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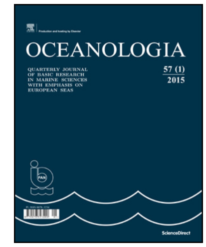

ORIGINAL RESEARCH ARTICLE

Coastal hydrodynamics beyond the surf zone of the south Baltic Sea

Rafał Ostrowski [a,*], Magdalena Stella [a], Piotr Szmytkiewicz [a], Jarosław Kapiński [b], Tomasz Marcinkowski [b]

[a] *Institute of Hydro-Engineering, Polish Academy of Sciences, Gdańsk, Poland*
[b] *Maritime Institute, Gdańsk, Poland*

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Summary The paper presents experimental and theoretical investigations of hydrodynamic processes in a coastal region located close to the seaward boundary of the surf zone. The analysis is based on field data collected near Lubiatowo (Poland) by measuring equipment operated simultaneously by the Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN) and the Maritime Institute in Gdańsk (IMG). The data consist of wind velocity and direction measured at the IBW PAN Coastal Research Station (CRS) in Lubiatowo, deep-water wave buoy records, current profiles and sea bottom sediment parameters. Mean flow velocities measured in the entire water column have almost the same direction as wind. Nearbed flow velocities induced by waves and currents, as well as bed shear stresses, are modelled theoretically to determine sediment motion regimes in the area. It appears that the nonlinear wave—current interaction generates bed shear stresses greater than those that would result from the superposition of the impacts of waves and currents separately. The paper discusses the possibility of occasional intensive sediment transport and the occurrence of distinct seabed changes at greater coastal water depths adjacent to the surf zone. It was found that this can happen under the joint influence of waves and wind-driven currents.

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* Corresponding author.
E-mail address: rafal.o@ibwpan.gda.pl (R. Ostrowski).

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1. Introduction

At large water depths, the influence of wave-induced oscillatory flows and wave-driven currents on the sandy seabed is much less intensive than in the nearshore region. Sediment motion rates in the offshore areas are significantly smaller, and therefore seabed changes become less noticeable. At such locations, the motion of water (and consequently sediment movement) in the nearbed layer can be related to currents typically occurring in the open sea, for instance, drift currents. In tidal seas, such as the North Sea, the occurrence and movement of large sandy bed forms called sand waves or sand banks at depths of 20—30 m are closely associated with tidal phenomena, see Carbajal and Montaño (2001) and Hulscher and van den Brink (2001). However, Belibassakis and Karathanasi (2017) have recently shown that in a tidal basin (Saronic-Athens Gulf) a complex configuration of the coastline orientation, bathymetry, wave conditions and strong winds during extreme storms makes tidal currents less important to sediment transport. Similar large bed forms have also been observed, albeit sporadically, in a non-tidal environment, namely in the south Baltic coastal areas at depths of 15—30 m, see Rudowski et al. (2008). Moreover, it was observed that, in the south-eastern part of the Baltic Sea in the vicinity of Władysławowo (with water depths between 14 and 17.3 m), post-dredging pits, 11 months after sand extraction, were shallower by about 2—2.5 m, and traces left by a trailing suction hopper dredger disappeared completely. It is believed that the cause of this phenomenon was both slope slipping and the supply of deposits from the surrounding area. Another study in the southern Baltic Sea indicates that at depths of 15—20 m, a 0.4—0.8 m thick sand layer moves under storm conditions (Uścinowicz et al., 2014).

Open sea currents, such as gradient, geostrophic, inertial and gravitational currents or those arising as a result of seiches, are unlikely to generate intensive sediment transport at depths of less than 30 m. Recent research by Ostrowski and Stella (2016) shows that, aside from waves, wind-driven currents have the most important impact on hydrodynamic processes at a depth of ca. 20 m.

In the coastal zone (particularly in the surf zone), wind-driven flows are dominated by wave-driven currents. The role of wind-driven currents in marine hydrodynamics increases in regions more distant from the shoreline. On the other hand, the influence of wind-induced currents on bottom sediments decreases at bigger depths. Precise determination of the boundary between the zones of domination of wave-driven currents and wind-driven currents is difficult. This is mainly due to the fact that the parameters of both types of currents strongly depend on instantaneous local conditions: wind speed and direction, wave characteristics (height, period and direction of propagation) and the morphology of the coastal bottom. On the basis of field data collected at CRS Lubiatowo and theoretical modelling with the commercial software MIKE 21, Sokolov and Chubarenko (2012) found the wind-induced component of currents in the surf zone to be quite high. It appears that wind can contribute almost 50% to the generation of the longshore current if it blows parallel to the shoreline and more than 20% if it blows at an angle of 45% to the shoreline. In all cases, however, the wave-driven longshore current is the predominant flow in the surf zone. The situation seawards of the surf zone are most probably different.

In coastal areas of the Baltic Sea, the influence of the Coriolis effect may be neglected. A wind-driven current occurring in shallow basins has almost the same direction in the water column as the wind blowing over the water surface. Because the surface Ekman layer and the bottom Ekman layer overlap, the development of the Ekman spiral is hindered, and the wind-induced flow takes place in the wind direction (Krauss, 2001; Trzeciak, 2000; Valle-Levinson, 2016). The present paper deals with wind-driven currents occurring locally and temporarily. Hence, the wind-driven current velocity profile can be described by a directionally invariable distribution.

Wave-induced orbital nearbed velocities also have some impact on the sea bottom beyond the surf zone. The seaward boundary of this influence is conventionally related to the so-called depth of closure (h_c), at which even stormy waves do not cause intensive sediment transport (the so-called sheet flow). The corresponding extreme wave conditions are most often represented by the "effective" significant wave height (H_e), which is exceeded only 12 h per year, or 0.137% of the time. Simple formulas derived by Birkemeier (1985), or earlier by Hallermeier (1978, 1981), for the assessment of the depth of closure h_c from the effective significant wave height (H_e) and period (T_e), are discussed, for example, by Dean (2002). On a second front, the depth of closure h_c can be determined directly from bathymetric changes if only sufficient data are available.

For the multi-bar shore, characteristic of the south Baltic Sea, Cerkowniak et al. (2015a) obtained (from bathymetric surveys) actual values of the depth of closure h_c = 6.0—7.7 m, greater than the ones calculated using parameters of the effective significant wave height (h_c = 4.9—6.5 m). According to Cerkowniak et al. (2015b), wave-induced bed shear stresses during storms (with the deep water significant wave height H_s exceeding 3.5 m) cause intensive sediment transport (sheet flow) even at depths of 13—15 m. Such wave conditions, however, last no longer than 24 h per year, and it is interesting whether, by themselves, they cause distinct changes in the sea bottom, leading to the appearance and movement of large offshore bed forms. The research finding by Cerkowniak et al. (2015a) that direct bathymetric measurements of the shore yield larger values of the depth of closure than do theoretical calculations based on waves only, leads to the conclusion that another factor should be included. One should take into account that such forms at these depths can probably appear and evolve only if stormy waves are accompanied by strong sea currents.

The above considerations give rise to a hypothesis about an important role of currents typically occurring beyond the surf zone and interacting with wave-induced oscillatory flows. Under storm conditions, this interaction presumably generates bed shear stresses sufficient to cause intensive sediment transport and, consequently, distinct sea bottom evolution.

Verification of the above hypothesis requires a precise determination of the sediment driving forces (represented here by bed shear stresses) resulting from the interaction of nearbed wave-induced oscillations (orbital velocities) with steady currents occurring during severe storms at the seaward boundary of the surf zone and beyond the surf zone.

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