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FIELD STUDIES AND MODELLING OF INTERACTION BETWEEN NEARSHORE CURRENTS AND BARRED COAST

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Abstract: The study is aimed at on the description of longshore and cross-shore currents at a bar crest and at an adjacent trough. Field measurements and theoretical modelling tested against and driven by the field data were carried out. The field data were collected during several field campaigns comprising a multi-bar coastal zone. The recent field investigations revealed some specific features of nearshore hydrodynamics, e.g. significant longshore current velocities not only in the surf zone but beyond its offshore boundary as well. These velocities occurred even during almost perpendicular wave incidence. On a second front, the cross-shore currents were found to be much depth-variable, with the velocities sometimes directed seawards at the bar crest and landwards at the bar trough. The phase-resolving sediment transport computations incorporated a three-layer model with the bedload layer based on the water-soil mixture theory and two sub-layers of suspended load. This sediment transport model was nested in the phase-averaged modelling framework of hydrodynamics. Sea bed changes were calculated from spatial variability of the net sand transport rate. The records of nearshore topography were investigated with Extended Empirical Orthogonal Functions (EEOF) to seek large scale, long-term morphodynamic patterns.

Key words: Field surveys, Coastal hydrodynamics, Sediment transport, Coastal morphology

1. INTRODUCTION

Nearshore multiple bars form very complex systems of interacting currents and bed forms. Their key hydrodynamic elements are both the longshore current and undertow, whereas the most important morphological factor are the bars. The study is focused on the assessment and analysis of the longshore current and undertow at two characteristic areas of barred seabed, *i.e.* near bar crest and in the neighboring trough. These areas are very dynamic and because of their configuration they are able to generate specific water circulations. They are also featured by breaking waves and dissipation of major part of their energy partly generating a mechanism controlling changes in main water flows in form of the longshore current.

The major problems addressed in the study are: how much multiple bars can deform classical configuration of nearshore currents, how much are the nearshore currents different from each other over a crest and in a trough, what are the exact locations of longshore current maximums and whether they coincide with breaker locations, and finally how much the stability and shape of bars is affected by nearshore currents. The complexity of these problems and the related scales imply the most realistic solutions should be sought by means of *in situ* observations and studies.

Coastal Research Station (CRS), situated on the southern coast of the Baltic Sea at Lubiatowo, Poland offers data sets from several years, which are suitable for investigations of interactions between currents and multiple bars. The presence of multiple bars results in very complicated patterns of multiple breakers during the transformation of wave trains. The data sets were collected during complex field campaigns, results of the current study originate from the analysis of the data collected during the last field experiment from 2002.

On the basis of parallel theoretical investigations, a multi-module framework for the modeling of waves, currents, sediment transport and evolution of barred, nearshore bed topography was elaborated. An outline of this framework is presented in this paper. Novel elements, such as the generation and propagation of a roller, inclusion of other sources of nearshore current generation than breakers and the generation of nearshore currents outside the surf zone for nearly perpendicular angles of wave incidence were highlighted.

2. SITE DESCRIPTION

The study area of Coastal Research Station (CRS) Lubiatowo (Poland) is situated at the south Baltic coast, some 70 km northwest of Gdansk. The station encompasses measuring towers arranged in a row, perpendicular to the shoreline which role is to accommodate sensors and measuring devices, see Fig. 1. The towers are cable connected to the data recording and processing centre. Besides, autonomous battery-powered sensors with built-in memory have been used for many times, as well as gauges with radio data transmission systems.

The shore in the vicinity of CRS Lubiatowo is an open and natural beach, characterised by a gentle slope (about 1.5%), with sediment diameter oscillating about the average value of d_{50}=0.22 mm. The shore is relatively stable, although a very gentle erosive tendency has been observed over last years. The mean beach width lies between 15 and 50 m. It is bounded by dunes and featured by multi-bar cross-shore profiles, which usually show 4 stable bars (see Fig. 1) plus the ephemeral one, near the shoreline.

The resultant long-term wave energy flux is directed obliquely to the shoreline, thus generating eastwards directed net longshore sediment transport.

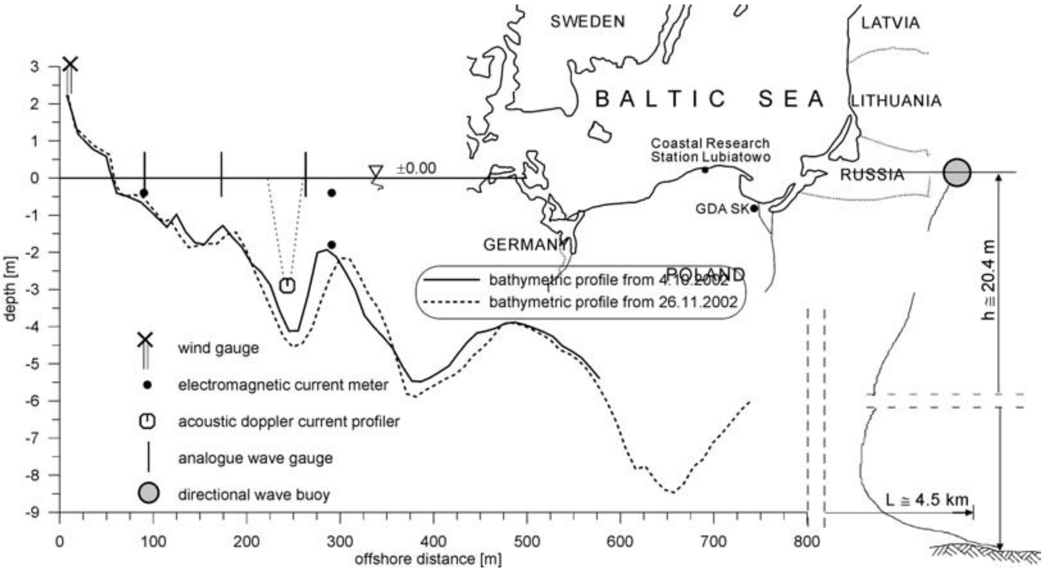


Fig. 1 Location of CRS Lubiatowo and shape of measuring profile with instrumentation

3. FIELD STUDY: SCOPE AND ANALYSIS

The multi-bar coastal zone constitutes a compound bathymetric system and causes a complicated wave transformation and equally complicated current circulation. Because of complexity of coastal processes, the most realistic assessment of them is provided by field investigations.

Longshore and cross-shore currents play a key role in the coastal zone. The measurements of current circulations were carried out at CRS Lubiatowo within three field campaigns in 1987, 1996 and 2002. The present paper mostly concerns the last one. The campaign was aimed at identification of distributions and mechanisms of water flows nearby bar crest and trough. The measurements also helped in further verification and development of the IBW PAN model of coastal circulations. The major goal of the venture was to clarify: What are the differences (if any) in longshore current distributions at bar crest and trough? Where the maximum longshore velocities occur for the multi-bar shore profile (at bar crests or at other locations)? Are there any other significant sources, aside from wave breaking, of longshore currents in the coastal zone?

The deep-water wave parameters were recorded with the Directional Waverider buoy, situated at a depth of about 20 m. The nearshore waves were registered by string gauges at locations 10 m offshore (h=3.8 m), 120 m (h=1.4 m) and 50 m (h=0.6 m), see Fig. 1. The currents were measured at the bar crest (2 vertically aligned electromagnetic current meters 0.2 m and 1.9 m above bed, with the water depth of about 2.3 m), at the bar trough (Acoustic Doppler Current Profiler 1.5 m above bed and upwards – to the water level every 0.2 m, with the water depth of about 4.5 m) and close to the shoreline at h=0.6 m (1 electromagnetic current meter 0.2 m above bed), see Fig. 1.

The measuring verticals were located almost identically as during the previous campaign in 1996. Such a layout of instrumentation nearby the second bar enables the measurements of water flows in vast range of hydrodynamic conditions. For mild wave motion (wave breaking close to the shoreline) the measured velocities at the bar had the character of mass transport. For moderate wave conditions (wave breaking around the first or the second bar) the first measuring vertical was located at the offshore boundary of the surf zone. During storms all the measuring verticals were located within the surf zone and the measured velocities were the classical wave-driven longshore currents and undertows. The exemplary distributions of the currents registered during the field survey “Lubiatowo 2002” are plotted in Fig. 2.

The analysis of variability of the recorded longshore currents demonstrates that for storms as well as moderate waves water velocity in the trough was usually somewhat greater than over the crest. The recorded velocities near the surface, i.e. about 1m below SWL were nearly identical both for the trough and near the crest. By contrast, during moderate waves, in the area of 1m above the seabed, certain discrepancies of that velocity were observed in relation to those observed near the surface in a the trough and near bed over the crest. The results of measurements indicate that for most wave situations a shift between the breaker location and the location of maximum water velocity could be discerned. In other words, there is a delay between breaking waves and the generated water flow.

Detailed analysis of the recorded water velocities, obtained during the Lubiatowo’96 field experiment, shows that systems with multiple bars are featured by mainly alongshore water flows outside the surf zone. Frequently omitted or ignored, these flows were observed even for nearly shore normal angles of wave incidence, suggesting their generation mechanism should be different from mere wave breaking. On a second front, the measured cross-shore currents were varied substantially along the water column. Importantly, in some instances opposite directions of water flows were observed over the crest (offshore) and in the trough (onshore). These result point to the possibility of existence of specific cross-shore circulations in a vertical plane. Such hydrodynamic patterns are little known and poorly described until nowadays. They also suggest that apart from wave breaking there are other mechanisms of the generation of nearshore water flows as well.

The measured configurations of longshore currents are plotted in Fig. 3 as the function of alongshore component of deepwater wave energy ($E_0L_0\sin\theta$) for both the nearbed region and the area near the surface. From the approximating straight lines it can be inferred that the longshore currents in the trough are somewhat greater from those recorded at the same time and conditions near the crest.

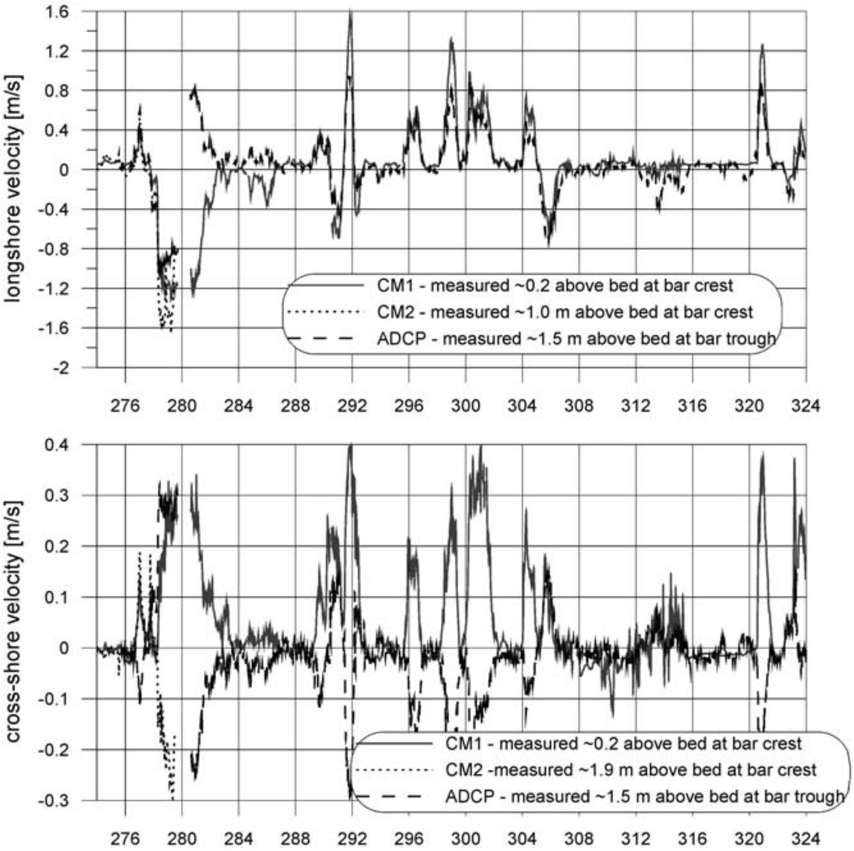


Fig. 2 Measured longshore and cross-shore velocities at bar trough and crest during field survey "Lubiatowo 2002"

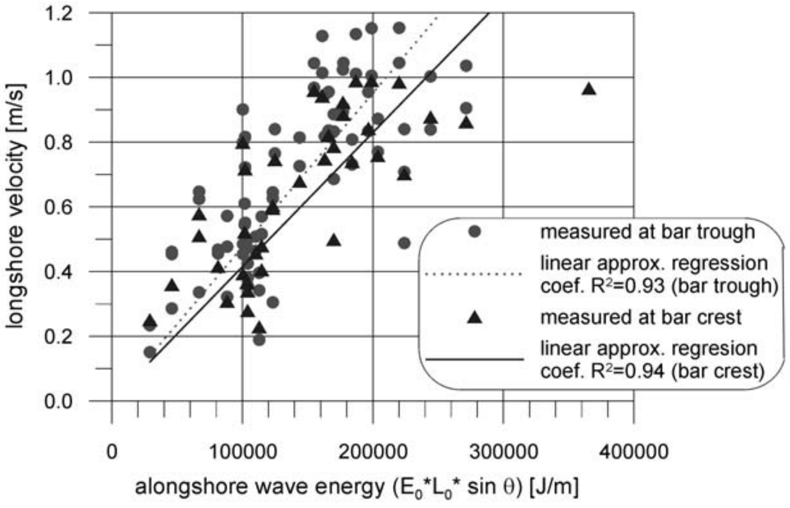
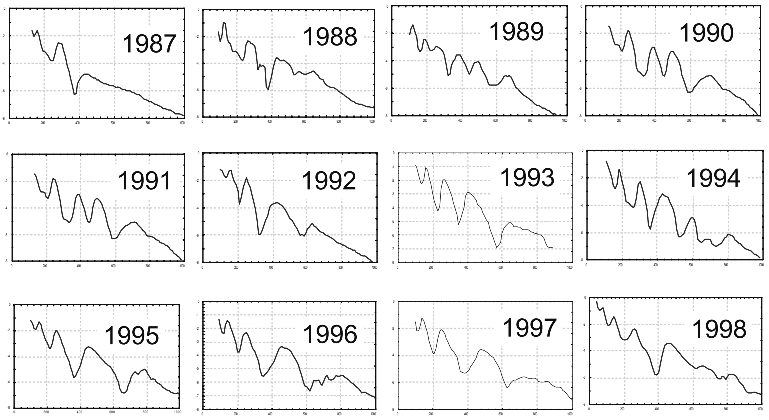


Fig. 3 Measured longshore current velocity as a function of wave energy

4. LONG-TERM BAR EVOLUTION AND INTERACTIONS WITH CURRENT FIELD

As demonstrated by the measurements of longshore currents over the bed with multiple bars, the behavior of currents strongly depends on the existence, geometry and dynamics of bed forms. Long-term evolution of a characteristic cross-shore profile at CRS Lubiatowo between 1987 and 1998 is presented in Fig. 4. To extract morphodynamic patterns, typical for the bed with multiple bars that interact with wave and current fields, extended empirical orthogonal functions (EEOF) were employed. Fig.5 presents the most important EEOF reconstructed component, showing the bars perform cross-shore oscillations about mean depths. Interestingly, positions of crests and troughs lie close to the nodes (130, 180, 260, 350, 430, 610 and 710m from baseline), which hardly move at all, whereas onshore and offshore bar slopes undergo substantial evolution, producing antinodes (160, 230, 390, 570, 610 and 900m from baseline). Hence, a bar slope near trough may become a slope near crest and *vice versa*. The oscillation period is about 16–20 years, in combination with relatively stable mean positions of crests and troughs it results in clearly visible four bars and troughs at one extreme and flat seabed with up to six small crests at the opposite. This is related to the rising of crests and sinking of troughs at the 1st extreme and to the sinking of crests and rising of troughs at the opposite.



Profile 4 1987-1998; across - distance offshore,
down - depth of seabed

Fig. 4 Annual records of exemplary beach profile at CRS Lubiatowo

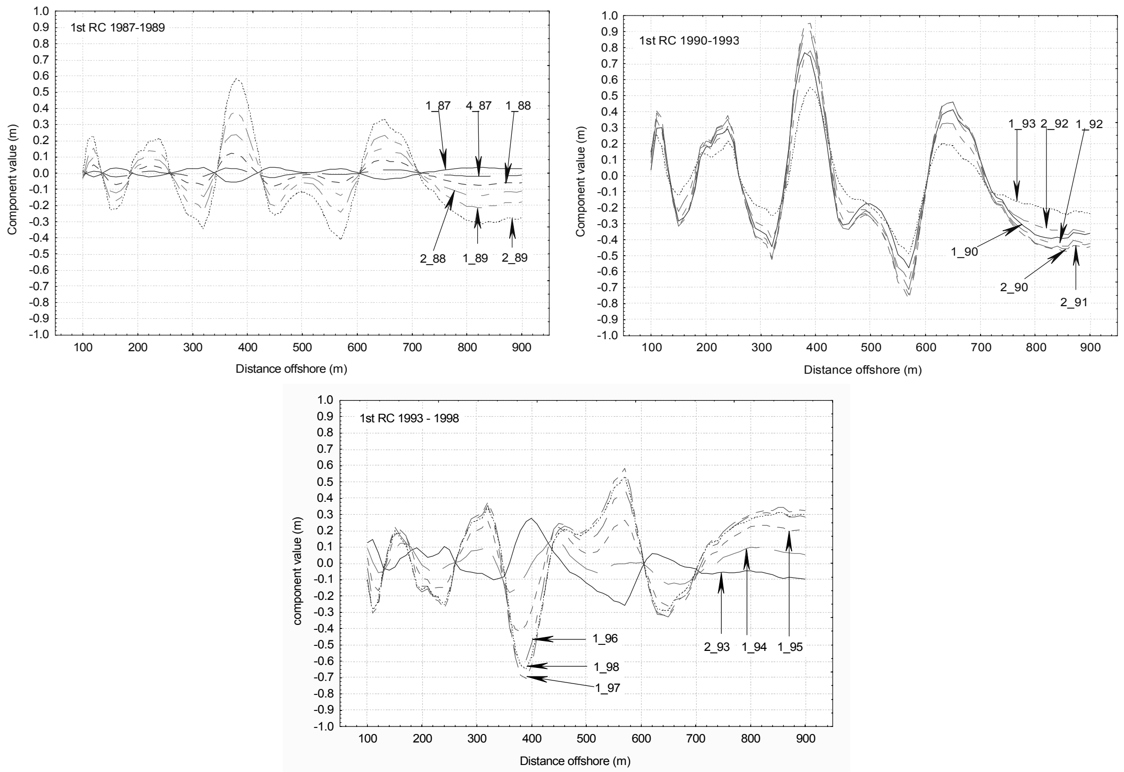


Fig. 5 Values of 1st EEOF reconstructed component for a beach profile at CRS Lubiatowo

The analysis of longshore bathymetric evolution of multiple bars at CRS Lubiatowo indicates morphodynamic changes over decades may significantly contribute to various hydrodynamic regimes. The experimental results of bar evolution, connected with the wave and current fields, indicate the existence of isolated cross-shore circulation cells. The existence of such cells is much less likely in cases where the bed is flat with many small crests; circulation cells should not develop at such instances. In other words, multiple bars can generate different hydrodynamic patterns, *i.e.* closed circulation cells with separated streams of sediment transport. It results in generation of new mechanisms and interactions between water flows and seabed in the situation where bars are both hardly visible and well pronounced. It implies that the intensity of longshore current over the crest and in the trough is of the same order of magnitude. Then these cells can be destroyed and the cross-shore movements of sediment are much less restricted.

5. PROCESS-BASED MODELLING APPROACH

Developed at IBW PAN, the theoretical model comprises two modules, i.e. hydrodynamics and morphodynamics. The latter consists of sediment transport and cross-shore profile evolution models.

5.1. HYDRODYNAMICS MODULE

Under the assumption of mutually parallel isobaths, a quasi three-dimensional model, called CUR-3DQ, enabling computation of depth-variable velocities of the longshore current and undertow was developed, see Szmytkiewicz (2002). The model has been formulated for the multi-bar sea bed profile and multiple wave breaking. A so-called “roller effect” is also taken into consideration. This means that the lag between wave breaking and appearance of currents is represented in the equations of momentum and energy by a rotating roller of water, located on the crest of the breaking wave. According to this concept, the wave energy lost during wave breaking is first transferred for roller induction and then the water flows appear.

The wave height H is computed in the model from the equation of the energy flux conservation:

$$\frac{\partial}{\partial x}(E \cdot C_g \cdot \cos\theta) + \frac{\partial}{\partial x}(E_r \cdot C \cdot \cos\theta) = -D \tag{1}$$

where: E – total wave energy, E_r – kinetic energy of the roller, C and C_g – phase and group velocity of waves, respectively, θ – wave approach angle, D – wave energy dissipation, in accordance with the approach of Battjes & Janssen (1978).

In the model formulation, an imbalance assumed between the derivative of the radiation stress ($\partial S_{xx}/\partial x$) and the spatial change of a free surface slope is a driving force of the resultant offshore flow. The longshore current velocities are calculated on the basis of dissipation of wave energy flux described by Eq. (1).The exemplary computational results for wave transformation and nearshore currents are compared with corresponding field data in Fig. 6.

5.2. MORPHODYNAMICS MODULE

The proposed model comprises the phase-averaged solution of wave-current field in the coastal zone and the phase-resolving computation of net sediment transport rates, as presented by Kaczmarek & Ostrowski (2002). The instantaneous sediment transport rates are integrated over wave period and the net sediment transport rate is obtained at each location of the cross-shore profile.

In the present model, the respective free stream velocity, described either by the Stokes approximation or by the cnoidal theory, is used in the momentum integral model of the bed shear stress. From the shear stress distribution in the wave period, instantaneous sediment transport rates are calculated by the three-layer model, which comprises the bedload layer (below the theoretical bed level) and two layers of suspension, namely the contact load layer (nearbed suspension of sediment) and the outer layer (suspension in the water column).

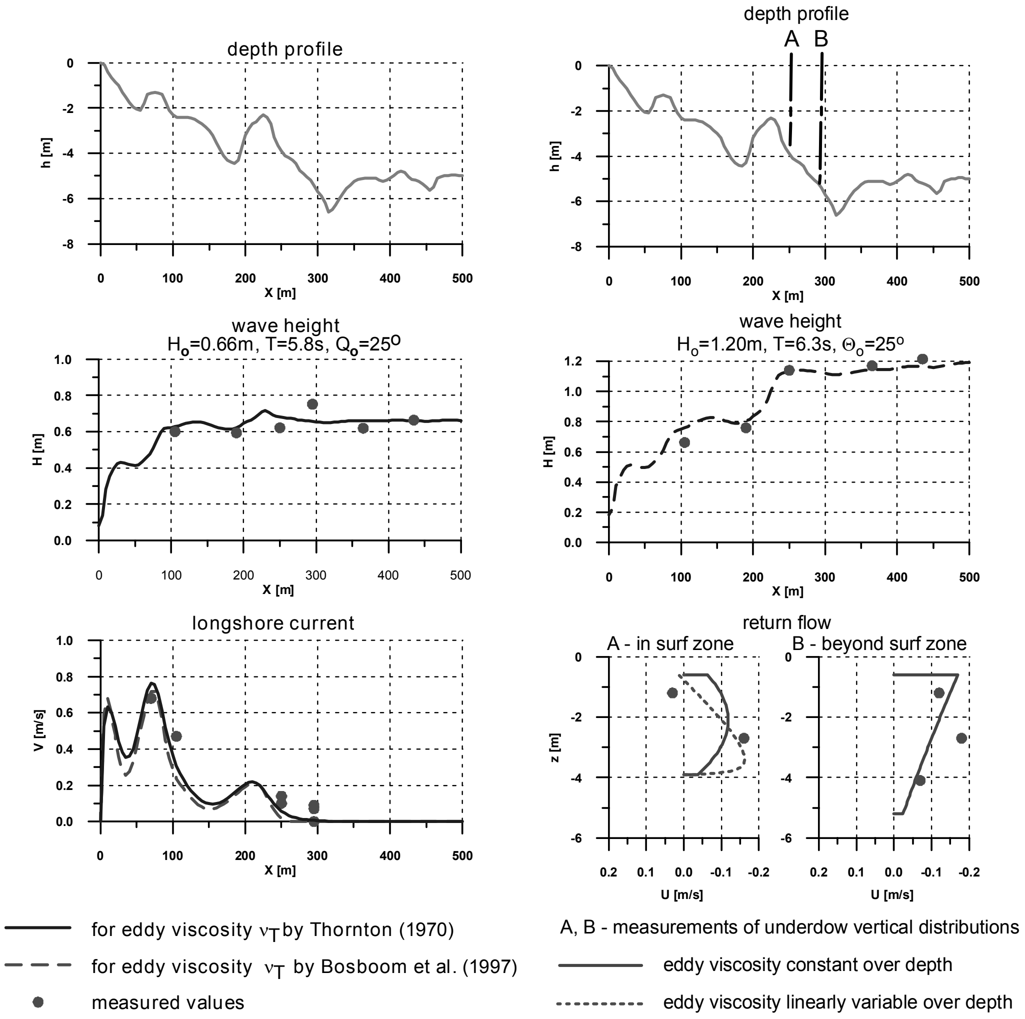


Fig. 6 Wave heights and velocities of wave-driven currents over barred beach: computational results versus field data of CRS Lubiatowo

The bedload transport model, with the instantaneous bedload velocities $u(z,t)$ and concentrations $c(z,t)$, is based on the water-soil mixture approach, with a collision-dominated drag concept, and is described by the following set of equation:

$$\alpha^0\left(\frac{c-c_0}{c_m-c}\right)\sin\varphi\sin 2\psi+\mu_1\left(\frac{\partial u}{\partial z'}\right)^2=\rho u_f^2 \qquad (2)$$

$$\alpha^0\left(\frac{c-c_0}{c_m-c}\right)\left(1-\sin\varphi\sin 2\psi\right)+\left(\mu_0+\mu_2\right)\left(\frac{\partial u}{\partial z'}\right)^2= \left.\left(\frac{\mu_0+\mu_2}{\mu_1}\right)\right|_{c=c_0}\rho u_f^2+\left(\rho_s-\rho\right)g\int_0^{z'}c\,dz' \qquad (3)$$

in which ρ_s is the soil density, α^0 is a constant, c_0 and c_m are the solid concentrations corresponding to fluidity and the closest packing, respectively, μ_0, μ_1 and μ_2 are functions of the solid concentration c, φ is the quasi-static angle of internal friction and ψ is an angle between the major principal stress and the horizontal axis.

In the contact load layer, use has been made of the concept presented by Deigaard (1993).

The instantaneous values of the sediment transport rate are computed from distributions of velocity and concentration in the bedload layer and in the contact load layer:

$$q_{b+c}(t)=\int_{0}^{\delta_b} u(z',t)\cdot c(z',t)dz' + \int_{k_e'/30}^{\delta_c} u(z,t)\cdot c(z,t)dz \qquad (4)$$

where $\delta_b(\omega t)$ is the bedload layer thickness while δ_c denotes the upper limit of the nearbed suspension (contact load layer). The net transport rate in the bedload layer, contact load layer and suspended load layer s is calculated as follows:

$$q_b+q_c+q_s=\frac{1}{T}\int_{0}^{T} q_{b+c}(t)dt+\int_{\delta_c}^{h}\bar{u}(z)\cdot\bar{c}(z)dz \qquad (5)$$

The spatial variability of net sediment transport rates gives rise to the sea bed profile evolution, which is modelled from the following well known equation:

$$\frac{\partial h(x,t)}{\partial t}=\frac{1}{1-n}\frac{\partial q(x,t)}{\partial x} \qquad (6)$$

where q denotes the net sediment transport rate [m^2/s] in the multi-bar cross-shore direction per unit width, n is the soil porosity while deposited, x and t stand for the cross-shore coordinate and time, respectively. The exemplary results of calculations are shown in Fig. 7.

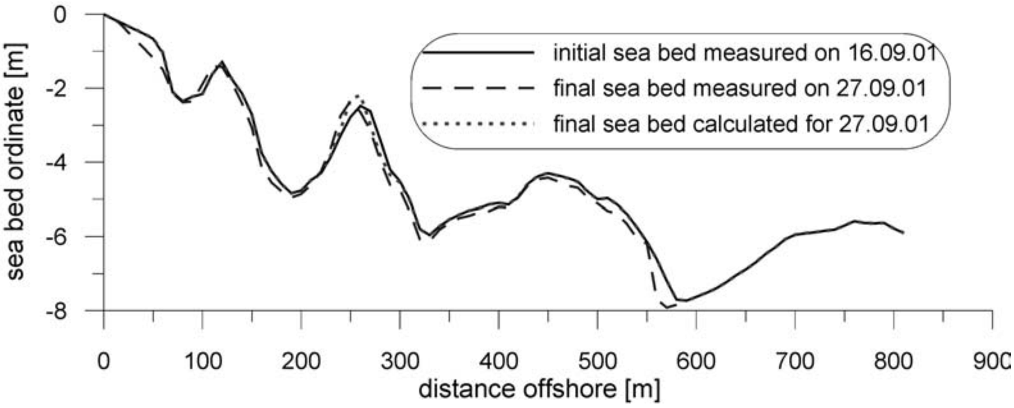


Fig. 7 Evolution of cross-shore profile at CRS Lubiatowo during field campaign in 2001: model results versus measurements (H_{rms}=1.05 m, T_p=6.5 s, assumed duration 20h)

The comparison presented in Fig. 7 shows that the model produces distinct sea bed changes at the second bar only, while the field data reveal the evolution of the entire cross-shore profile. At the second bar, however, the compliance between the theoretical and experimental results appears to be pretty good. It should be noted the model run for higher waves (H_{rms}=1.5 m and T_p=7.0 s) lasting 4-8 hours has produced some sea bed changes only at the third bar. These changes are, however, much less than the ones registered *in situ*. It can be supposed that the observed evolution of the sea bed has partly resulted from coastal morphodynamics in the longshore domain, not accounted for by the present model.

6. CONCLUSIONS

The analysis of the longshore currents shows that during storms there is a clear shift between the breaker location and the location of maximum longshore current velocity.

The results confirm the idea outlined by Nairn (1990) that the delay of wave energy dissipation is related to the generation of a roller that serves as a storage of turbulent kinetic energy. The generation of wave driven nearshore currents is triggered the moment the roller becomes fully saturated.

For a bed with multiple bars the presence of crests and troughs enforces the existence of a strong longshore current in a trough, that becomes a sort of riverbed.

Longshore currents outside the surf zone can be observed at coasts with multiple bars, they can even appear when the angle of wave incidence is nearly shore normal.

The recorded undertow, mainly generated by mild and moderate waves, significantly varies along the water column depth. For a number of waves it was found that offshore water flows over the crest coincided with onshore currents in a trough, forming large, relatively stable, quasi-vortical structures.

ACKNOWLEDGEMENTS

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