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Relief and internal structure of subaqueous sand dunes in the Vistula River mouth

Rzeźba i budowa form dna w korycie ujścia Wisły

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Abstract: This paper presents the results of bathymetric and seismoacoustic measurements carried out in the canal of the Vistula River mouth (pol. Przekop Wisły). Surveys were conducted with the use of a multibeam echosounder and a parametric sub-bottom profiler. It made this possible to obtain a high-resolution bottom morphology measurement, and to identify and characterize the internal structure of subaqueous bedforms. Presence of multiple series of small to large dunes, with their length ranging from 5 up to 55 m and height from 0.1 up to 1.5 m, was established. They were composed mainly of poorly graded medium-grained sands. The nature of sediment graining was relatively uniform. Significant diversity in terms of the formation sizes was observed, and it was only loosely dependent on their depth and location within individual relief units. Collateral medium and small formations were found everywhere among the large formations. The bedforms consisted of a well-developed steep cross-coset stratification structure. It has been ascertained that the cross-coset thickness of this formation was greater (or equal) than its height. The scope of this work is to identify the relief and structure of subaqueous dunes for the purpose of assessment of flow properties and bottom conditions in both recent and palaeoenvironments. The obtained results are crucial for determining the state of the Przekop Wisły canal, indicating potential limitations to unconstrained flow of spate water and ice drifting as well as navigation conditions.

Keywords: alluvial bedforms, cross-bedded deposits, multibeam echosounder (MBES), sediment echosounder (SES)

Streszczenie: Przedstawiono wyniki pomiarów fal piaszczystych występujących na dnie sztucznego kanału ujściowego rzeki Wisły (Przekop Wisły). Dno kanału pokrywają serie asymetrycznych fal piaszczystych, o długości do ok. 50 m i wysokości do ok. 1,5 m, zbudowanych z piasków średnio i gruboziarnistych, ze strukturą dobrze wykształconych zespołów stromego, skośnego warstwowania. Podstawę badań stanowiły rejestracje dna wykonane w 2013 roku z użyciem echosondy wielowiązkowej i parametrycznego profilowania sejsmicznego systemem SES. Zastosowanie echosond wielowiązkowej zapewniło możliwość prowadzenie pomiarów morfologii form w odniesieniu do obrazu rzeźby dna. Rejestracja SES posłużyła do rozpoznania i scharakteryzowania wewnętrznej struktury form. Określono relację fal piaszczystych względem uziarnienia osadu, położenia w obrębie jednostek rzeźby, głębokości oraz miąższości zespołów stromego, skośnego warstwowania. Stwierdzono duże zróżnicowanie wielkości form nie wykazujące ścisłej korelacji z głębokością czy położeniem w obrębie jednostek rzeźby. Wszędzie, oprócz form dużych, występowały również formy średnie i małe. Celem pracy jest rozpoznanie rzeźby i budowy fal piaszczystych dla oceny charakteru przepływu i stanu dna w środowiskach współczesnych i kopalnych. Uzyskane wyniki mają istotne znaczenie dla określania stanu kanału Przekop Wisły wskazując na ograniczoną możliwość zapewnienia swobodnego spływu wód wezbraniowych oraz lodu, a także na ograniczenie warunków nawigacyjnych.

Słowa kluczowe: formy dna skośnie warstwowane, echosonda wielowiązkowa, parametryczny profilomierz sejsmiczny

INTRODUCTION

Hydro- and lithodynamics of bedforms associated with water flow have constituted the subject of numerous studies for years (amongst others, Reineck and Singh 1980, Gradziński et al. 1986, Flemming 2000, Zieliński 2015). One of the most important issues is to determine the relation between the type of riverbed roughness and the water flow dynamics, which is necessary in the assessment of conditions and change tendencies in a given fluvial environment, also those associated with flood hazard as well as connected with navigation conditions or conditions of prospecting and extracting deposits.

So far, such studies have been based mainly on linear bathymetric profiles supplemented with surveys carried out in narrow, experimental canals, and on measurements of recent bedforms, both subareally exposed and observed and photographed directly by divers. The new methods allow accurate in situ and in vivo riverbed measurements of a riverbed. They are based on the use of multibeam echosounder systems (which provide a digital terrain model of the bottom surface) and seismic profiling via a sediment echosounder (SES system) (which ensures identification of the bottom structure with decimetre-scale accuracy in very shallow waters) (e.g., Lisimenka and Rudowski 2013).

Over 120 years ago, the Vistula River mouth changed its route as the Przekop Wisły canal was dug to prevent flooding in the Żuławy Wiślane and Gdańsk regions (Rudowski, Lisimenka et al. 2017). Sediments brought by the Vistula River and deposited at its mouth began to form an outlet cone, which made it necessary to occassionally lengthen the canal enclosed between two jetties. Nowadays, the Przekop Wisły canal (Fig. 1) is approx. 9 km long, the last 3 km of the final part of which have been subjected to detailed measurements. The canal is approx. 400 m wide and 2-8 m deep. Annual water discharge in the Przekop Wisły canal was 1 016 m3/s in years 1984–2013, with the maximum recorded level of 7 000 m3/s (Kałas et al. 2013).

With recent rich and original materials (Kałas et al. 2013) from surveys of the canal of the Vistula River mouth carried out with the use of the MBES and the SES, the authors made an attempt at drawing a comparative study of interrelations between the cross-set thickness, the size of subaqueous dunes and the depth of the bottom, which theoretically may enable researchers (Leclair 2002, Sambrook Smith et al. 2013) to assess the flow depth in both recent and fossil deposits.

The aim of this paper is to identify whether it is possible to assess the riverbed condition and the water flow properties (in recent and palaeoenvironments) on the basing on measurements of parameters of cross-sets' formations.

Results of measurements performed in 2013 associated with many years of research carried out previously by the Maritime Institute in Gdańsk were used to assess the condition and changes in the external delta and estuarial section of the Vistula River (Rudowski, Edut et al. 2017, Wróblewski et al. 2016).

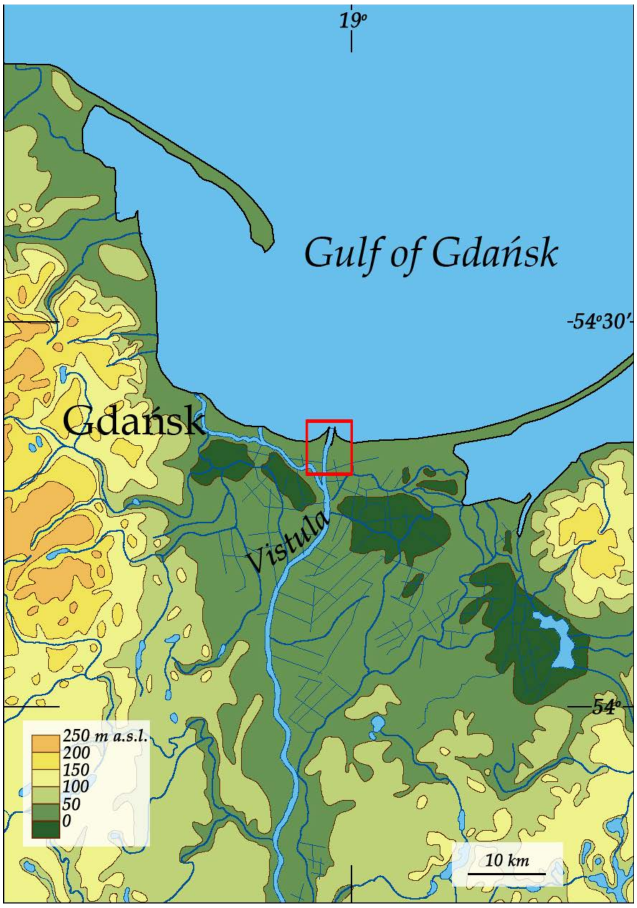

Fig. 1. Location of the research area. Hypsometric map acc. to Wróblewski et al. (2015).

MATERIALS AND METHODS

In situ measurements

Measurements of the riverbed surface relief were carried out with the use of a multibeam echosounder (MBES Reson SeaBat 7101) with a high resolution of 240 kHz, which ensured full coverage of the bottom's surveyed area (Rudowski, Edut et al. 2017). The outcome was a digital terrain model (DTM) of the riverbed surface allowing us to draw a detailed bathymetric map, a bottom relief map (Fig. 2), and (where necessary) bathymetric profiles, etc. with the accuracy of 20 cm.

Bottom structure surveys were carried out using a method of high-resolution seismic profiling with the Innomar SES-2000 parametric sub-bottom profiler with a frequency f=10 kHz. Data from measurements of eleven seismic profiles carried out along the canal were used (Fig. 2). Measurements were recorded in high, decimetre-scale resolution with penetration of up to 7 m in depth. The obtained internal structure seismic profiles of cross-bedded deposits refer closely to the bottom surface relief (mapped out on the basis of its digital model).

Bedform geometric dimensions

On the bottom surface, subaqueous dunes can be observed

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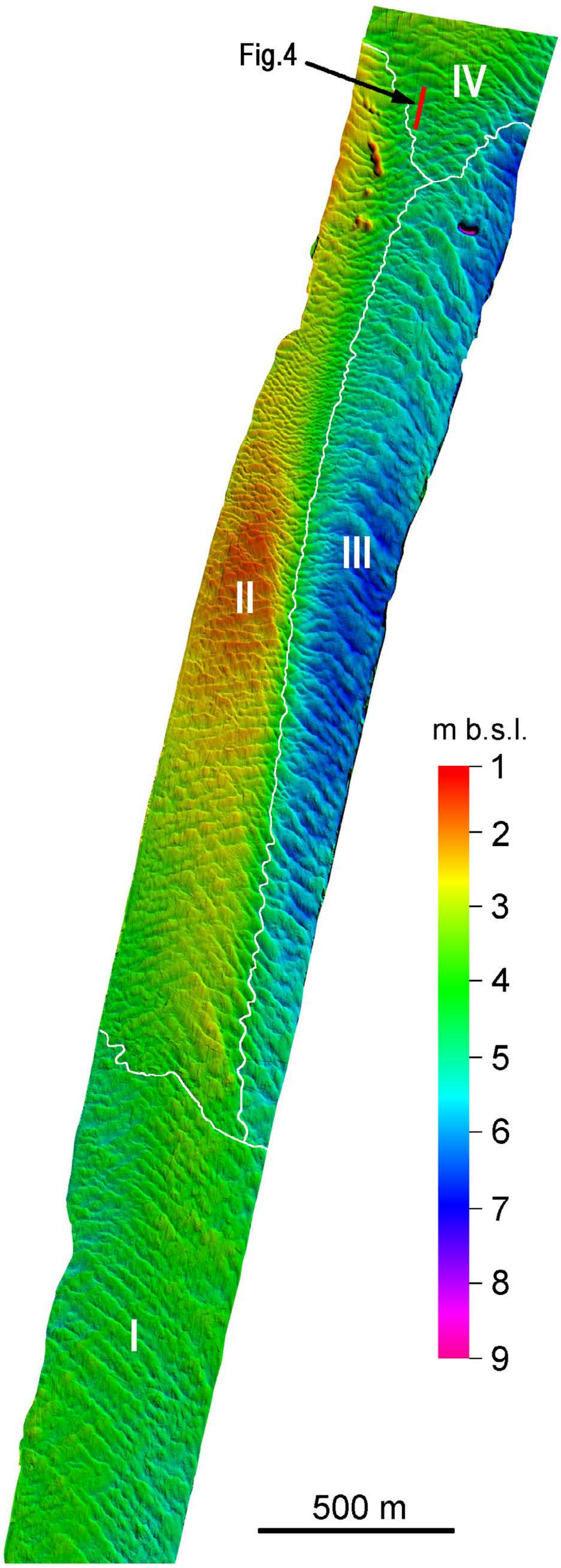

Fig. 2. Bottom relief image of Przekop Wisły canal in MBES registration Bottom state – October 2013. The main bottom units were marked (acc. to Wróblewski et al. 2016): I – rapid, II – side bar, III – pool, IV – front bar. The red lineshows the seismic profile site of the seismic profile shown in fig. 4.

(sensu Ashley 1990), the properties of which are varied within individual bottom units: rapid, side bar, pool, front bar (Fig. 2). On the basis of the MBES data, measurements of the subaqueous dunes (with plainly developed stoss and lee sides) were carried out. Horizontal plane projections of the stoss side (L1) and lee side (L2) lengths, depths above the crest (D1) and above the scour (D2) were measured perpendicularly to the crest lines (Fig. 3). Subaqueous dune length was calculated by adding values L1 and L2. Subaqueous dune height was obtained by subtracting D1 from D2. Steepness gradients for the stoss side (α1) and lee side (α2) (in degrees) were calculated as ratios of H/L1 and H/L2, respectively. Additionally, values of the elevation index (RI=H/L) and symmetry index (RSI= L1/L2) were calculated. Thickness (St) of the cross-coset forming subaqueous dunes was measured based on SES profiles (Fig. 4). Measurements were conducted for a given subaqueous dune with previously measured relief parameters. A cross-coset (sec. Gradziński et al. 1986, Rudowski 1986) is a set of laminae in cross-set stratification.

RESULTS

Chains of subaqueous dunes consisting of medium- and coarse-grained sand (Rudowski, Edut et al. 2017) occurred commonly on the bottom of the dug-through canal. Differences in granulation occurred mainly within a given subaqueous dune where grain size in the scour was usually coarser from that in the crest. In addition, sediments of the stoss side were thicker and usually better sorted than those of the lee side. Subaqueous dunes with a length 20–30 m and height of approx. 0.5 m dominated. The largest of them exceeded 55 m in length and were up to 1.5 m in height (Tab. I and II, Fig. 5). They were relatively flat bedforms (with the RI ratio below 0.07), usually highly asymmetrical (with RSI up to 10), with few bedforms that were nearly symmetrical (RSI of about 1.01). Steepness gradient values presented in the tables (Tab. I and II) refer to the mean steepness of an entire slope. It should be kept in mind that individual sections of these slopes are usually steeper (up to 30 degrees). Stoss sides are less steep and they point upstream. Smoothly, they curve into lee slopes, which point downstream.

A range of subaqueous dunes within each bottom unit (Tab. II) includes bedforms of different cubature, both large and small. The largest of them were over 50 m long and 1.5 m high, and were found in the pool. Large bedforms (over 40 m long and up to 1 m high) also occurred within the boundaries of other bottom units. No explicit relation between bottom formation size and bottom depth was identified, and the mean values of their ratios were: H/D=0.13 and L/D=6.57. Collateral medium and small formations occurred everywhere among large formations.

Bedforms with similar sizes occurred within individual bottom units, but certain differences could be observed in the formation distribution (resulting, most probably, from different stre-

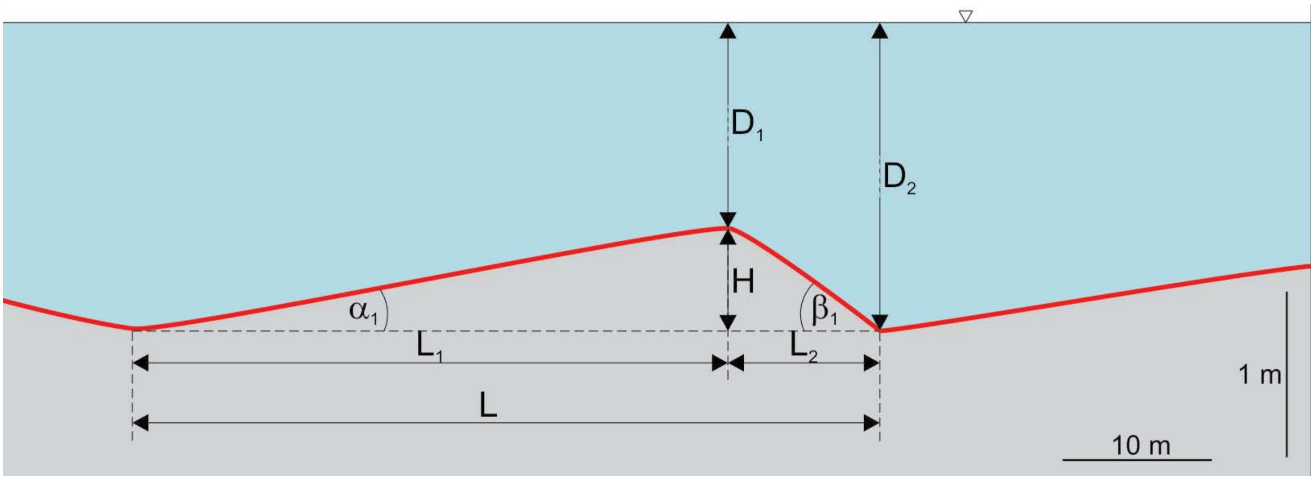

Fig. 3. Dimensions of subaqueous dune. L – length of subaqueous dune, L_1 – horizontal plane projection of length of stoss side, L^2 – horizontal plane projection of length of lee side, D_1 – depth above crest, D_2 – depth above scour, α_1 – steepness gradient for stoss side, β_1 – steepness gradient for lee side, H – height of subaqueous dune.

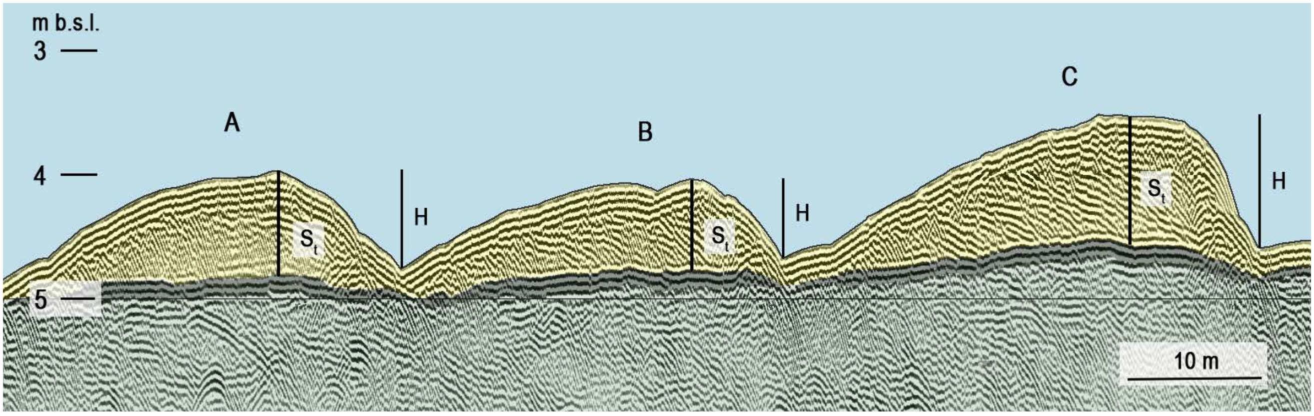

Fig. 4. Interpretation of seismic (SES) records of subaqueous dunes. Cross-stratification of active subaqueous dunes is well visible (yellow color). Surface of clear erosional unconformity was darkened. Location on fig. 2. Further explanations in text. H – height in subaqueous dune, S_t – maximum cross-cosets thickness of subaqueous dune.

am flow patterns). In the bottom of rapids spreading across the entire width of the river canal, rectilinear formations typically occurred, spreading at an angle in relation to the river canal axis and with lateral indentations which indicate the occurrence of interfering stream flow. The biggest formations were recorded within the boundaries of the pool, where they adopted rectilinear or cusp shapes indicating a homogeneous main current, with smaller lateral formations atop. Diversity within the rectilinear bedforms with lateral indentations in the up--stream part which produce diamond-like shapes (carved by cross-interfering stream flows) is a characteristic feature of side bars. In the most shallow part, large rectilinear formations (the crests of which run perpendicularly to the current) occur atop smaller formations, which are transverse to the current. In the down-stream part of the side bar, both rectilinear and wavy formations occur. The front bar also had rectilinear and wavy formations, the size of which increased with proximity to the river mouth.

SES registrations provided detailed records of the subaqueous dunes structure. Cross-sets of steep laminae pointing downstream, associated with the lee slope were recorded (Fig. 4). Surface parts of the subaqueous dunes sontained slightly inclined stratification cross-sets pointing upstream, which is associated with the long stoss sides. The base of the subaqueous dunes is a distinct unconformity surface, which is interrupted near the scours (due to erosive shearing followed by burying of the scours in the course of their migrations). Below the base of the active subaqueous dunes, groups of older, truncated formations with fragments of steep cross-sets occur.

Studies on subaqueous dunes (Leclair 2002, Sambrook Smith et al. 2013) suggest thickness measurements (St) of a single cross-set (occurring on its own and not in subaqueous dunes). Such measurements are designed as a basis for estimating the height of paleoforms. The subaqueous dunes surveyed by our team consisted of several cross-sets forming a cross-coset. Hence, the characteristic feature of a given subaqueous dune is not the thickness of the cross-set but that of the cross-coset (subaqueous dunes with a single cross-set occur rarely).

In our surveys, (Fig. 6, Tab. I and II) cross-coset thickness measure-

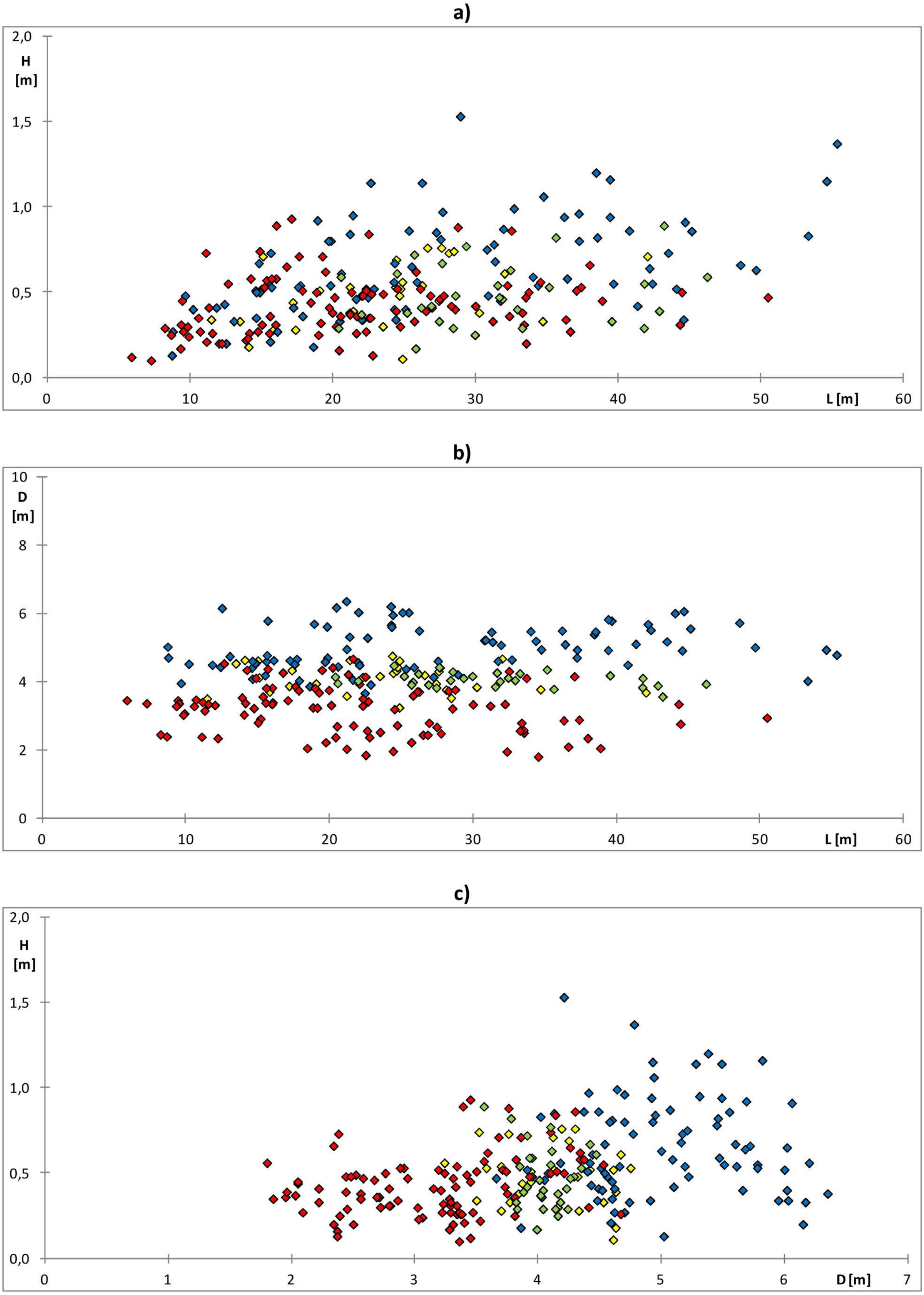

Fig. 5. Correlation diagrams of a) H/L index, b) D/L index, c) H/D index within the particular relief unit (Fig. 2): rapid – green, side bar – red, pool – blue, front bar – yellow

Tab. I. The maximum, minimum and average values of parameters and indices for forms from all relief units.

	L_1 [M]	L_2 [M]	$L=L_1+L_2$ [M]	H [M]	D [M]	S_T [M]	S_T/H	RI (H/L)	RSI (L_1/L_2)	α_1 [DEG]	α_2 [DEG]
maximum	46.81	16.16	55.33	1.53	6.35	1.39	2.27	0.07	9.94	6.16	10.99
minimum	3.70	1.65	5.88	0.10	1.80	0.40	0.54	0.01	1.01	0.34	1.02
average	18.74	6.32	25.06	0.52	4.03	0.73	1.45	0.02	3.15	1.85	4.92

The maximum, minimum and average values of parameters and indices for forms from all relief units. L_1 – length of stoss side (projection on horizontal plane), L_2 – length of lee side (projection on horizontal plane), L – length of subaqueous dune, H – height of subaqueous dune, D – water depth (to the ridge), S_t – thickness of cross-stratification deposits, RI – elevation index, RSI – symmetry index, α1 – steepness gradient for stoss side, α2 – steepness gradient for lee side

Tab. II. The maximum, minimum and average values of parameters and indices for forms within particular relief unit. Explanations in tab. I.

	L_1 [M]	L_2 [M]	$L=L_1+L_2$ [M]	H [M]	D [M]	S_T [M]	S_T/H	RI (H/L)	RSI (L_1/L_2)	α_1 [DEG]	α_2 [DEG]
						RAPID					
maximum	36.65	13.99	46.23	0.89	4.47	0.79	1.86	0.0287	5.51	2.40	7.21
minimum	14.06	4.06	20.39	0.17	3.56	0.40	0.64	0.0066	1.55	0.47	1.31
average	23.87	7.46	31.33	0.48	4.06	0.59	1.26	0.0158	3.34	1.22	3.80
						SIDE BAR					
maximum	42.79	11.14	50.48	0.93	4.67	1.19	2.25	0.0658	9.94	6.16	10.24
minimum	3.70	1.65	5.88	0.10	1.80	0.41	0.98	0.0057	1.06	0.42	1.34
average	16.42	5.29	21.72	0.42	3.17	0.69	1.58	0.0222	3.21	1.85	4.76
						POOL					
maximum	46.81	16.16	55.33	1.53	6.35	1.39	2.27	0.0529	8.52	5.03	10.99
minimum	5.55	2.14	8.72	0.13	3.66	0.55	0.54	0.0076	1.01	0.49	1.96
average	20.10	7.19	27.29	0.64	4.99	0.84	1.36	0.0256	3.08	2.11	5.54
						FRONT BAR					
maximum	34.43	9.58	42.04	0.76	4.75	1.02	1.84	0.0471	4.75	4.54	7.78
minimum	6.90	3.46	11.47	0.11	3.24	0.54	0.92	0.0044	1.46	0.34	1.02
average	17.34	6.05	23.39	0.49	4.09	0.73	1.44	0.0219	2.95	1.76	4.77

ments were carried out from the basis of a subaqueous dune to its maximum height (Fig. 4). At the same time, this value was also maximum thickness of the bedform. Therefore, value of cross-coset thickness (St) was always higher than the subaqueous dune height (H). This results mainly from burying the pools (the base of subaqueous dune height measurements) and relatively deep location of the subaqueous dune base (the base for the cross-coset thickness measurements). Hence, measurements indicated that the mean size of studied formations was $S_t/H=1.33$, and so $H=(0.75\pm0.24)St$.

These values differ from the ones included in descriptions of cross-coset fragments preserved in the sediments. In the case of subaqueous dunes, such as those in the Paraná river, (Sambrook Smith et al. 2013) the thickness is $S_t/H=0.3–0.4$, the average is 0.36; and the height is H=2.8St, while in the case of experimental surveys (Leclair 2002) $S_t/H=0.17–0.49$; the average is 0.3; $H=(2.9\pm0.7)St$. The S_t/H ratio is defined here as a preservation rate. In the authors' opinion, thickness of a single set may only indicate that the height of a bedform is not smaller than its thickness as it could not be determined whether or to what extent a given cross-coset had been preserved and subaqueous dunes with a single cross-set have been observed very seldom. It is especially important in further attempts at estimating flow depth on the basis of bedform height.

However, the concept of flow depth has not been defined explicitly. For instance, it is not clear whether it should be measured from the crest or from the scour. Moreover flow is usually equated with water depth (where the measurement method is not stated).

The results of our measurements indicate that flow depth (above dune crest) undoubtedly is not smaller than subaqueous dune height. Therefore, measurements of cross-set thickness (S_t) may be treated as reliable in calculation of bedform height and flow depth only when the entire form has been preserved. Thickness measurements of a preserved cross-set fragment (e.g., in the form of a fossil) can be only used in estimating that the subaqueous dune formed on it was not shorter than the thickness of the preserved fragment. The value of flow depth calculated from wave height determined in such a way is not smaller than the thickness of the preserved fragment either.

The measurements carried out did not reveal an evident relation between dune size and water depth. Large dunes occurred at the depth of both 7 m and 1.5 m, and both on the bottom of the pool and on surfaces of the bars. It does not imply that smaller dunes did not occur at such depths as well.

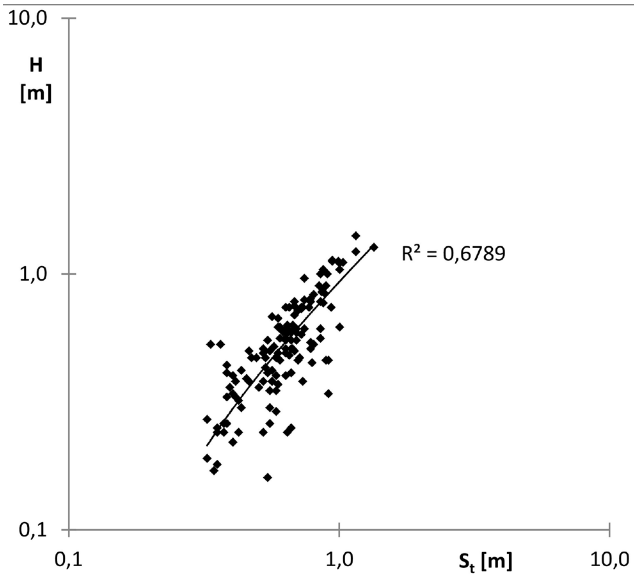

Fig. 6. Correlation diagram of cross-stratification thickness (St) versus height of subaqueous dune (H).

SUMMARY AND DISCUSSION

The obtained results were based on the riverbed relief image (obtained from the MBES in situ measurements) and the internal structure image (drawn on the basis of SES measurements). All subaqueous dune surveys known to the authors have been conducted with the use of either the SES systems but without MBESs (e.g., Sambrook Smith et al. 2013) or with the use of the MBES but without the SES solutions (e.g., Whitmeyer and FitzGerald 2006).

Two hundred and forty active subaqueous dunes located on the bottom of the Przekop Wisły canal were measured in detail. Based on these measurements, mean values of: dune height H=0.52 m, dune length L=25.06 m, elevation index RI=0.02, the symmetry index RSI=3.15, and cross-coset thickness St=0.73 m (with an average depth D=4.03 m) were calculated. These results indicate that the bedforms are relatively flat and highly asymmetrical, and have long stoss sides. All of them present homogeneous granulometry. The mean values of these bedforms' heights to the bottom depth ratios are: H/D=0.13 and L/D=6.57. Within individual bottom units, bedforms of similar sizes occurred, but certain differences could be observed in the distribution of these forms (resulting, most probably, from different flow stream patterns).

Similar data describe (Whitmeyer and FitzGerald 2006) the subaqueous dunes occurring in comparable environmental conditions in the East Pass canal connecting the Choctawhatchee Bay to the Gulf of Mexico in the vicinity of the Panama City. The canal is confined by jetties leading to the outlet cone (the Choctawhatchee Bay is a lagoon protected by a sand barrier). Series of subaqueous dunes with a length of 20–30 m and height of ca. 1 m on average (up to 70–100 m in length and 2 m high during tides) occur in this area. Very similar data can be also found in descriptions of formations with the depths of 4–8 m occurring on the bottom of the Paraná river (Sambrook Smith et al. 2013). Subaqueous dunes were 0.12–1.57 m high there, with an average height of 0.77 m, and ratios H/D=0.13 and L/D=3.7. Investigated subaqueous dunes from the seabed of the North Sea coast (van Dijk and Kleinhans 2004) were up to 760 m long and 1.5 m high with the following values of indices: RI=0.002, RSI=10.7, and α_1=0.2˚, α_2=1.11˚ (at depth of up to 20 m). Hence, these bedforms were very flat and highly asymmetrical. In the open sea, where depths reached 26–30 m, subaqueous dunes were approx. 200 m in length and approx. 1.8 m in height (RI=0.01; RSI=4.2; α_1=0.7˚; α_2=2.3˚).

In terms of the internal structure of subaqueous dunes, cross-cosets consisting of several cross-sets, cutting older formations, and located on the erosional unconformity surface were identified. The thickness of cross-cosets (S_t) measured from this surface to cross-coset peaks was usually higher than the height of these formations, average value of which was S_t=1.33H.

All obtained data allowed us to determine the state of the bottom as corresponding with an intensive sediment redeposition with an ongoing and relatively homogenous supply of material in the conditions of the upper layer of the bottom flow regime. The redeposition surface in a subaqueous sand dune base indicates that the conditions of top regime water flow occur periodically, which intensively erodes the bottom and develops into the second smooth phase towards the top, thus forming a plain bed without ripples.

So far, neither reference ranges of applied terminology nor the methods of measuring depth, subaqueous dune parameters and cross-set thickness have been specified.

In depth measurements, it is crucial to determine whether the depth was measured from the crest or the scour of a subaqueous dune, or whether it was the hydrographic (official) depth of a given watercourse. Defining flow depth is a separate issue, especially in the case of considerable or great bottom depths (Flemming 2000).

Measurements of cross-set thickness require determination of whether it was the entire cross-coset (its largest horizontal plane) or rather a cross-set selected from its structure that was actually measured. It is also important to specify the base of a cross-coset associated with the structure of a given bedform. Its location usually differs from that of the subaqueous dune depth (it is deeper).

The correlation between the cross-cosets and the bedform's height allows us to state that thickens of a cross-coset (St) is usually higher that of the wave height (H). Therefore, subaqueous dune height estimation based on a cross-set fragment preserved in a fossil sediment is very limited and, in our opinion, grossly reduced.

Thus, the calculated height of a subaqueous dune is next used for calculating depth (D). According to Sambrook Smith et al. (2013) D = ca. 5H, while Leclair (2002) states that it is ca. 7.7H. Subaqueous dunes of the Przekop Wisły canal were estimated at a similar value of D=7.7H on average. In our opinion, the estimated water flow depth (based on the calculated height of the formation) should be assumed as the minimum acceptable value (measured from the crest) equal to the height of the formation at least. The bedform's height (H) to depth (D) ratio is variable, but depth always exceeds 1H (and it can be 5H or even higher).

The results demonstrated that the applied methods were very useful in determining the structure and relief of subaqueous dunes to the level that allows us to specify properties of both recent and palaeoenvironments and to assess the current status and change tendencies in the case of modern canals. The height of migrating subaqueous dunes may have a significant impact on changes in navigation conditions by reducing the official depth of the bottom. Presence of subaqueous dunes on the bottom of a canal may significantly limit the free flow of spate water and drifting ice, thus blocking the canal's mouth. This may constitute a significant flood hazard.

CONCLUSIONS

All bedforms present homogeneous granulation, which makes it easier to determine the impact of other factors on the nature of subaqueous dunes. Significant diversity within the formation size was observed in the entire surveyed area of the riverbed. Variations were not heavily dependent on the location within individual relief units. The height of the formations only demonstrates that its depth is not smaller than the height. All information provided by the thickness of a single cross-set (e.g., one preserved in the form of a fossil) is that the height of the formation has never been smaller than its value. Hence, calculations of flow height are significantly limited and are for general information purpose only.

Properties of bedforms are illustrated accurately by the bottom in its current shape, described in this case as one associated with intensive sediment redeposition in the bottom traction, in the conditions of the upper layer of the bottom flow regime with an ongoing supply of sandy debris. This results in migration of the formations towards the river mouth, making it increasingly more shallow.

The surveyed formations have developed on an erosional unconformity surface associated with an intensive flow in the conditions of the upper flow regime, which causes softening of the bottom, and next, with the flow force downturned, inducing accumulation corresponding to the second smooth phase in the lower level of the upper flow regime.

The new solutions in the subaqueous dunes surveys should be used widely in surveys and measurements of such bedforms on the bottoms of other rivers, lakes and even seas. It is necessary to collect ample material to carry out a proper, broader assessment of subaqueous dune features understood as flow parameter indicators.

It should be noticed that collecting high-resolution data to quantify the sedimentary architecture within contemporary alluvial channels remains one of the outstanding challenges in fluvial sedimentology (Sambrook Smith et al. 2013) and quantifying the three-dimensional sedimentary architecture of alluvial successions is a central component of paleoenvironmental reconstructions and the prediction of the geometry of sedimentary deposits (Hajek and Heller 2012).

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