

# ENHANCED DUNE EROSION DUE TO ATTENUATION OF COASTAL ICE PHENOMENA

Krzysztof Piłczyński, Institute of Hydro-Engineering of Polish Academy of Sciences, [krzysztofpilczynski@ibwpan.gda.pl](mailto:krzysztofpilczynski@ibwpan.gda.pl)  
Piotr Szmytkiewicz, Institute of Hydro-Engineering of Polish Academy of Sciences, [piotrszmytkiewicz@ibwpan.gda.pl](mailto:piotrszmytkiewicz@ibwpan.gda.pl)

## INTRODUCTION AND AIM OF THE WORK

The Baltic Sea is a shallow, non-tidal, relatively small basin. 75% of the South Baltic coast are sandy, dissipative, multi-bar coastal segments with well-developed dunes. Wide beaches and sufficiently high dunes serve as a natural protection of the hinterland from both erosion and marine floods.

Enhanced loss of beaches and destruction of dunes have been observed in recent decades. It is estimated that at the turn of the 21st century the mean rate of shore recession for the entire Polish coast was in the range of 1- 2 m/year and now tends to grow (Frankowski et al. 2009).

Prior to the recent increase in climate warming, which has been intensifying in recent years, the ice cover that existed in the coastal zone, on the beach, and in the dunes had been observed for decades and centuries, providing significant protection against wave action during winter. Consistent with the global trend of decreasing ice covers, this phenomenon is also taking place in the southern Baltic Sea. In line with the global trend of declining ice covers, this phenomenon is also occurring in the southern Baltic Sea.

The Baltic Sea's climate and the changes occurring within it are significantly influenced by the large-scale atmospheric circulation over the European and North Atlantic regions (Chen and Hellström, 1999). During autumn and winter along the coast in Southern Baltic Sea, the atmospheric circulation results in a noticeable increase in sea levels. These changes in sea level are associated with wind-induced piling up. Strong onshore winds increase the threat of extreme storm surges, leading to a higher risk of severe coastal erosion, impacting beaches and dunes. Studies regarding sea levels in the Baltic Sea (Suursaar et al., 2006; Andersson, 2002; and Janssen, 2002) indicate a growing correlation between atmospheric circulation and sea levels during winter months. Furthermore, Różyński and Pruszek (2011) indicate a long-term increase in storminess in the Southern Baltic, concurrently showing a strong relationship between the North Atlantic Oscillation (NAO) and significant wave height ( $H_s$ ) in January. Inspection of the winter index of the North Atlantic Oscillation (NAOWI) serves as a reliable proxy indicator for storminess (Różyński and Szmytkiewicz, 2012). Positive values of NAOWI denote more storms and warmer temperatures, which, as a result, cause the formation of coastal ice barriers to be delayed and winter erosion to be enhanced. In addition to low temperatures, climatic factors also influence the formation, distribution, and dynamics of sea ice in the Baltic Sea region. These ice phenomena in the Baltic Sea are particularly sensitive to factors such as cloud cover and sunlight during the summer, as well as air and sea surface temperatures and wind speed over the Baltic Sea during late autumn and winter, just before

the appearance of ice (Leppäranta and Myrberg, 2009). Additionally, the presence of sea ice in the Baltic Sea depends on the duration of periods when dry and cold polar-continental air masses persist over the Baltic Sea; these occur due to the influence of eastern anti-cyclonic circulation, ocean currents, and the general characteristics of the specific basin, including its size, depth, exposure to open sea, coastline configuration, wind directions, and river inflows.

When analyzing the impact of ice cover on dune protection, two aspects should be considered. One is related to the presence of ice in shallow waters, while the other involves the freezing of dunes and beaches during cold periods (Girjatowicz and Łabuz, 2020; Pruszek et al., 2012). While the former effect is becoming less frequent each year, due to climate change, periods with cold days (temperatures below 0° C) are still present. These situations do not lead to the freezing of the Baltic (they are too short-lived for that), however, they do last long enough to contribute to the freezing dunes and beaches. This study aims to assess the impact of the freezing process of dunes and beaches, as well as occurring ice covers events on dune stability and coastal erosion processes. As a result, an empirical formula has been developed that aims to illustrate the relationship between dune erosion, storm surge, deep water wave height, and the occurrence and duration of sub-zero temperatures.

## METHODOLOGY AND RESEARCH FRAMEWORK

The conducted research comprises two study areas: in-situ measurements and experiment set-up.

### *In-situ measurements*

The first study area involves the analysis of in situ measurements on a three-kilometer-long, natural, undeveloped segment of the coastal dune system on the coast of South Baltic Sea. The analyzed measurements include 30 years of bathymetric and tachymetric data (collected on a monthly basis), records of air temperature, deep water wave heights, and water levels (storm surges). In this step, historical data are used to assess the differences in beach and dune evolution during conditions with similar storm wave and water level situations, with and without dune icing events. From this analysis, conclusions are drawn regarding the general impact of dune icing on coastal stability.

### *Experiment set-up*

To compare the erosion level of frozen dunes against unfrozen dunes in a controlled laboratory conditions, a new run-up flume has been constructed. The flume is 30 m long, 4.8 m wide and 1.2 m tall (Fig. 1). The research involved comparing the transformation of the beach and dune under frozen and unfrozen conditions. This was

achieved by constructing a beach and dune slope. Subsequently, equipment was activated to induce wave run-up processes on the beach and dune. The wave action was then halted, and measurements of the beach and dune transformation were taken. This procedure was applied for various wave run-up heights, different beach and dune configurations, as well as for frozen and unfrozen beach and dune conditions. Corresponding measurements were mutually compared, and conclusions were drawn from these comparisons. For comprehensive examination of this process, an overhead camera was employed to monitor the free surface movement over the tank. Additionally, during the experiment, the real-time evolution of the dune profiles were recorded with an a high-speed three-dimensional FARO Laser Scanner. To enhance the contrast between the water and the ramp, a dye was added to the water.



Figure 1 - View of the experimental set-up.

## RESULTS AND CONCLUSIONS

The analysis of tachymetric measurement data, wave data, water level data and air temperature data shows that in the 1980s and 1990s of the 20th century, under conditions where the significant wave height in deep water was less than approximately 2.0 m, frost occurred for at least 10 days, the coastline experienced about 20% less erosion compared to periods with the same wave conditions but positive temperatures. When the wave height exceeded 2.0 m, the influence of freezing on dune erosion diminished.

Data collected for the 21st century indicates that the previously observed regularity has ceased to be unambiguously noticeable. Measurements show that during this period, the number of storm events decreased, while the occurrence of storm surges increased, and periods with negative temperatures occurred less frequently, although with greater intensity (larger temperature fluctuations). The trend identified for the 1980s and 1990s of the 20th century is only observed in approximately 30% of the data in the 21st century. This would suggest that the influence of dune freezing increases dune stability by only about 12%.

Series of measurements conducted in the laboratory have allowed the development of a theoretical formula that links the wave run-up velocity, the slope angle of the

coastline, dune erosion, and accounts for dune freezing. The mean squared error of this formula and the conducted measurements is approximately 0.87. Considering the significant simplification used to describe the studied phenomenon and the strong non-linear processes associated with dynamic wave run-up on the coastline and dune, as well as the non-uniformity of dune freezing, a general conclusion can be drawn. Firstly, the conducted measurements confirm the positive impact of dune freezing on their stability. Secondly, the formula that has been developed should be tested under natural conditions.

## REFERENCES

- Andersson (2002): Influence of long-term regional and large-scale atmospheric circulation on the Baltic Sea level, *Tellus A* 54: 76-88.
- Chen, Hellström (1999): The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: spatial and temporal variations, *Tellus* 51A: 505-516.
- Frankowski, Graniczny, Juszkievicz-Bednarczyk, Kramarska, Pruszek, Przedziecki, Szmytkiewicz, Werno, Zachowicz (2009): Principles of documentation of geological-engineering foundation conditions for marine structures and coastal protection measures, Polish Geol. Inst., Warsaw, 201 pp., (in Polish).
- Girjatowicz, Łabuz (2020): Forms of piled ice at the southern coast of the Baltic Sea, *Estuar. Coast. Shelf Sci.*, 239, 106746, <https://doi.org/10.1016/j.ecss.2020.106746>.
- Janssen (2002): Statistical analysis of multi-year variability of the hydrography in North Sea and in the Baltic Sea, PhD thesis, Univ. of Hamburg.
- Lepparanta, Myrberg, (2009): *Physical Oceanography of the Baltic Sea*. Springer-Praxis, Heidelberg, Germany, 378p.
- Pruszek, Schönhofer, Różyński (2012): Spatiotemporal analysis of variations of certain morphological beach forms, *Coastal Engineering Proceedings*. 1. 10.9753/icce.v33.sediment.82.
- Różyński, Pruszek (2011): Long-term rise of storminess of the Baltic Sea near Poland; Possible origin and consequences, *Coastal Engineering Proceedings*. 1. 10.9753/icce.v32.management.1.
- Różyński, Szmytkiewicz (2012): Long term evolution of Baltic Sea sandy beach forced by winter North Atlantic Oscillation (NAOWI). *Coastal Engineering Proceedings* 1 (33): sediment.70.
- Suursaar, Jaagus, Kullas (2006): Past and future changes in sea level near the Estonian coast in relation to changes in wind climate, *Boreal Env. Res.* 11: 123-142.