INDEX COPERNICUS
INTERNATIONAL

ORIGINAL ARTICLE
Bulletin of the Maritime Institute in Gdańsk

MARITIME INSTITUTE IN GDAŃSK

Depth of closure in the multi-bar non-tidal nearshore zone of the Baltic Sea: Lubiatowo (Poland) case study

Głębokość zamknięcia w wielorewowej bezpływowej strefie przybrzeżnej Morza Bałtyckiego: studium Lubiatowo (Polska)

Grzegorz R. Cerkowniak, Rafał Ostrowski, Magdalena Stella

Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN) 7 Kościerska, 80-328 Gdańsk, Poland

Article history: Received: 09.07.2015 Accepted: 24.11.2015 Published: 15.12.2015

Abstract: The paper deals with the natural sandy nearshore zone, located close to Lubiatowo in Poland (the south Baltic Sea). The study site is characterised by multi-bar sea bottom profile, intensively dissipating wave energy. The paper presents a verification of the depth of closure concept. The analysis and theoretical considerations are based on field data collected at the IBW PAN Coastal Research Station in Lubiatowo. The data comprises cross-shore bathymetric profiles and the deep-water wave buoy records. The depth of closure determined from bathymetric surveys was found to be bigger than the one calculated using parameters of the effective significant wave height.

Keywords: depth of closure, bathymetry, wave climate, sea bottom morphology changes.

Streszczenie: Artykuł dotyczy naturalnej piaszczystej strefy przybrzeżnej znajdującej się w pobliżu Lubiatowa w Polsce (południowy Bałtyk). Miejsce badań charakteryzuje się wielorewowym Profilem dna morskiego, powodującymi intensywną dyssypację energii fal. Praca przedstawia weryfikację koncepcji głębokości zamknięcia. Analiza i rozważania teoretyczne opierają się na danych terenowych zebranych w Morskim Laboratorium Brzegowym IBW PAN w Lubiatowie. Dane te zawierają profile batymetryczne poprzeczne do brzegu oraz rejestracje z głębokowodnej boi falowej. Głębokość zamknięcia wyznaczona z pomiarów batymetrycznych okazuje się większa niż obliczona z parametrów efektywnej fali znacznej.

Słowa kluczowe: głębokość zamknięcia, batymetria, klimat falowy, zmiany morfologii dna morskiego

Introduction

Sediment transport rates and sea bed changes depend on intensity of nearbed hydrodynamic impacts. Motion of water near the sea bottom can be related to currents typically occurring in the open sea, such as drift currents, for instance. Appearance of sand waves (named also sand banks) in the North Sea at the depth of 20-30 m is closely associated with tidal phenomena [4, 9]. In the zone of wave transformation, the nearbed motion of water and sediments is most often caused by wave-induced oscillatory flows and wave-driven currents (in the direction along the shore or perpendicularly to the shore, including rip currents), characteristic for the nearshore regions in which wave energy dissipation takes place.

Spatial variability of sediment transport rates is a direct reason for accumulative and erosive processes occurring at the sea bed. These processes are most intensive in the surf zone, where the impact of waves and wave-driven currents on the bottom is very strong. Farther from the shore, at greater depths, sediment transport rates decrease, and the sea bed morphology changes become weak.

A so-called depth of closure (h_c) is conventionally assumed to be a seaward boundary of the sea bed changes [5]. At location of the depth of closure, even extremely high waves are said not to cause intensive sediment transport. The respective extreme wave conditions are most often represented by the "effective" significant wave height (H_e) as that is exceeded only 12 hours per year or 0.137% of the time. Simple formulas, derived by Birkemeier [2] or earlier by

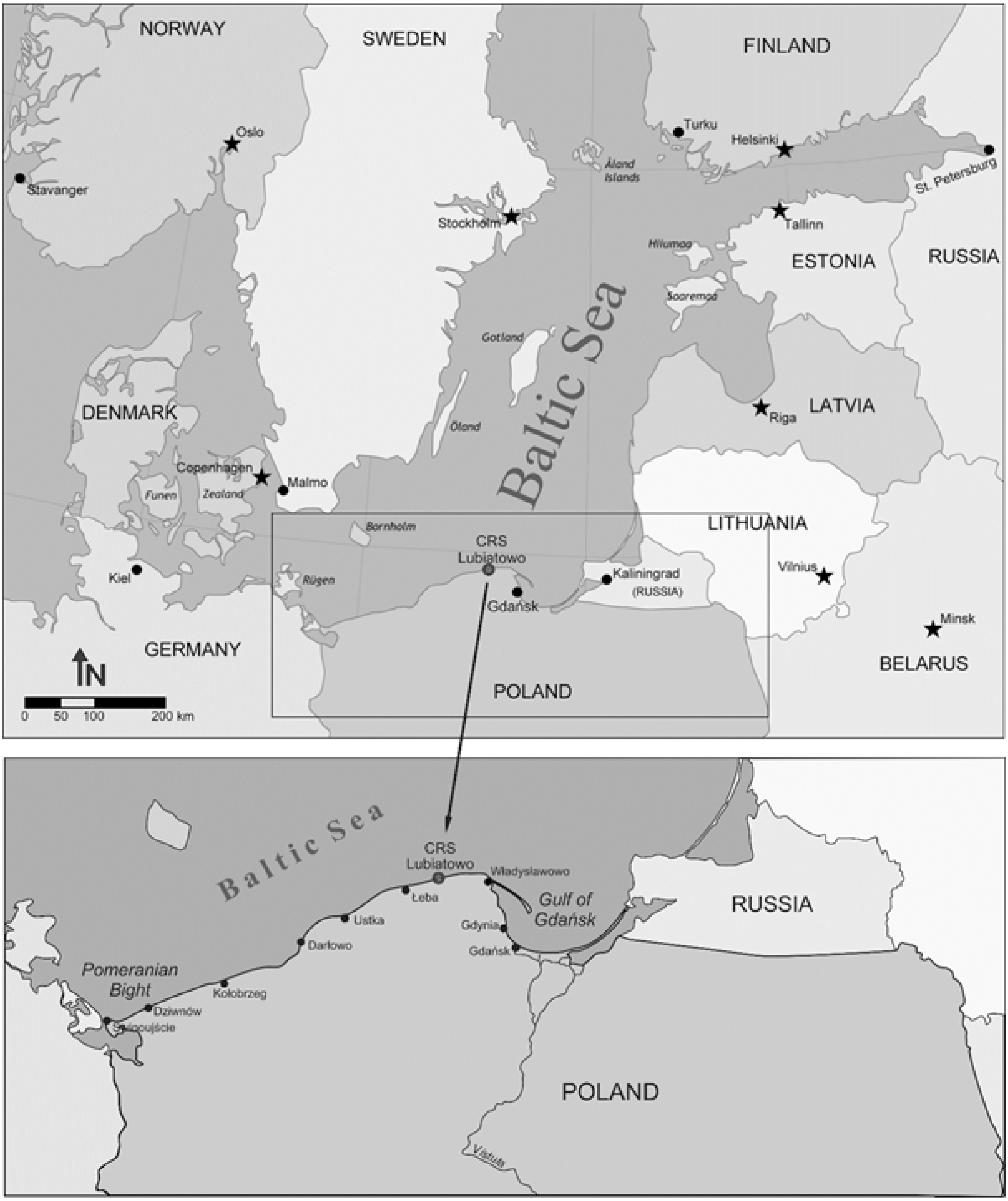

Fig. 1. Location of Coastal Research Station (CRS) in Lubiatowo

Hallermeier [7, 8], enabling assessment of the depth of closure h_c from the effective significant wave height (H_e) and period (T_e), are discussed e.g. by Dean [5].

Obviously, the depth of closure h_c can be determined directly from bathymetric changes only if sufficient data are available. First, one ought to assume the maximum range of the sea bottom level changes Δh, below which the sea bed can be treated as inactive. The span Δh is mainly dependent on reliability and accuracy of the bathymetric data.

The classical definition of the depth of closure h_c can be general-

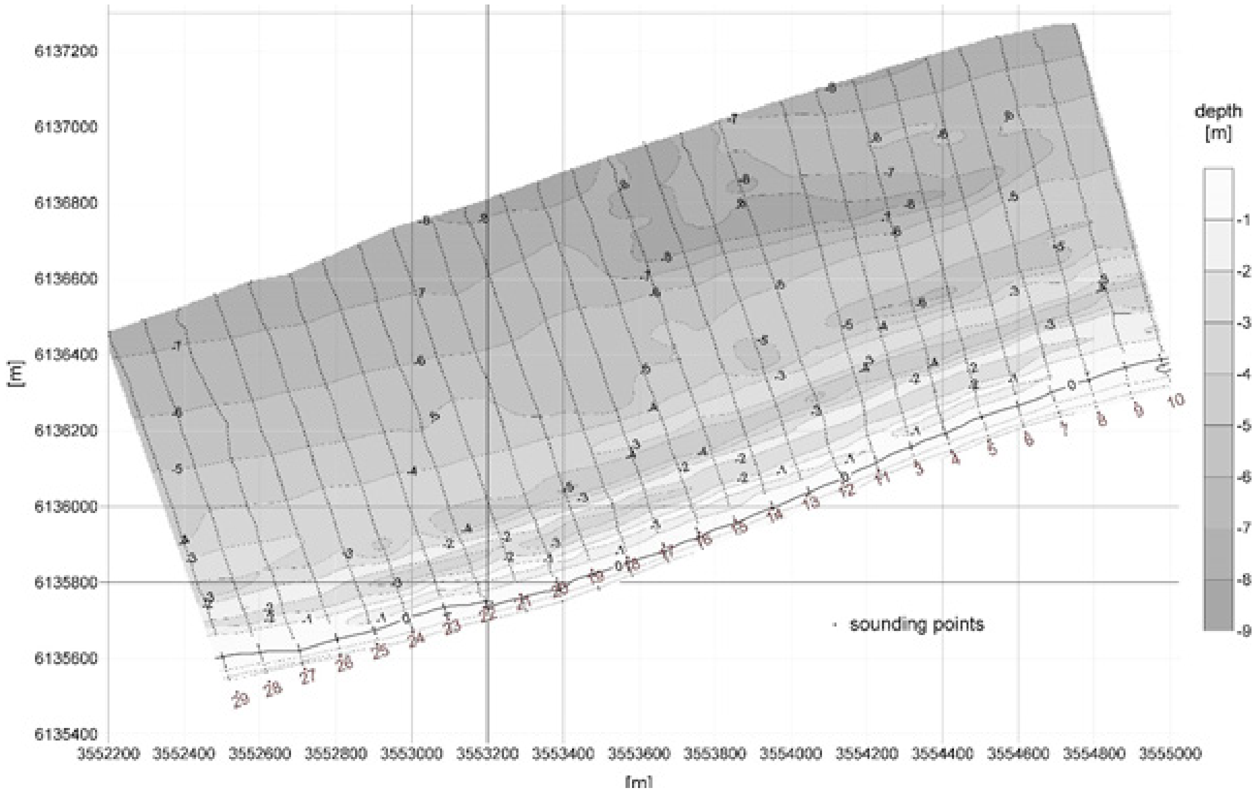

Fig. 2. Notation of bathymetric profiles and nearshore bottom relief in the region of CRS Lubiatowo

ized for shorter or longer time periods: the longer time domain (single storm, season, year, decade), the bigger depth of closure h_c. In long time scales, the depth of closure h_c occurs far from the shoreline in regions where the sea bed changes are usually found to be very small. In such cases, the quantity Δh is assumed as 0.06-0.15 m only. For shorter time scales, higher ranges of this quantity are allowed, namely Δh=0.2-0.3 m [3, 10, 11].

In the investigations carried out for the reflective (i.e. reflecting wave energy) single-bar Atlantic nearshore sea bottom at the Duck Point Field Research Facility (USA), while considering time periods of several years, Capobianco et al. [3] and Nicholls & Birkemeier [10] assumed Δh=0.1-0.3 m. For such cases, the depth of closure values (h_c) reached about 8 m. The conventional one-year depth of closures amounted to h_c=5 m, h_c=4.5 m and h_c=4 m for Δh=0.1 m, Δh=0.2 m and Δh=0.3 m, respectively.

The first studies devoted to the depth of closure in various time scales at the dissipative (i.e. dissipating wave energy) multi-bar south Baltic nearshore zone were carried out at the Coastal Research Station (CRS) in Lubiatowo, Poland [12]. Those investigations yielded values of h_c lying in the range from 5 m to 10 m. Obviously, low figures of h_c were obtained for short time scales (months) and big Δh values (e.g. Δh=0.3 m), while high figures of h_c were associated with longer periods (years) and small Δh values (below 0.2 m). The longest analysed time period comprised ca. 12 years (1987-1996) and was similar to the longest periods considered by Nicholls & Birkemeier [10] for the Duck Point site [1,11].

Studies on the depth of closure, based on wave climate along the Baltic coast, show its rather low values. According to estimations by Soomere et al. [13], the depth of closure at the coasts of the eastern Baltic sea, based on the effective significant wave height obtained over the time interval 1970–2007, lies between 3.00 and 7.25 m, where the latter occurs along the coast of the Baltic Proper (open sea, beyond the bays). On the other hand, estimations of h_c, based on measured sea bottom changes, show its higher values. For bathymetric change of Δh=0.05 m in the period of 100 years, the depth of closure in the west part of the southern Baltic equals about 12 m [14]. For the Pomeranian Bight (see Figure 1), this value rates from 8 m for the 20-year period to 12.45 m for the 100-year period [6].

The paper aims to determine the actual depth of closure in the multi-bar south Baltic coastal zone and identification whether the depth of closure can be calculated from parameters of the effective significant wave height with satisfactory accuracy. The following sections of the paper contain descriptions of the study site and data, as well as the method of analysis. Next, results of the study are discussed, after which final remarks and conclusions are formulated.

Study site and data

The measurements were carried out near CRS Lubiatowo, operated by the Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN). The study area of CRS Lubiatowo is situated about 70 km NW of Gdańsk (see Figure 1) with the laboratory building at the coordinates 54°48'42.0"N 17°50'25.6"E and is a typical south Baltic sandy coast. Field surveys conducted in Lubiatowo comprise coastal hydrodynamics, lithodynamics, and morphodynamics. For the needs of the present study, bathymetric data were used, as well as deep-water wave buoy data (significant wave height and period).

The nearshore sea bottom at Lubiatowo is mildly sloped (with an inclination of 1-2%) and consists of quartz sand of median grain diameter d_{50}=0.22 mm. The cross-shore bathymetric profiles display 3-4 stable bars and the additional one, ephemeral, occurring close to the shoreline. Such a multi-bar profile of the sea bottom is favourable to gradual wave energy dissipation, taking place within multiple wave breaking. As a result, a small amount of wave energy reaches the shoreline.

Bathymetric surveys are carried out in the alongshore span of 2600 m and reach the distances of 800-1000 m from the shoreline (sometimes a bit more). Since the 1990s, these measurements have been conducted using a single-beam echo-sounder, installed on a GPS-positioned boat, along 27 bathymetric profiles perpendicular to the shore. The profiles are numbered from 3 to 29 and organised in two groups from 3 to 10 (numbering increasing eastwards) and from 11 to 29 (numbering increasing westwards). In each group, the profiles are mutually parallel and spaced 100 m from each other. The sea bottom relief and layout of the bathymetric profiles at the considered site are shown in Figure 2.

Frequencies of the bathymetric surveys and their seaward ranges depend on weather conditions and the research needs, variable from one year to another. Therefore, the bathymetric data have been collected rather irregularly, 1-2 times per year on average. There are, however, years in which no echo-sounding data were collected. Some bathymetric profiles stretch to the depth not exceeding 5-6 m, thus covering the nearshore zone only. Those data concern the sea bed, which is very dynamic in short time scales, even under moderate wave conditions. Such bathymetric information is insufficient for the needs of the present study.

Investigations of hydrodynamics of the multi-bar coastal zone require knowledge of deep-water wave parameters, constituting the input data for theoretical considerations (including mathematical modelling) on wave transformation, wave-driven currents, and sediment transport. Since the 1990s, the offshore wave parameters at CRS Lubiatowo have been monitored using directional wave buoys (“Directional Waverider Buoys”), produced by the Dutch company Datawell BV, namely Waverider Mk. II and DWR-7 Mk. III. These devices ensure accuracy of measurements of water surface elevations amounting to 1 cm. Due to technical and financial constraints, however, long-term continuous monitoring of wave parameters has not been possible. Since 2001, all the offshore wave measurements have been carried out at 15-18 m water depth, located at 54°50’ N and 17°50’ E, at a distance of 1.0-1.5 Nm (i.e. about 2-3 km from the shoreline).

Studies, concerning the closure depth concept, require at least 12-month deep-water wave record and bathymetric measurements in the beginning and end of this record. The offshore range of bathymetric surveys in the south Baltic conditions should reach the depth of not less than 8 m [12]. It is also convenient to have a considerable number of the bathymetric profiles available. These criteria are rarely satisfied, especially in the old IBW PAN data (collected before 2001). Taking into account the above requirements on joint availability of the appropriate wave and bathymetric data, the best data set from the period 2001-2014 was selected, namely wave parameters recorded in the period from 19 September 2006 to 2 August 2007. The boundaries of this period correspond to the dates of bathymetric surveys, comprising 14 profiles.

The selected time frame is about 10.5 months, thus slightly shorter than required in determination of the “classical” [7, 8] depth of closure from analysis of waves measured for 12 months. The end of this period should lie around 18 September 2007. The wind and wave data registered at the considered site in the period from 2 August to 18 September 2007, however, show that this period is characterised by mild to moderate hydro-meteorological conditions. According to the definition of the effective significant wave height H_e, the parameters of this wave result from analysis of the stormiest conditions in a year. The wave data from the period 19 September 2006 – 2 August 2007, therefore, are satisfactory to determine the conventional annual depth of closure.

Method of analysis

The analysis comprised determination of the effective significant wave height (H_e) and period (T_e) for the considered time frame.

Actual seaward ranges of bottom changes and depths corresponding to these ranges were determined from the bathymetric data collected in the beginning and end of the considered period, i.e. on 19 Sep. 2006 and 2 Aug. 2007, respectively, as well as the data taken on 28 Nov. 2006. Within the analysis, 14 bathymetric profiles, nos. 3-16 (see Figure 2) were analysed. Except for one profile (no. 8), all the analysed transects stretched at least 900 m offshore. Bearing in mind such parameters as accuracies of the echo-sounder (0.05-0.10 m) and the spatial repeatability of the bathymetric surveys (ca. 5 m), the maximum range of the sea bed evolution below which the sea bed can be treated as unchanged (Δh) was assumed equal to 0.3 m.

Calculation of the depth of closure h_c was carried out by use of the following formulas, proposed by Hallermeier and Birkemeier, respectively [5]:

$$h_c = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right)$$

$$h_c = 1.75H_e - 57.9\left(\frac{H_e^2}{gT_e^2}\right)$$

in which g denotes acceleration due to gravity.

It seems curious that the above equations only contain the wave climate parameters and are lacking size of grains building the sea bed. On the basis of laboratory and field data, however, Hallermeier and Birkemeier [7, 8, 10] positively verified Eq. (2) for a wide range of grain diameters (from 0.16 to 0.42 mm). The sand grain dimensions at the study site (d_{50}=0.22 mm) lie within the limits of the validity of Equations (1) and (2).

Results and discussion

The depth of closure quantities (h_c) determined using Equations (1) and (2) are given in Table I.

The depth of closure determined by Eq. (1) is by 33% greater than the one obtained from Eq. (2). This is probably due to different empirical and site-specific background of these equations.

Actual ranges of the coastal sea bed change (x_c), together with actual depths of closure corresponding to these ranges (h_{xc}), have been provided by the analysis of the bathymetric transects. Exemplary profiles measured in the period from 19 Sep. 2006 to 2 Aug. 2007 are plotted in Figures 3-8. In some cases, namely for transects 4, 6, 11, 13, 14 and 16, one has not managed to determine the ranges of bottom change x_c and the respective depths of closure h_{xc}. This was because either the boat course on the offshore end of the profile was not accurately the same as the charted profile (the navigational error exceeded 10 m), or the time variability of the bottom level on the offshore end of the profile was bigger than Δh=0.3 m (see exemplary Profiles 4 and 16 in Figures 3 and 8, respectively).

Figures 3-8 imply that significant changes of the sea bottom take place at depths much bigger than h_c=4.9 m obtained from Eq. (2). These depths are also slightly bigger than h_c=6.5 m, yielded by Eq. (1). For instance, time variability of Profile 16 (see Figure 8) suggests that the depth of closure on this profile amounts to not less than 9 m. The complete results of analysis of the bathymetric profiles surveyed in the period from 19 Sep. 2006 to 2 Aug. 2007, namely the actual ranges of the coastal sea bed change (x_c) and actual depths of closure corresponding to these ranges (h_{xc}), are given in Table I.

The actual depths, corresponding to the offshore ranges of sea bottom changes (h_{xc}) given in Table II, are generally similar to the value h_c=6.5 m obtained by Eq. (1), see Table I. The value of h_{xc} is smaller than h_c (by 0.5 m) in one case only, i.e. for Profile 8. In another specific case (Profile 10), these quantities

Tab. I. Depth of closure h_c from the formulas of Hallermeier and Birkemeier

Time period	H_e [m]	T_e [s]	$h_{c,\,Hallermeier}$ [m]	$h_{c,\,Birkemeier}$ [m]
19.09.2006 – 02.08.2007	3.5	7.7	6.5	4.9

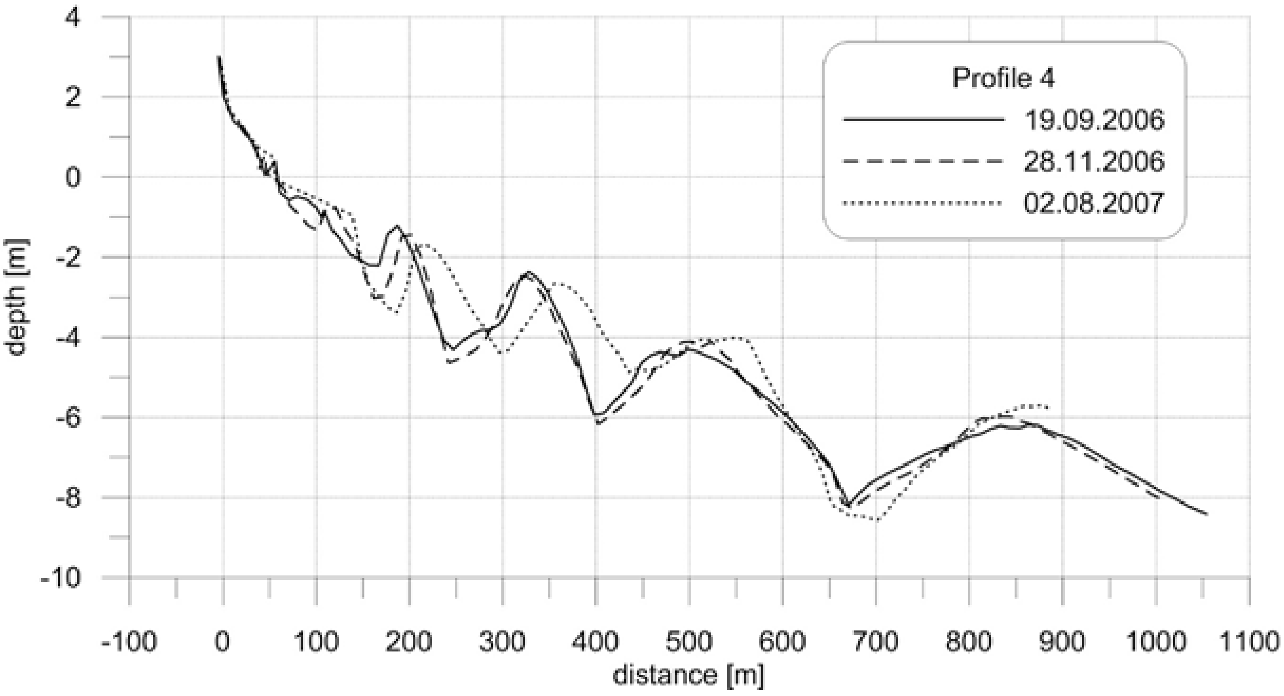

Fig. 3. Bathymetric changes of Profile 4 in the period from 19 Sep. 2006 to 2 Aug. 2007

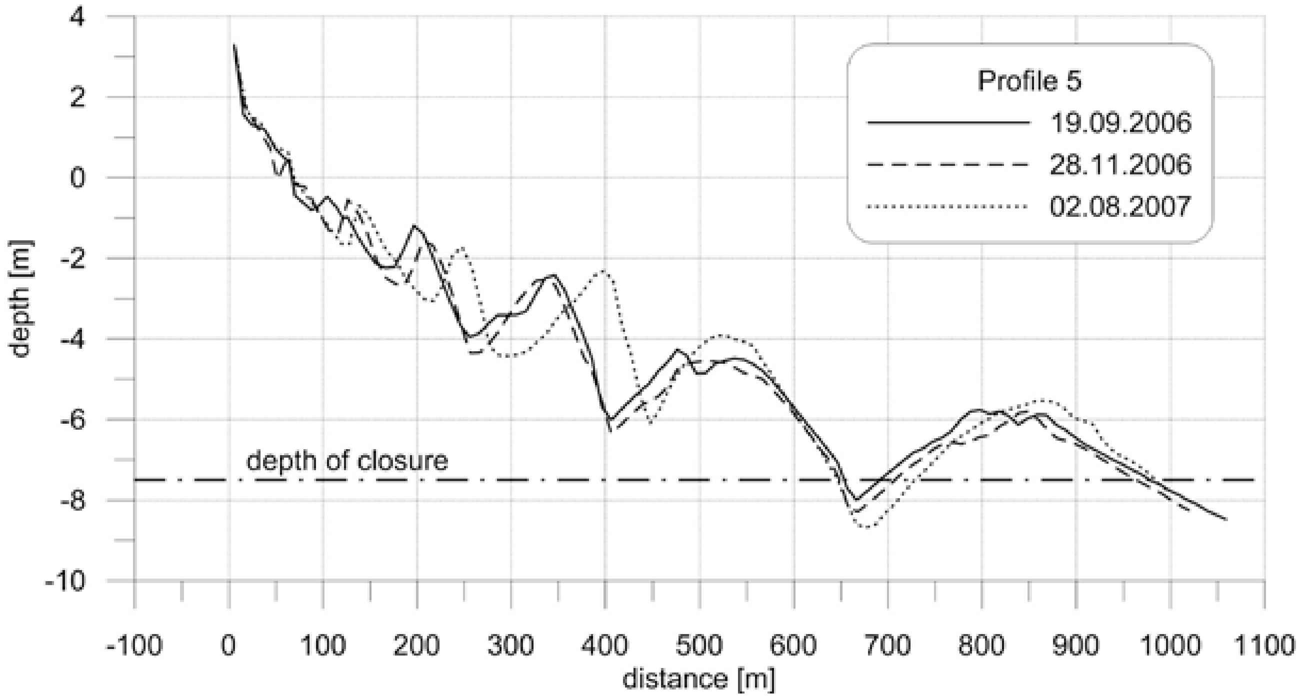

Fig. 4. Bathymetric changes of Profile 5 in the period from 19 Sep. 2006 to 2 Aug. 2007

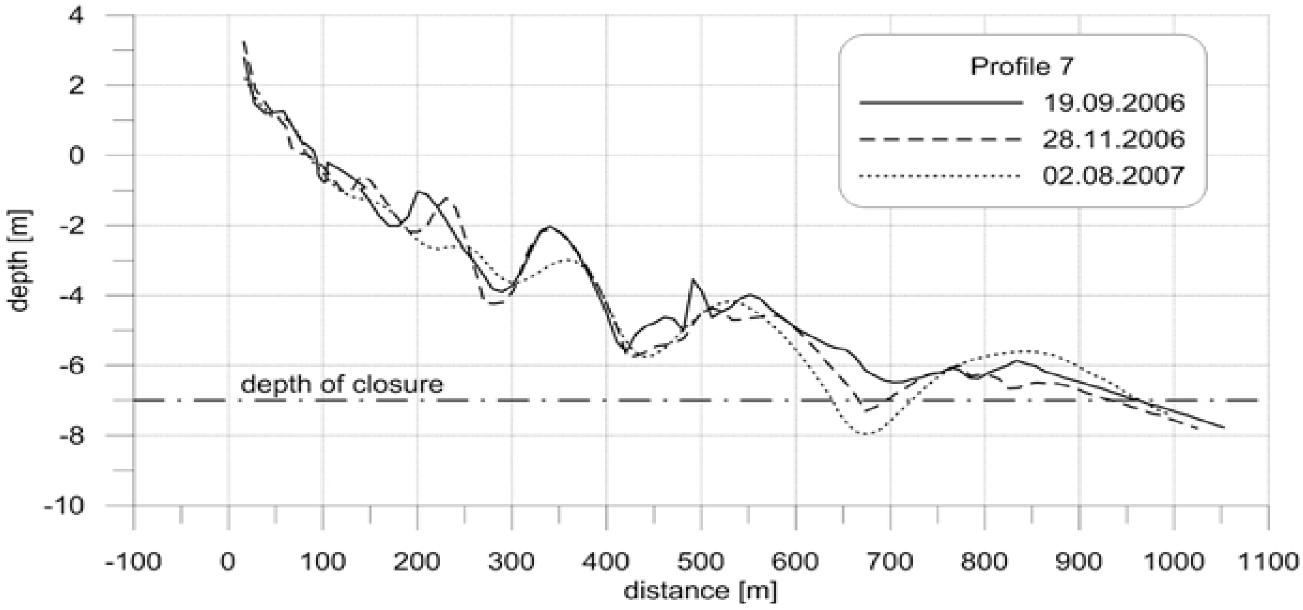

Fig. 5. Bathymetric changes of Profile 7 in the period from 19 Sep. 2006 to 2 Aug. 2007

are identical ($h_{xc}=h_c$). With respect to the remaining profiles, the analysis shows the actual depth of closure h_{xc} is a bit bigger (by 19% at maximum) than the theoretically determined value (h_c). For six of fourteen profiles (unanalysed Profiles 4, 6, 11, 13, 14 and 16), the actual depths of closure h_{xc} would most probably be considerably bigger than both theoretical h_c=6.5 m and the maximum actual h_{xc} (equal to 7.7 m, see Table II). Hence, it can be concluded that the theoretically calculated depth of closure h_c is underestimated for the multi-bar coastal zone, gradually dissipating wave energy.

Final remarks and conclusions

As pointed out e.g. by Dean [5], semi-empirical formulas enabling determination of the depth of closure h_c, i.e. Equations (1) and (2), have been derived with the assumption that the bed shear stresses generated by the nearbed wave-induced oscillatory flows are the driving force for sediment transport. It is possible, however, the nearbed wave-driven oscillations at depths bigger than 6-7 m interact with sea currents, for instance, like wind drift or gradient currents. It can be expected

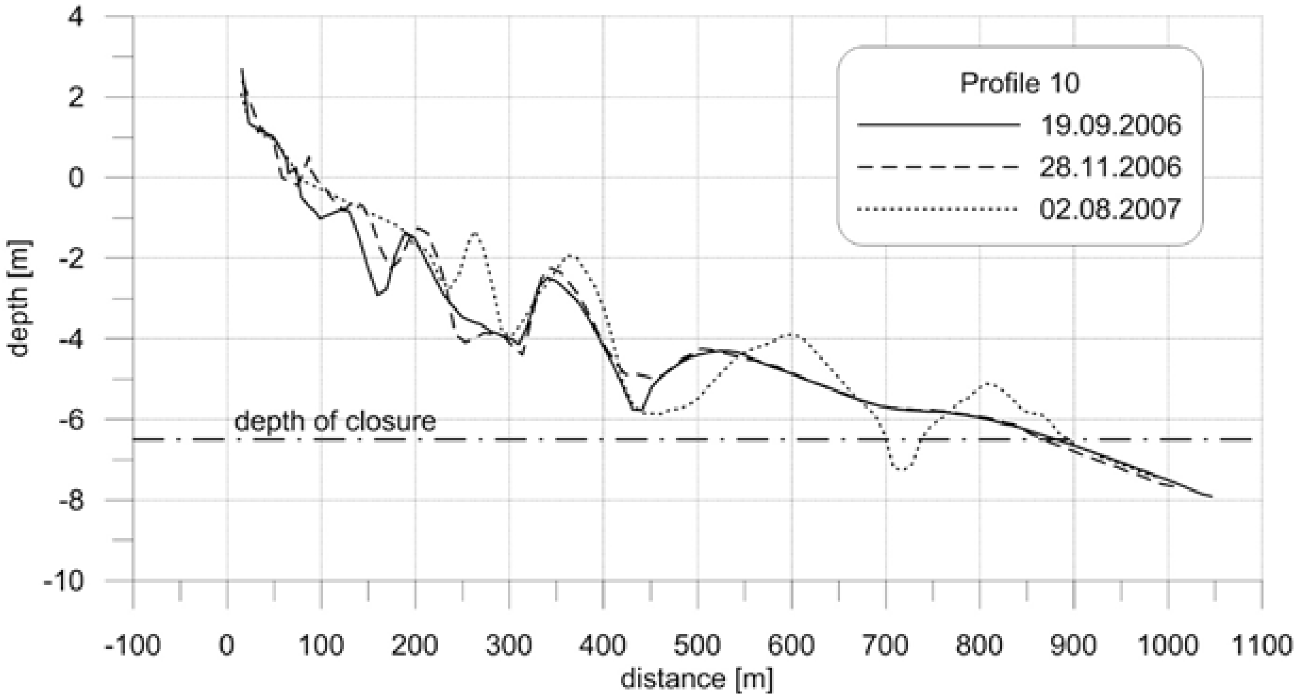

Fig. 6. Bathymetric changes of Profile 10 in the period from 19 Sep. 2006 to 2 Aug. 2007

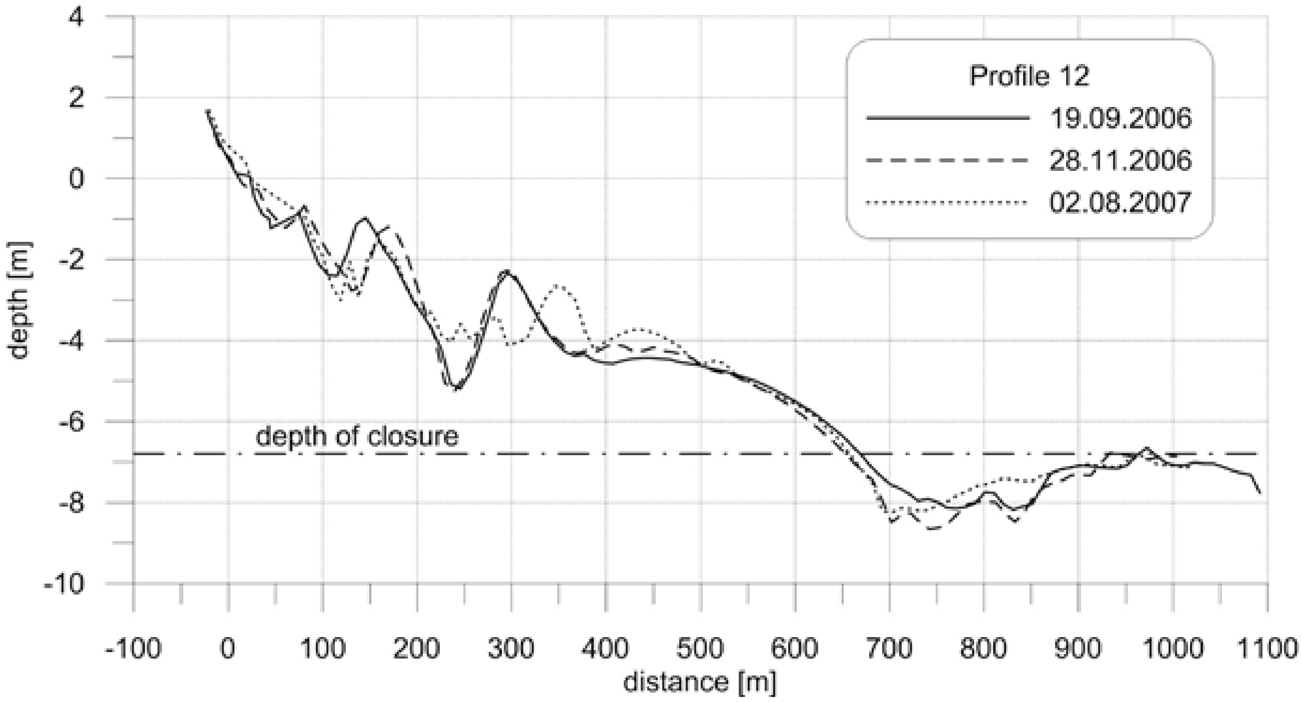

Fig. 7. Bathymetric changes of Profile 12 in the period from 19 Sep. 2006 to 2 Aug. 2007

that such currents superimposed on wave-induced water flow cause considerable growth of the bed shear stress, so sediment motion begins, which would not take place if the sea bed was affected by waves only.

The investigations carried out for the multi-bar nearshore zone, characteristic in the south Baltic Sea, show that the actual depth of closure (determined from bathymetric surveys) are bigger than the ones calculated using parameters of the effective significant

DOI: 10.5604/12307424.1185577

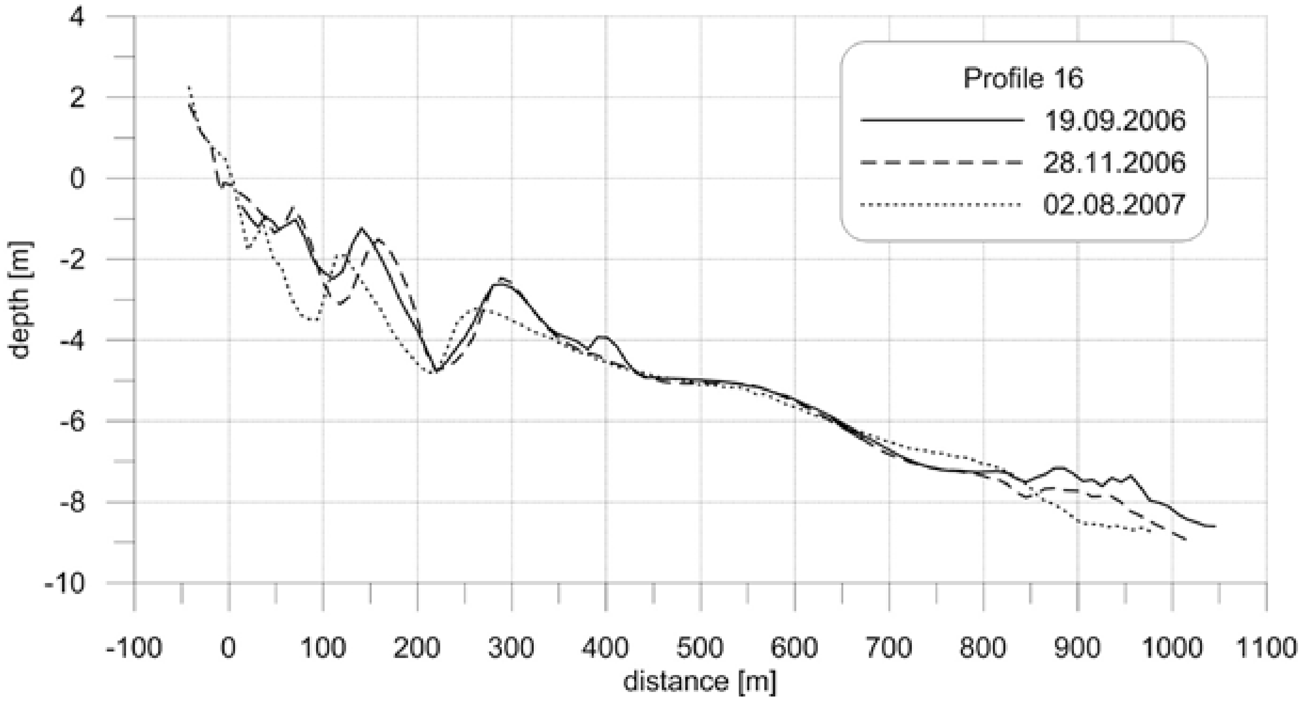

Fig. 8. Bathymetric changes of Profile 16 in the period from 19 Sep. 2006 to 2 Aug. 2007

wave height. This conclusion gives rise to a hypothesis, concerning an important role of the currents typically occurring beyond the surf zone and interacting with wave-induced oscillatory flows. In storm conditions, this interaction presumably generates the bed shear stresses satisfactory to cause intensive sediment transport and, consequently, distinct sea bottom evolution.

It is, therefore, worthwhile to continue research on the offshore boundary of the range of sea bed changes in various time scales. Further activities related to this topic will be aimed at precise determination of the sediment motion driving forces, namely bed shear stresses (as the dimensionless Shields parameter), in extreme wave-current storm conditions of various return periods. In particular, the research effort will be focused on interaction of the nearbed wave-induced oscillations (orbital velocities) with the steady currents observed at the seaward boundary of the surf zone and beyond the surf zone. Flow velocities in the bed boundary layer of the Baltic Sea beyond the surf zone have never been measured. Such measurements, together with thorough observations of the sea bed changes, would shed new light on the nearbed hydro- and lithodynamics in a transitional region between the surf zone and the deep sea.

Acknowledgements

We are grateful to both reviewers for the helpful comments on an earlier version of this manuscript. The study was sponsored by the Ministry of Science and Higher Education, Poland under mission-related programme no. 2 of IBW PAN and the research project no. 2012/05/B/ST10/00926 (Analysis of impact of wind and infragravity waves on coastal and seabed evolution – extension and verification of mathematical and numerical models).

References:

[1] Beavers, R., Howd, P., Birkermeier, W. & Hathaway, K. (1999). Evaluating profile data and depth of closure with Sonar Altimetry. *Proc. Coastal Sediments Conf.*, ASCE, 479-490.

[2] Birkemeier, W. A. (1985). Field data on seaward limit of profile change. *Journal of Waterway, Port, Coastal and Ocean Engineering* (3), 598-602.

[3] Capobianco, M., Larson, M., Nicholls, R. J. & Kraus, N. (1997). Depth of closure. A contribution to the reconciliation of theory, practice and evidence. *Proc. Coastal Dynamics Conf.*, ASCE, 506-515.

[4] Carbajal, N. & Montano, Y. (2001). Comparison between predicted and observed physical features of sandbanks. *Estuarine, Coastal and Shelf Science* (52), 435-443.

[5] Dean, R. G. (2002). Beach nourishment. Theory and practice. *Advanced Series on Ocean Engineering*, World Scientific Publishing Co. Pte. Ltd., 397 pp.

[6] Deng, J., Zhang, W., Harff, J., Schneider, R., Dudzińska-Nowak, J., Terefenko, P., Giza, A. & Furmańczyk, K. (2014). A numerical approach for approximating the historical morphology of wave-dominated coasts – A case study of the Pomeranian Bight, southern Baltic Sea. *Geomorphology* (204), 425-443.

[7] Hallermeier, R. J. (1978). Uses for a calculated limit depth to beach erosion. *Proc. 16th International Conference on Coastal Engineering*, ASCE, 1493-1512.

[8] Hallermeier, R. J. (1981). A profile zonation for seasonal sand beaches from wave climate. *Coastal Engineering* (4), 253-277.

[9] Hulscher, S. M. & van den Brink, G. (2001). Comparison between predicted and observed sand waves. *Journal of Geophysical Research*, 106 (C5), 9327–9338.

[10] Nicholls, R. J. & Birkemeier, W. (1997). Morphological and sediment budget controls on depth of closure at Duck, NC. *Structures Congress XV*, ASCE, 496-505.

[11] Nicholls, R. J., Birkemeier, W. & Hallermeier, R. J. (1996). Application of the depth of closure concept. *Proc. 25th International Conference on Coastal Engineering*, ASCE, 3874-3887.

[12] Różyński, G., Pruszak, Z., Okrój, T. & Zeidler, R. (1998). Depth of closure and seabed variability patterns. *Proc. of 26th International Conference on Coastal Engineering*, ASCE, 2926-2939.

[13] Soomere, T., Viška, M. & Eelsalu, M. (2013). Spatial variations of wave loads and closure depths along the coast of the eastern Baltic Sea. *Estonian Journal of Engineering*, 19 (2), 93–109.

[14] Zhang, W. Y., Harff, J., Schneider, R. & Wu, C. Y. (2010). Development of a modeling methodology for simulation of long-term morphological evolution of the southern Baltic coast. *Ocean Dynamics*, 60 (5), 1085–1114.

Word count:	3000 Page count: 6 Tables: 2 Figures: 8 References: 14
Scientific Disciplines:	Geoscience
DOI:	10.5604/12307424.1185577
Full-text PDF:	www.bullmaritimeinstitute.com/fulltxt.php?ICID=1185577
Cite this article as:	Cerkowniak R., Ostrowski R., Stella M.: Depth of closure in the multi-bar non-tidal nearshore zone of the Baltic Sea: Lubiatowo (Poland) case study: BMI 2015; 30(1): 180-188
Copyright:	© 2015 Maritime Institute in Gdańsk. Published by Index Copernicus Sp. z o.o. All rights reserved.
Competing interests:	The authors declare that they have no competing interests.
Corresponding author:	Rafał Ostrowski; Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN; e-mail: rafal.o@ibwpan.gda.pl