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Cliff Retreat Induced by Series of Storms at Międzyzdroje (Poland)

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ABSTRACT

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In Międzyzdroje, a coastal town in Poland, significant cliff retreat has been observed in recent times. It used to be considered mainly a response to storm events with particularly high water levels and wave energy. However, morphology of cliff coasts is shaped not only by the most extreme storm surges or by a number of accompanying processes such as precipitation. Much wider effects are now being linked to the occurrence of series of subsequent storms. This research uses a set of five terrestrial LiDAR surveys carried out between November 2016 and April 2017 to determine short-term cliff erosion associated with two major storm surges and several smaller storms. The surveys covered the whole cliff profile as well as the topography of the adjacent beach.
Results indicate a considerable reduction in beach levels as a first important effect. Frequency of the storm events prevented the beach from recovering between the surges, allowing the waves to directly attack the cliff base. Consequently, the cliff foot line retreated up to 4.7 m. This resulted in an erosion volume exceeding 25.000 m^3 within 5 sections of the coastal cliff analysed, which are 500 m long in total.
This work demonstrates that the development of the coastline is not only directly linked with the rate of erosion at given storm parameters. More importantly, the frequency of extreme events has to be considered.

ADDITIONAL INDEX WORDS: *cliff coast, cliff erosion, extreme events, storm effects, terrestrial LiDAR.*

INTRODUCTION

The Wolin Island cliff formation and its dynamic morphology has long been a matter of widespread interest by researchers. Numerous works describe erosion rates measured either directly in the field (both with traditional and modern measurements techniques) or by analysing historical maps (Hartnak 1926, Kostrzewski and Zwoliński, 1995, 2012, Kolander, Morche and Bimböse 2013, Kostrzewski *et al.,* 2015). All the research carried out thus far indicate that the weather conditions are the primary factor influencing cliff erosion, though the interrelation between cliff and foreshore is relevant as well (Lee and Clark, 2002). Decreased beach width and elevation directly correspond with higher rates of cliff erosion (Sallenger *et al.,* 2002) though both mathematical models (Walkden and Hall, 2005) and in situ observations (Lee, 2008; Dornbush *et al.,* 2008) emphasize that beach elevation changes are more important than beach width in controlling the wave attack at the cliff base.

This paper presents results of an analysis of short-term cliff erosion associated with a series of storm surges at Międzyzdroje (Wolin Island, Poland). The goal is to analyse (1) effects of weather conditions on erosion, (2) investigate the relationship between changes in beach elevation and cliff erosion rates and (3) study the cumulative effect of several storms reaching the coast within a short period of time.

STUDY AREA

The Wolin Island cliff coast is located in northwest Poland. The steep cliffs were cut by the sea in a terminal push moraine, which is the most significant landform in the northern part of the island. In the investigated 500-meter-long segment of the coast cliffs are up to 54 m high, and are built from strongly distorted post-glacial sediments covered by aeolian sands (Borówka *et al*., 1982).

Coastal erosion at the Wolin Island have been previously studied in short (Kolander, Morche and Bimböse 2013, Terefenko *et al.,* 2017), medium (Kostrzewski and Zwoliński, 1986, 1995, 2012, Subotowicz, 1982) and long-term (Heiser, 1925, Szopowski 1961) analysis. The latter found that in the long perspective (1695-1886) cliff top recession rate reveal an average of 1.0 m/year. Recent measurements (Kostrzewski *et al.,* 2015)

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highlight a significant reduction in cliff retreat rates down to 0.24 m/year (in years 1985-2012) underling that locally cliff top line retreat was fluctuating from nil up to 4.33 meters. However precise volumetric changes computed by Kolander *et al.,* (2013) on a small, 70-meter-long test site have revealed that small changes of cliff top line do not always correspond to the volume of eroded sediment.

It is known that on the Baltic, where the tide amplitude does not exceed a few centimetres, the storm surges have the highest significance within the aspect of coastal erosion. Disastrous consequences on the coast are observed especially when a storm surge overlaps with a high volume of water in the Baltic, also known as "basin filling". In recent decades, the highest absolute amplitude of sea level changes in the study area was recorded during year 1984 (2.79 m), whereas the most extreme storm surge occurred in November 1995 (+1.61 m above mean) (Wolski *et al.,* 2013). However, extreme value analysis have shown that a 100-year storm surge in the western part of the Polish coast could reach +1.71 m above mean, and a 500-year event would exceed 2 m (Paprotny and Terefenko, 2017). The highest recorded sea level in the timeframe of this study was 1.4 m and corresponds approximately to an event with a return period of 20 years.

As the Wolin cliff is subject to intense erosion parts of the coast are artificially protected. On the study area the beach is protected by a series of flat concrete blocks digged into the sand around half-way between the water line and cliff base line.

METHODS

The data used in this study cover a survey timeline from November 2016 to April 2017. Five topographic surveys were obtained with the terrestrial laser scanner technology – LiDAR (Light Detection And Ranging), which is broadly used in surveying and monitoring of coastal processes (Buckley et al., 2008, Nunes et al., 2011), including Wolin Island (Kolander et al., 2013). The LiDAR system used for the scannings was Riegl VZ-400. Each LiDAR survey of 500-meter-long test site was performed from 10 spots acquiring 90 to 100 points per m2 with an estimated vertical accuracy better than 5 mm. Having the first basic LiDAR measurement obtained before the storm season, the other surveys were conducted in a two-way manner. The first considers "intervention" measurements performed as fast as possible after all storms events, while the second monitoring type had a "cyclic" character of measurements independent of factors controlling cliff recession. For purpose of interpretation the periods between each LiDAR surveys are referred henceforth as periods I, II, III, and IV. Period I refers to the time between first and second survey and so on for other periods.

In one case (period I), due to the weather conditions between two storms the measurements were not realized and the coastal response will be described corresponding to both events.

In order to facilitate data analysis calculations of sediment balance of erosion and accumulation were performed in five sections and coast changes were presented on the differential rasters. From each survey the cliff base line and a 1-meter contour above mean sea level (MSL) were extracted. Additionally, five profiles, one in each section, were drawn in locations with distinct cliff recession.

The sea level data was obtained from a tide gauge in Świnoujście owned by the Institute of Meteorology and Water Management - National Research Institute in Poland and available online as part of a weather forecast service (www.pogodynka.pl).

Estimates of significant wave height (Hs) and their direction were obtained from the WAM model, which utilizes wind data from the COAMPS model, and is provided by the Interdisciplinary Centre for Mathematical and Computational Modelling of Warsaw University (ICM) in the framework of the project HIPOCAS EU (Cieślikiewicz and Paplińskia-Swerpel, 2008).

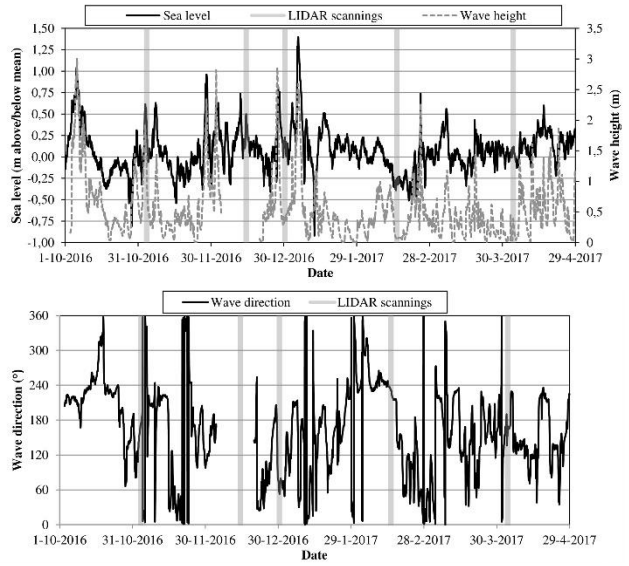


Figure 1. Offshore significant wave height along with sea level above/below MSL (upper graph) and wave direction (bottom graph). Vertical gray lines represent performed LiDAR surveys.

RESULTS

During the monitoring period study area was exposed to five major storms (Figure 1) with offshore significant wave heights (H_S) exceeding 2 m and the water level more than 0.5 m above MSL. The first two storms occurred in a short time during period I, with maximum H_S of 2.34 m (28 November 2016) and 2.82 m (2 December 2016). The water levels during those storms reached maximums of 0.96 m and 0.59 m above MSL, respectively. Almost one month later, during period II (27 December 2016), the highest H_S in the whole analysed half-year was registered (2.86 m), with sea level reaching a maximum of 0.82 m. After a significant water level drop to -0.02 m within 48 hours another storm was registered five days later in period III (4 January 2017). Although the H_S was lower than in previous ones reaching at most 2.59 m, the water level hit its highest value of 1.4 m above MSL. The last episode recorded in period IV characterizes with much lower maximums with significant wave height of 2.27 m and water level reaching 0.74 m.

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Table 1. Measurements of shoreline retreat, cliff foot line retreat, average beach height change and volume change between surveys.

Variable	Section	Period I	Period II	Period III	Period IV	Total change
Shoreline (1 m above MSL) retreat in selected profile (m)	I	1.52	-3.40	-0.14	1.24	-0.78
	II	-2.01	-4.40	6.47	-0.07	-0.01
	III	-3.01	-1.79	2.05	1.45	-1.30
	IV	-4.62	-0.66	0.62	0.65	-4.01
	V	-4.89	-0.42	-3.45	7.27	-1.49
Cliff foot line retreat in selected profile (m)	I	-0.11	-0.04	-3.6	-0.02	-3.77
	II	-0.37	0.06	-2.11	1.09	-1.33
	III	-0.46	-0.92	-4.12	0.35	-5.15
	IV	-0.18	-0.39	-2.41	0	-2.98
	V	0.02	0.05	-3.67	-0.03	-3.63
Average beach height change in selected profiles (m)	I	0.12	-0.31	0.02	0.14	-0.03
	II	-0.19	-0.54	0.40	-0.01	-0.34
	III	-0.11	-0.31	0.18	0.09	-0.15
	IV	-0.30	-0.22	0.12	0.02	-0.38
	V	-0.39	-0.06	0.09	0.15	-0.21
Volume change (m^3)	I	-205.1	-358.8	-1612.8	-538.7	-1971.6
	II	-204.2	-700.9	-1000.7	-584.0	-1701.6
	III	-366.7	-860.2	-2541.0	-710.9	-3401.2
	IV	-742.6	-441.5	-5334.2	-623.3	-5775.7
	V	-295.2	-1217.0	-5268.8	-1377.1	-6485.8

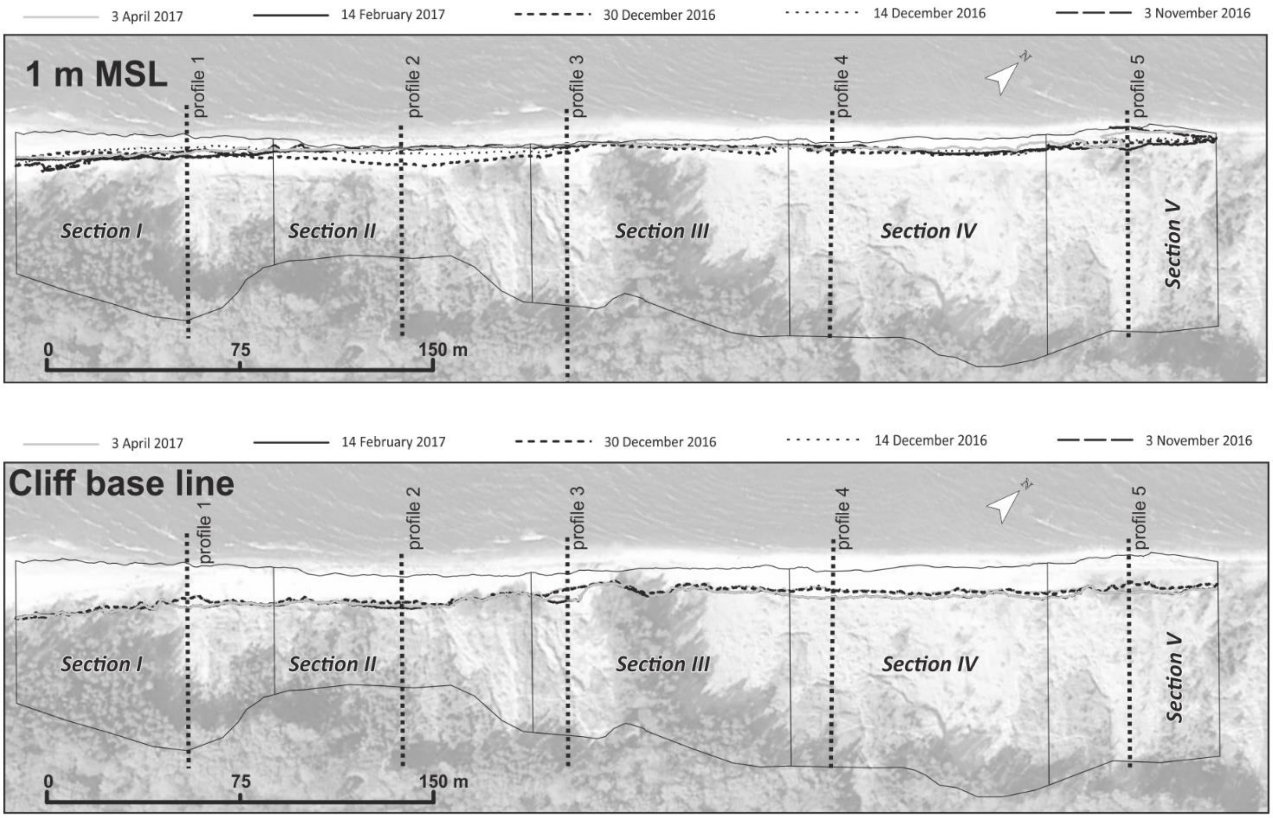


Figure 2. Retreat of the 1 m MSL contour (upper graph) and cliff foot line (bottom graph) with the orthophoto map from 2010 in the background.

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The impact of the registered storms has been observed in the beach-cliff system and is presented numerically in Table 1 and graphically in Figures 2 and 3. From a volumetric comparison it is clear that erosion processes dominated in the investigated area. In a 500-meter-long segment of the coast the total amount of eroded materials during one winter season reaches a value of over 25.000 m^3. Notwithstanding the clear erosion dominance across the whole study area, the retreat of the cliff top was almost unnoticeable. By contrast, the retreat at the cliff base averaged 3.3 m. Measurements of the beach topography revealed large variations in beach height. In different time periods investigated, both accumulation and erosion was observed in all profiles.

Detailed analysis of shoreline retreat, cliff base line changes, beach height changes and volumetric changes in different sections of the area during the monitoring periods reveals several important points. The general trend of lowering beach height can be observed. Final total changes in all sections show a decrease in beach level with values varying from 0.03 to 0.38 m. The beach lowering processes run differently in each section, though some similarities are visible. Highest erosion rates on the beach are directly linked with first two storms representing events with the highest H_S. They managed to lower the beach significantly enough to uncover concrete blocks digged into the sand to protect the coast. Profile no. 1 (Figure 3) demonstrates examples of the beach-cliff system changes in the westernmost part of the study area. While the cliff top was stable all the time, a noticeable shoreline retreat was observed mainly in the first two periods.

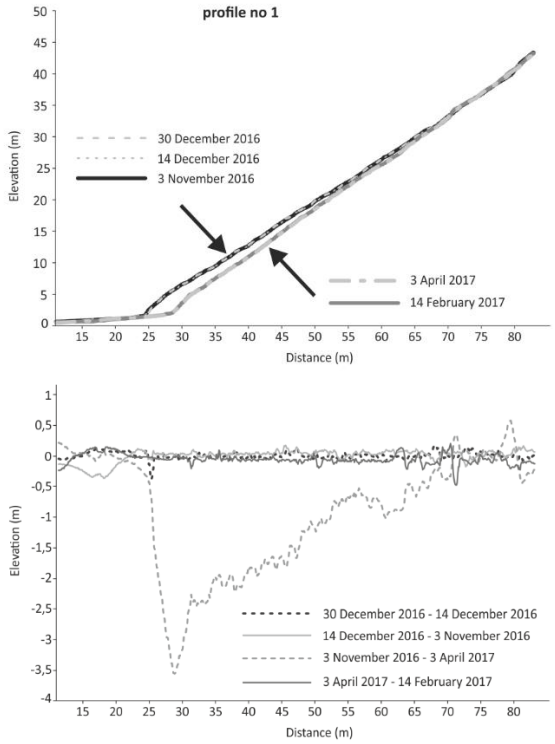


Figure 3. Selected beach-cliff profile number 1 (upper graph) and elevation differences between surveys along the profile (bottom graph).

Concurrently with a beach lowering of up to 0.40 m, the shoreline receded from 2 to almost 5 m. Both storms managed to significantly lower the beach. In sections I, II and V 95% of volume loss is attributed to changes in the beach. In those periods storms affected the cliff itself only in sections III and IV which is represented respectively by 9% and 13% of eroded material. In period III even though the conditions (in terms of H_S) were not at their most extreme, low beach and particularly high water levels enabled the storm to attack the cliff face directly. In effect, the cliff base line pulled back from 2.11 m in section II up to 4.12 m in section IV. Cliff face was cleaned from massive amounts of debris which was later partially distributed on the beach. The percentage of ,material transferred to the beach varied from a minimum of 20% in section I up to maximum of 57% of in section II during period III and from null in section II to 21% in section V during period IV. Finally, over 15.700 m^3 of material from the whole area was transferred from the study area to the sea. This accounts for 63% of all material balance in the whole investigated period.

It is possible to observe that the first two periods (three storms) were mainly responsible for beach height lowering and shoreline retreat, while in period III the dominant process was cliff erosion and recovering of beach height and length. Finally the last event (period IV) partially continues the recovery process (section V) or restarts the beach erosion (section II).

DISCUSION & CONCLUSIONS

Studies realized on Polish dune coasts have shown that the strongest correlation is associated mainly with sea level rise during the storm surge and secondly with significant wave height values (Terefenko *et al.,* 2017). It is also proved that beach elevation changes plays a crucial role in controlling the wave attack at the cliff base (Dornbush *et al.,* 2008) and storm waves can be extremely effective in causing cliff recession, especially on soft, sandy cliffs (Lee and Clark, 2002). Generally the presence of the beach provides cliff protection since the wave energy dissipates on the foreshore (Nunes *et al.,* 2011). In the study area, the beach has been artificially strengthened with concrete blocks. Their role is not only to reduce the wave energy, but also to prevent massive debris removal.

In the study area the succession of first three storms with wave peak between 2.4 and 2.8 m H_S and sea levels between 0.6 and 0.96 above MSL significantly reduced both the beach length and height, even if relatively low volume changes have been observed. It is therefore possible to presume that between the storms the beach managed to recover partially. This assumption is also supported by the decreasing values of shoreline retreat and beach depletion after each storm, even though their parameters did not differ much.

The cumulative impact on the coastal system appears when the storms hit the coast within a short period of time. When the storm hit the investigated area on 4th January 2017 it was just 7 days after previous event, the beech recovery was prevented due to frequency of events. As a result, a rapid cliff foot debris removal was observed. Although almost 25% of this material was redeposited on the beach, marine erosion determined a consequent sediment loss from the beach-cliff system additionally uncovering the cliff face to different landslide processes (Figure 4).

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The results presented here confirm previous studies on the role of factors that determine the magnitude of coastal erosion in the southern Baltic, especially in connection to the process of beach depletion. It also clearly demonstrates how the effects of intense storms are magnified by their frequency.

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Figure 4. Wolin cliff coast in section I. Situation before (upper image) and after (bottom image) the 4th January storm.

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