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Interrelation of morphometric parameters of the submarine shore slope of the Curonian Spit, Lithuania

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Abstract The morphometric parameters of the submarine shore slope of the Lithuanian part of the Curonian Spit (Kuršių Nerija) were analysed: width and inclination of the submarine slope, the width of the nearshore zone, its curvature, inclination, depth at the beginning, depth above the outer bar and the number of bars; the width and inclination of the offshore. Alongshore dynamic patterns of these parameters and their interdependence were determined. The data analysis revealed that most of parameters vary depending on the changes of submarine slope angle. Based on the data on submarine shore slope parameters and wave transformation patterns the variations of height of the breakers forming along the investigated shore sector at the marine boundary of the nearshore were determined. Calculation results showed that the height of breakers followed an increasing pattern from north to south along the Curonian Spit.

Keywords *Baltic Sea, Curonian Spit, submarine shore slope, nearshore, morphometric characteristics.*
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INTRODUCTION

It is commonly known that the morphology of submarine shore slope influences the status of the shore. Scientific literature (Short 1987; Wright et al. 1979) offers a widespread classification according the types of shores (reflective, intermediate and dissipative) are distinguished based on morphological features of the submarine shore slope. Namely they are responsible for the degree of wave field energy dissipation in the nearshore and, concomitantly, for shore status dynamics (Wright et al. 1979; Wright & Short 1984; Short 1987). Therefore, analysis of spatial dynamics and interrelations of morphometric parameters of submarine slope is important not only for theoretical speculations but also for choice and successful implementation of coastal protection measures.

The Lithuanian submarine shore slope has been thoroughly morphometrically investigated (Kirlys et al. 1972a, 1972b, 1974a, 1974b; Kirlys 1974; Kirlys & Močiekienė 1975; Kirlys & Žaromskis, 1980; Geological atlas... 2004; Janukonis 2000; Gelumbauskaitė 2003). Unfortunately, emphasis would always be placed on the spatial or temporal distribution patterns of depths. The interrelations of morphometric parameters of the submarine shore slope would not be analysed. The present article is designed as an attempt to at least partially fill this gap.

MATERIAL AND METHODS

The investigated area includes the Lithuanian part of the Curonian Spit (Kuršių Nerija – a 51-km long coastal segment from the southern jetty of the Port of Klaipėda up to the Lithuanian-Russian border). The data of morphometric measuring in the nearshore, published in the Lithuanian Coastal Atlas of the Baltic Sea (Geological atlas … 2004), were used. The morphometric measuring was done in 47 cross profiles approximately up to the depth of 15 m (Trimonis et al. 2005). Unfortunately, morphometrical data below 15 m depth are not published in the mentioned atlas. Notwithstanding, computed inclination of submarine shore slope up to a 15-m depth reflect quite well inclination of whole submarine shore slope. The morphometrical data of 44 cross profiles were used (Fig. 1). From that cross profiles the following morphometric parameters of the submarine shore slope were measured: width and inclination (ratio between the depth and width – tgα) of the submarine shore slope; the width of the nearshore zone, its curvature of bars (ratio between the straight and winding (by the nearshore surface) distance of the nearshore zone), inclination, depth at the beginning of nearshore zone, depth of the outer bar crest and the number of bars; the width and inclination of the offshore (Fig. 2). It should be pointed out that these parameters reflect not only the morphological features of the submarine shore slope but also the wave energy field dissipation patterns in it. It should be noted that the terminology used in the article is according to a glossary of coastal research terms (Gudelis 1993).

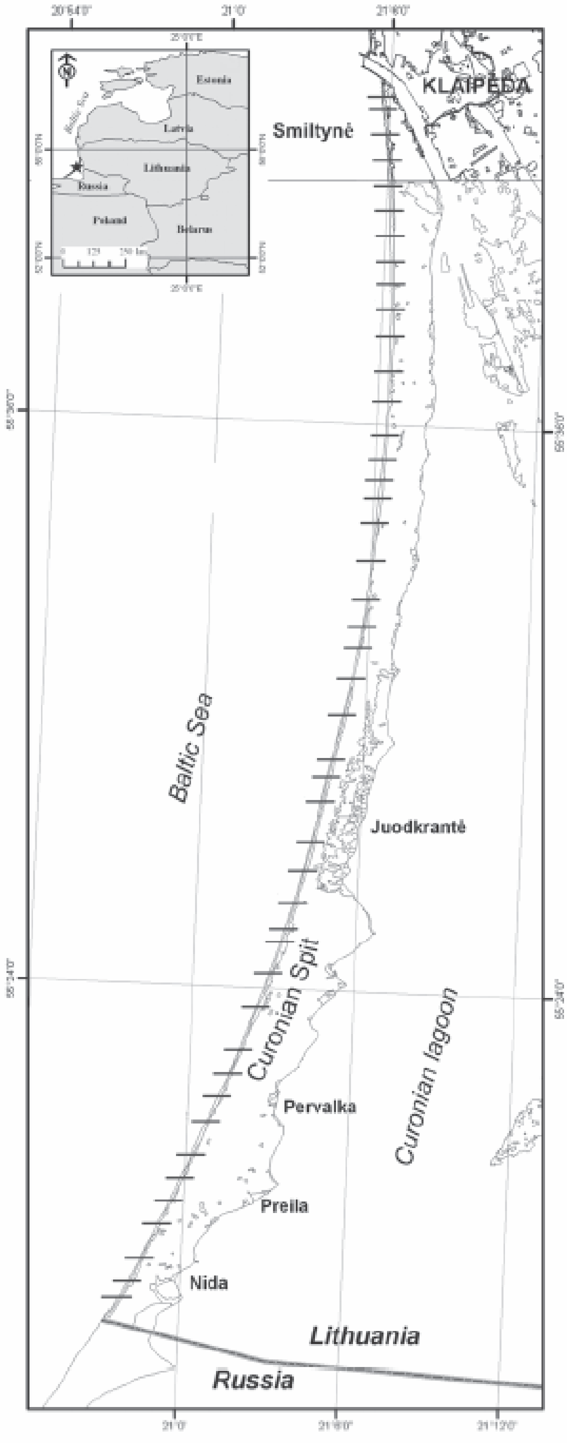

Fig. 1. Situational map of the study area and location of morphometric profiles (according to Geological Atlas … 2004) of the submarine shore slope.

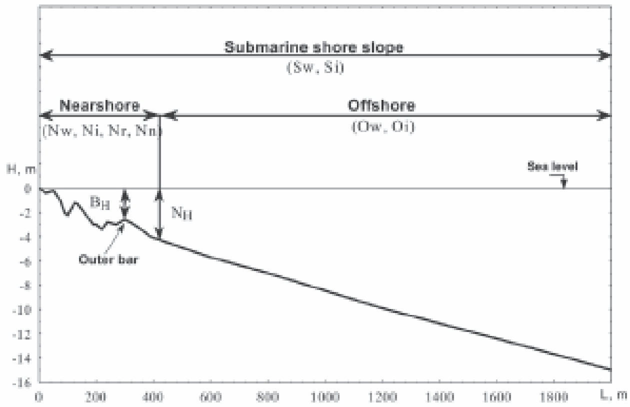

Fig 2. Location of investigated morphometrical characteristics of the submarine shore slope: submarine shore slope width (Sw), nearshore width (Nw) and offshore width (Ow); submarine shore slope inclination (Si), nearshore inclination (Ni) and offshore inclination (Oi); curvature of bars (Nr); number of bars (Nn); nearshore depth (NH) and outer bar (BH) depth.

A correlation matrix (using statistical program Statistica) was created in order to find out possible interdependences of various morphometric parameters of submarine shore slope.

MORPHOMETRICAL CHARACTERISTICS

Width (Sw) and inclination (Si) of submarine shore slope. The width (up to the 15-m isobath) of the submarine shore slope of Curonian Spit follows a relatively regular reduction pattern from almost 2 km (1980 m) in Kopgalis up to 1.5 km (1445–1450 m) at Juodkrantė (20^{th}–24^{th} km). South of Juodkrantė, Sw again increases and south of Nida (50^{th} km) it reaches about 1650 m (Fig. 3). It was established that a relatively adequate variation pattern is characteristic of Sw up to the depth of 10 m. As the inclination of the submarine shore slope is a derivative dimension indicating the ratio between the depth and the width it is obvious that its variation

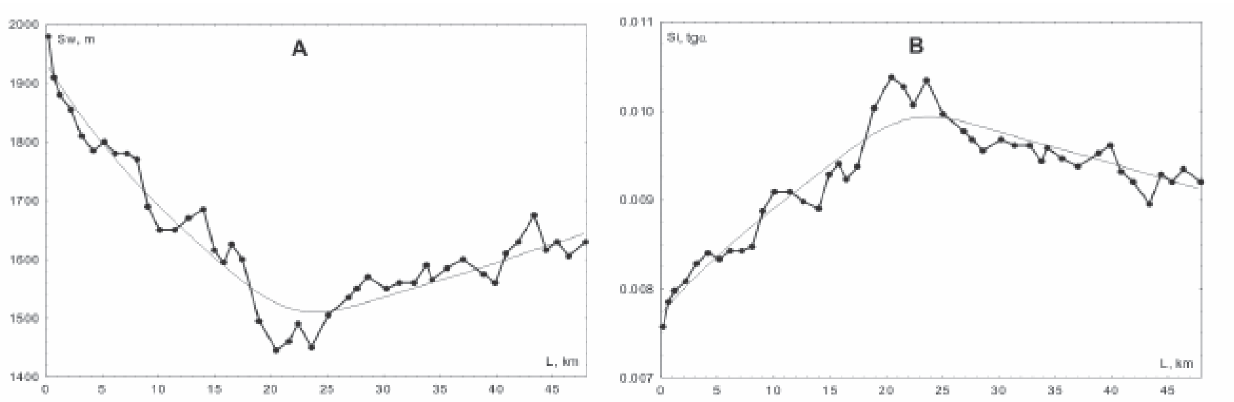

Fig. 3. Variation (and its smoothed trend) of submarine shore slope (up to depth of 15 m) width (A) and inclination (B) along the Curonian Spit. "0" on abscissa axis – Klaipėda Port jetty.

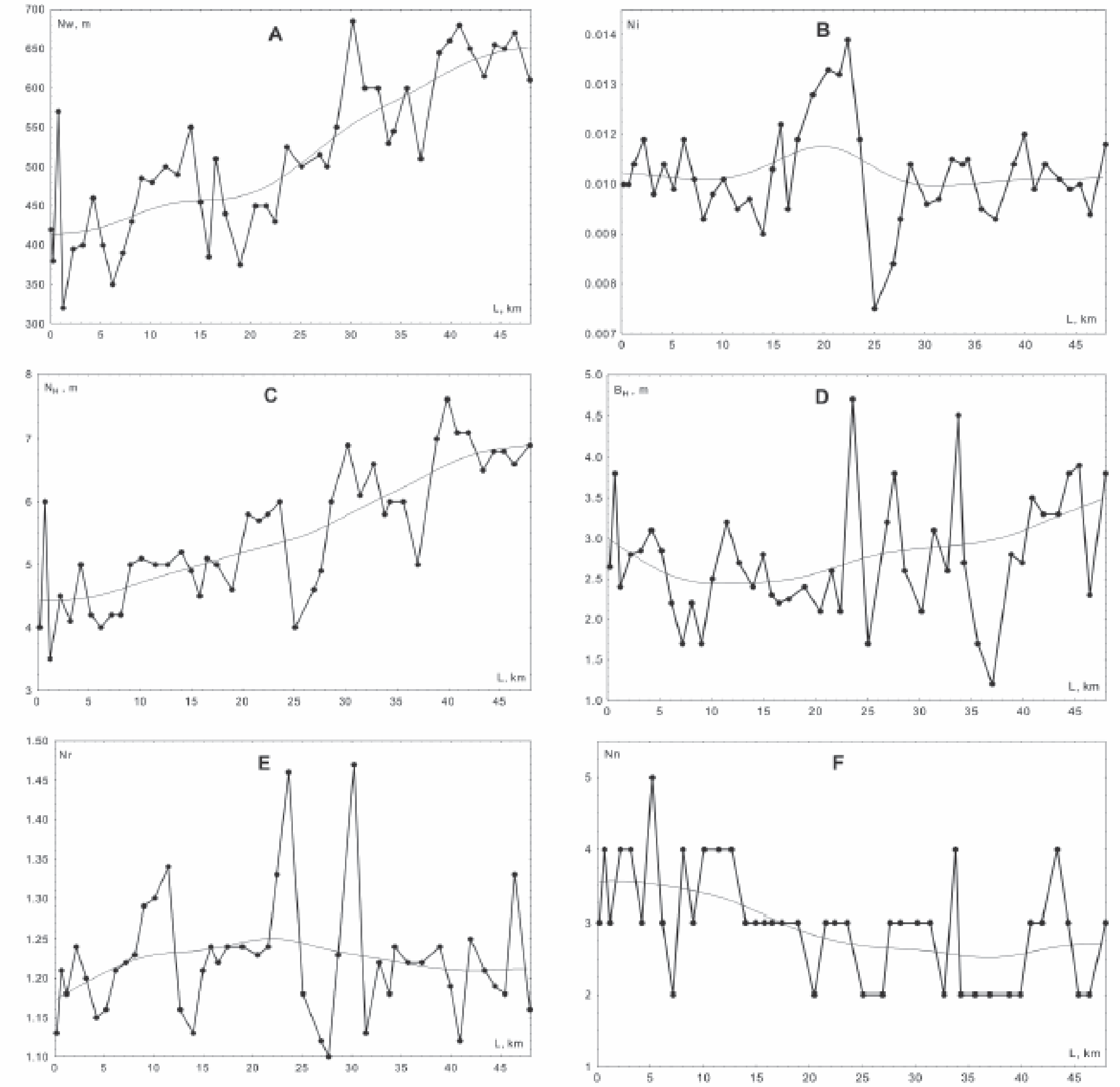

Fig. 4. Variation (and it smoothed trend) of nearshore width (A), inclination (B), depth (C), outer bar depth (D), curvature of bars parameters (E) and number of bars (F) along Curonian Spit. "0" on abscissa axis – Klaipėda Port jetty.

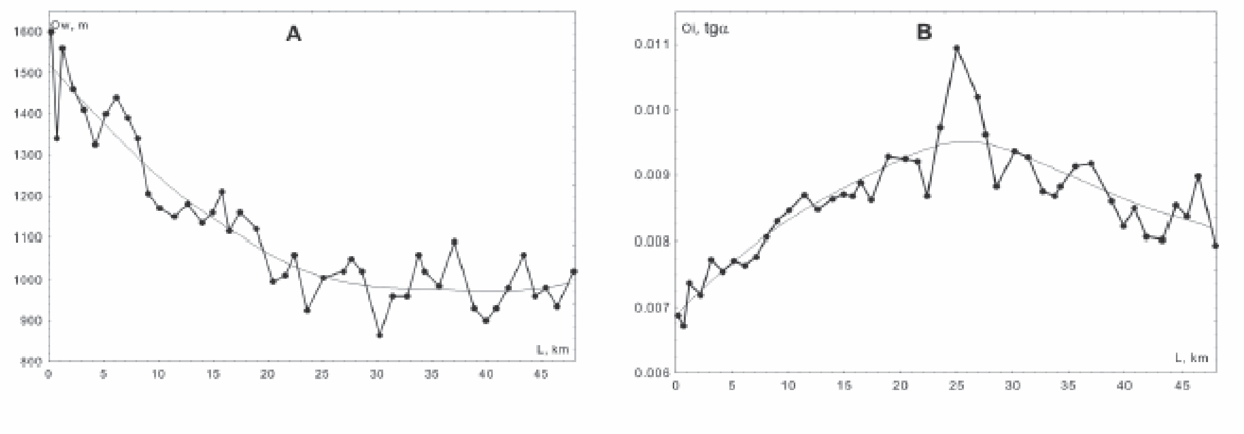

Fig. 5. Variation (and it smoothed trend) of offshore (up to depth of 15 m) width (A) and inclination (B) along the Curonian Spit. "0" on abscissa axis – Klaipėda Port jetty.

pattern along the Curonian Spit (the depth of 15 m in this case is a constant) is in inverse proportion to width dynamics (Fig. 3).

Nearshore width (Nw), inclination (Ni), depth (N_H) and depth of the outer bar (B_H). Moving southward from the Klaipėda Port jetties along the Lithuanian shore of Curonian Spit, the width of the nearshore zone relatively evenly increases from 380 m at Kopgalis to 650–670 m at Nida. A similar variation pattern is characteristic of the depth of the outer part of the bar zone: from 3.5–4 m at Kopgalis to 7 m at Nida (Fig. 4). The variation amplitude of the outer bar along the Curonian Spit nearshore is relatively large (3.6 m). The smallest depth of the outer bar crest is only 1.3 m and the largest is 4.9 m. It should be noted that notwithstanding that the data generalised by least square method imply a regular reduction of depths above the outer bar southward from the Klaipėda Port up to the northern part of Juodkrantė and their increase further southward till the Lithuanian–Russia border, they may considerably vary within different shore sectors (Fig. 4).

The inclinations in the southern and northern parts are comparable varying within a small range from 0.009 to 0.012. Marked changes of variation amplitudes of inclinations (from 0.0074 to 0.014) were determined only in the central part of the investigated sector.

Nearshore curvature (Nr) and number (Nn) of bars. Only generalised measuring data revealed certain patterns of curvature of bars variations along the Curonian Spit, i.e. increasing curvature of bars parameters from the Port of Klaipėda up to Juodkrantė and reducing those from Juodkrantė up to the Russian border. Yet in some nearshore sectors parameters of curvature of bars may strongly vary (Fig. 4). It is important to note that the number of bars not necessarily predetermines higher curvature of bars. In some nearshore sectors With two bars the curvature of bars are higher than in the sectors with three bars. The distribution pattern of bars along the Curonian Spit nearshore is more regular: usually 3–4 bars can be found in the northern part, 3 bars in the central part and 2–3 bars in the southern part. At Smiltynė II (6 km south of the Port of Klaipėda), even 5 bars were observed though in one measuring profile only.

Offshore width (Ow) and inclination (Oi). The width of the offshore evenly reduces from Klaipėda to Juodkrantė. Further southward it shows no pronounced tendency of change. In the sector from Klaipėda (0.00067) towards the southern part of Juodkrantė (0.011), the inclination of the offshore increases. Further to the south, it again reduces to 0.0078 at Nida (Fig. 5).

INTERELATION OF MORPHOMETRIC CHARACTERISTICS

A correlation matrix was created in order to find out possible interdependences of various morphometric parameters of submarine shore slope (see Table 1).

As is shown in Table 1, correlation coefficients of many measured and calculated morphometric parameters of submarine shore slope are low implying

Table 1. Correlation matrix of morphometric characteristics. Denotations of indices see in Fig. 2

	Ni	Si	Oi	Nw	N_H	Sw	Ow	Nr	B_H	Nn
Ni	1	0.2226	-0.1891	-0.2196	0.1826	-0.1679	-0.0109	0.1640	-0.0101	-0.0767
Si	0.2226	1	0.8871	0.3833	0.5078	-0.9914	-0.8774	0.4032	0.2030	-0.2400
Oi	-0.1891	0.8871	1	0.2882	0.2482	-0.8889	-0.7601	0.3310	0.0945	-0.2045
Nw	-0.2196	0.3833	0.2882	1	0.9092	-0.4145	-0.7720	0.1362	0.3723	-0.2484
N_H	0.1826	0.5078	0.2482	0.9092	1	-0.5123	-0.7964	0.1943	0.3657	-0.3026
Sw	-0.1679	-0.9914	-0.8889	-0.4145	-0.5123	1	0.8983	-0.4104	-0.2249	0.2182
Ow	-0.0109	-0.8774	-0.7601	-0.7720	-0.7964	0.8983	1	-0.3521	-0.3367	0.2719
Nr	0.1640	0.4032	0.3310	0.1362	0.1943	-0.4104	-0.3521	1	0.0482	0.1501
B_H	-0.0101	0.2030	0.0945	0.3723	0.3657	-0.2249	-0.3367	0.0482	1	0.3776

Table 2. Correlation matrix for morphometric characteristics smoothed by the least squares method. Denotations of indices see in Fig. 2.

	Ni	Si	Oi	Nw	N_H	Sw	Ow	Nr	B_H	Nn
Ni	1	0.2741	0.2650	-0.4373	-0.3457	-0.2417	0.0522	0.5654	-0.4625	0.1159
Si	0.2741	1	0.9801	0.4250	0.4693	-0.9973	-0.8791	0.7988	0.0226	-0.8119
Oi	0.2650	0.9801	1	0.2956	0.3320	-0.9725	-0.7990	0.8348	-0.1017	-0.7375
Nw	-0.4373	0.4250	0.2956	1	0.9948	-0.4669	-0.8035	-0.1210	0.8521	-0.8300
N_H	-0.3457	0.4693	0.3320	0.9948	1	-0.5094	-0.8295	-0.0677	0.8385	-0.8508
Sw	-0.2417	-0.9973	-0.9725	-0.4669	-0.5094	1	0.9015	-0.7818	-0.0580	0.8303
Ow	0.0522	-0.8791	-0.7990	-0.8035	-0.8295	0.9015	1	-0.4681	-0.4543	0.9642
Nr	0.5654	0.7988	0.8348	-0.1210	-0.0677	-0.7818	-0.4681	1	-0.4959	-0.3238
B_H	-0.4625	0.0226	-0.1017	0.8521	0.8385	-0.0580	-0.4543	-0.4959	1	-0.5563
Nn	0.1159	-0.8119	-0.7375	-0.8300	-0.8508	0.8303	0.9642	-0.3238	-0.5563	1

weak links or their absence. Whereas measuring data generalised by least squares method (se Figs. 3–5) show a rather consistent spatial distribution of parameters and rather close links between them (Table 2). The incongruity can be explained by specific character of measuring, specific features of hydrodynamic processes in the shore zone and high morphological diversity of adjacent sectors:

- the depth has been measured perpendicularly to the shore whereas the approaching angle (depending on wind direction) of wave field (forming the relief of the submarine shore slope) varies during different storms and it is not always perpendicular to the shore, i.e. the measuring profile may not coincide with the propagation direction of forming waves;

- the mean distance between the measuring profiles was about 1 km. As the nearshore is marked by high diversity, the measuring data obtained in two adjacent points may strongly differ (for example, one measuring is done over the bar top and some other over the bar gate or gap, etc.).

In order to eliminate the data fluctuations occurring due to the mentioned or some other causes, a correlation matrix for data sets generalised by the least squares method was created (Table 2).

As shown in the correlation matrix, analysis of the links between the variations of morphometric parameters along the Curonian Spit instead of the links between the measuring data revealed the indistinguishable or unpronounced regularities. The correlation links especially improved between the parameters whose values changed most markedly, e.g. between the parameters of curvature of bars (Nr) or outer bar depth (B_H). On the other hand, it became clear what parameters were not interrelated, e.g. the inclination of the nearshore (Ni) and most of other parameters. This means that the mentioned parameter is not representative as its calculation does not take into account the complex relief of the nearshore, i.e. specific features of bars, bar gates and other forms of relief and their influence on hydrodynamic processes.

Analysis of the data given in Table 2 leads to a conclusion that many parameters depend on the inclination of the submarine slope. With decreasing inclination (Si) and increasing width of the submarine shore slope the width of the bar zone and the depth of its offshore part decreases as also the number of bars do, but their parameter of curvature decreases. On the contrary, with increasing inclination (Si) and narrowing submarine shore slope the widening bar zone reaches greater depth. The depth of outer bar crest also increases. The number of bars decreases but the bars become larger. The mentioned regularities become especially obvious

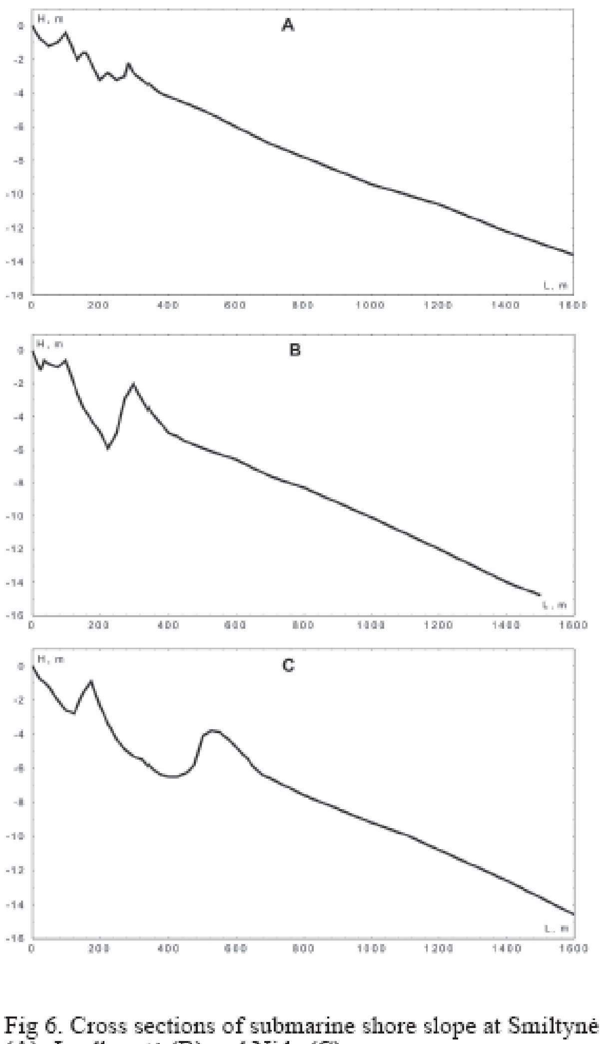

Fig 6. Cross sections of submarine shore slope at Smiltynė (A), Juodkrantė (B) and Nida (C).

by comparison of the profiles of the northern, central and southern parts of the submarine shore slope of Curonian Spit (Fig. 6). In the northern part of the spit (Smiltynė) the submarine shore slope is flat and wide whereas the bar zone is comparatively narrow and has 3–4 small bars. In the central and southern parts (Juodkrantė and Nida), the submarine shore slope is steeper and narrower but the bar zone is wider and has 2–3 rather large bars with wide and deep gates.

DISCUSSION

The discussed variation of morphological parameters along the submarine shore slope of Curonian Spit and their interrelations show that hydrodynamic activity in its central and southern parts is more intensive than in the northern part. As thorough investigations of wave field energy dissipation at the Lithuanian shores have never been carried out, the above given proposition may be confirmed based on the known hydrodynamic patterns.

Results of theoretical and laboratory investigations of wave transformations in the shallow sandy subma-

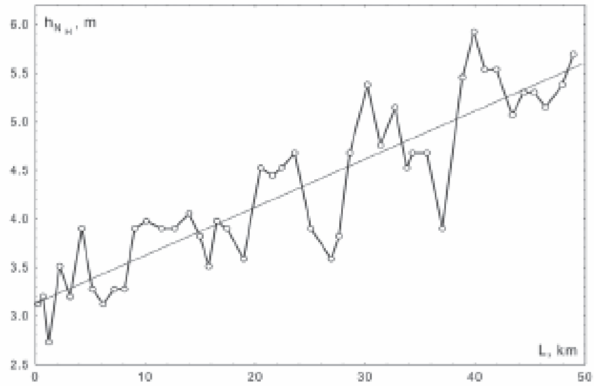

Fig.7. Variation (and it smoothed trend) of the calculated height ($_{hNH}$, m) of breakers (at the outer boundary of the nearshore) along the Curonian Spit (L, m). "0" on abscissa axis – Klaipėda Port jetty.

rine shore slope and their verification with field data (Longinov 1963; Kajima et al. 1982; Sunamura 1982; Iwata & Sawaragi 1982; Bowen & Huntley 1984; Stive 1984; Battjes & Stive 1985; Dally et al. 1985) show that linear (consecutively deepening) deformations (formation of bars and bar gates) of the slope under the impact of generated waves are in direct dependence on the dominant wave parameters and profile morphometry of submarine shore slope. Field data also revealed the influence of bottom inclination on the wave height. The wave height (at a stable depth) increases more rapidly in a steep bottom profile than in a flat one (Loginov 1963). It is a common knowledge that wave transformation (breaking) depends on the depth of the submarine shore slope (McCowan's criterion): h/H=0.78, where h – wave height and H – depth in the breaking area. Based on McCowan's criterion and measured depths near the outer boundary of the BAr zone (where as a result of wave transformation the linear relief of the submarine shore slope is replaced by the bar zone of complicated morphology) the variation pattern of breaker (forming near the outer boundary of the nearshore; see Fig. 2) height (h_{NH}) could be calculated. The obtained results (Fig. 7) show that breaker height regularly increases from north to south along the Curonian Spit. The nearshore relief in the northern part of Curonian spit (at Smiltynė) has been formed by lower breakers (about 3–3.5 m) whereas in the southern part (at Nida) by considerably higher ones (about 5–5.5 m). Unfortunately lack of field data does not allow explaining the considerable difference between the breaker heights in the investigated area.

The determined wave intensity variation pattern along the Curonian Spit also explains why the width of the submarine shore slope is in good correlation with the number of bars and relief parameters. Yet the link between the number of bars and relief parameters is weak. Larger waves and stronger currents in the southern and central parts of Curonian Spit nearshore are responsible for higher "loads" on the submarine shore slope. The number of bars in these parts is smaller but the bars are larger. Due to lower wave intensity and weaker alongshore water mass transport the bar zone in the northern part of the spit is narrower. The bars are smaller but their number is greater. This is partly proved by investigation results on sand differentiation features in the shore zone of Curonian Spit (Jarmalavičius & Žilinskas 2006).

It should be noted that the offshore relief of the investigated area the changes are negligible. Meanwhile the nearshore relief of Curonian Spit and its changes are predetermined by recent coastal processes. The shallow nearshore in the northern part of Curonian Spit has developed under a strong influence of anthropogenic activity: the influence of the Klaipėda port jetties on the alongshore sediment migration (Žilinskas 1998).

Analysis of above presented data show that morphological peculiarities of the submarine shore slope are mainly predetermined by the interaction between hydrodynamic factors (waves and currents) and morphology (conditioning wave deformation and transformation) of submarine shore slope. Thus, it is obvious that recent relief of the submarine shore slope of Curonian Spit is a result of this interaction. Analysis of the interaction of these factors reveals the existence of reciprocal relationship between hydrodynamic and morphological parameters directed at suppression of the process. This means that a more intensive hydrodynamic environment produces physiologically better expressed morphometric parameters which reciprocate suppression of hydrodynamic factors. This natural self-preservation mechanism of the sandy submarine shore slope is reflected in the interdependence of morphometric parameters.

CONCLUSION

Analysis of investigation data shows that some of the chosen morphometric parameters of submarine shore slope vary along the Curonian Spit following a regular pattern. Moreover, the variations of some parameters are interrelated. With decreasing of inclination (Si) and increasing width of the submarine shore slope the width of the bar zone and the depth of its offshore part decrease as decrease also the number of bars. Yet their parameters of curvature become smaller. On the contrary, with increasing inclination (Si) and narrowing submarine shore slope the widening bar zone reaches greater depth. The depth of the crest of outer bar also increases. The number of bars reduces but the bars become larger.

Based on calculations, a regular pattern of breaker (near the outer boundary of the nearshore) height variation along the Curonian Spit (from north to south) was determined. The nearshore relief in the northern part of Curonian Spit (at Smiltynė) has been formed by lower breakers (about 3–3.5 m) and in the southern part (at Nida) by considerably higher ones (about 5–5.5 m).

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