 that the rate of the sediment transport increases away from the shoreline towards the depth where most of the waves break. The local transport rate is mainly a function of the local current and wave breaking characteristics, as the breaking waves mobilize the sediment and the mean current transports it. The maximum current velocity is found near the breakpoint, where the maximum wave energy dissipation also

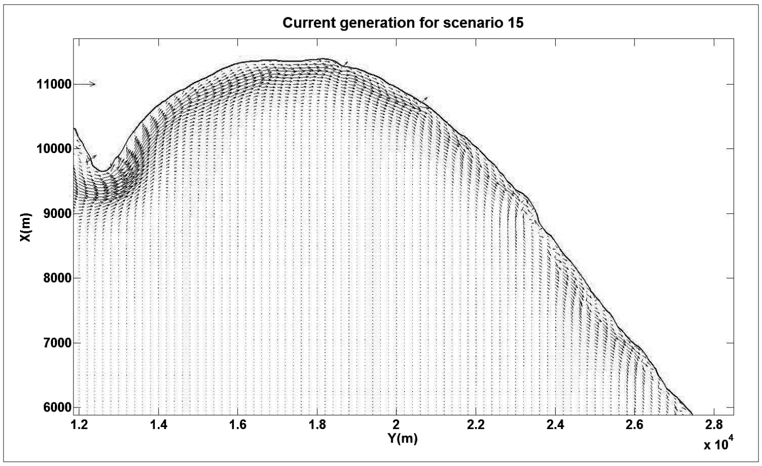

Figure 6. *Current field for waves traveling towards NE, Scenario 15.*

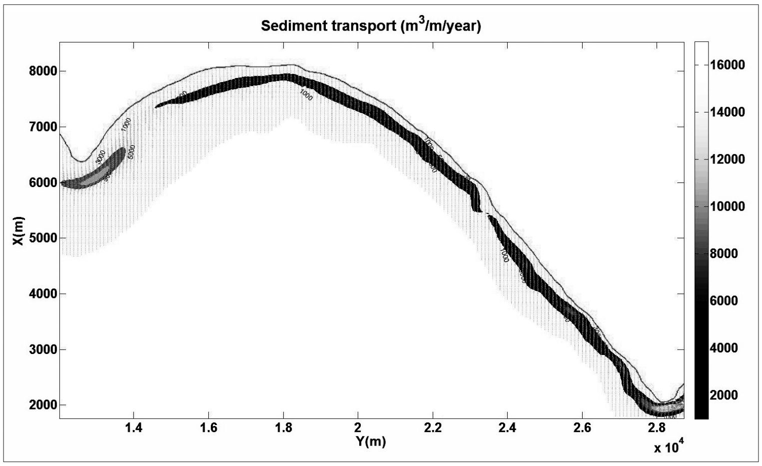

Figure 7. *The total sediment annual transport rate (m^3/m/year) in Ystad Bay.*

occurs. In deeper water the mean current is small and no wave breaking takes place, so the sediment transport is small. This is indicated in Figure 7, where the transport rate at the shoreline is considerably higher compared to the rest of the bay. The total local transport rate is calculated to be up to 2000 m^3/m/year along the shoreline. The main direction of the sediment transport is from the western part of the bay to the eastern part. The gradients in the transport rate along the bay indicate erosion in the western part and accumulation in the eastern part of the bay (Figure 8). This is qualitatively in agreement with field observations.

6 Conclusion

The major conclusions derived from this study are summarized in the following:

- The application of the numerical models for the simulation of waves, currents and sediment transport is generally an appropriate method for the investigation of the present and future hydrodynamic conditions of the bay.
- The results from the sediment transport calculations and bottom topography change assessment are in good agreement with observations.
- Based on the wind-generated waves from the Baltic Sea, the south Swedish coast, and particularly Ystad Bay, will keep experiencing eastern-directed transport with erosion in the western part of the bay and accumulation in the eastern part.
- Due to the high speed of erosion in the western part of Ystad, more coastal protection is needed.

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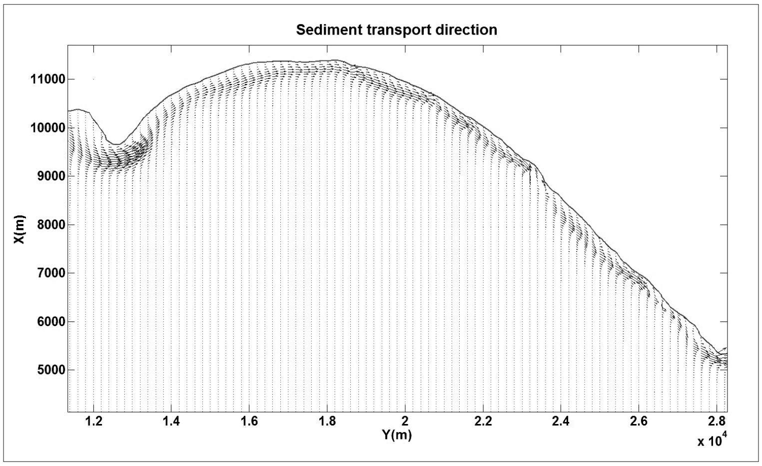

Figure 8. *The sediment transport pattern and local directions in Ystad Bay.*

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