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GEOLOGICAL STRUCTURE OF THE SOUTHERN BALTIC COAST AND RELATED HAZARDS

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Abstract. Polish coast of the Baltic Sea has a total length of 498 km (without internal lagoons coasts). Quaternary deposits dominate coastal zone, similar to central and northern Poland. According to morphology and geological structure, three types of coast are distinguished: cliffs (*c.* 101 km), barriers (380 km) and coast similar to wetlands (salt marshes) (*c.* 17 km).
Generally, three types of mass movements can be distinguished on cliff coast: eboulements (rock falls) dominated on the cliffs built mainly by tills, talus and landslip, dominated on sandy cliffs, and typical landslides occurred on cliff stretches with a complex structure where the main role play clay layers being initial slide layers for other deposits.
Serious risks are related to erosion of low and narrow barriers, which could be easy broken during storm surges. Storm floods in case of barrier being broken threaten lowlands behind the barriers. Similar flood hazard exists also on lagoon coasts located behind large and relatively stable barriers. It is caused by barographic high water stands, which in extreme cases reach up to 2 m above the mean sea level, and water back flow into straits connecting lagoons with the sea.

Key words: cliffs, barriers, coastal erosion, landslides and storm floods, southern Baltic.

Abstrakt. Długość polskiego wybrzeża morskiego wynosi 498 km (bez linii brzegowej Zalewów Wiślanego i Szczecińskiego). W budowie geologicznej strefy brzegowej, podobnie jak środkowej i północnej Polski, dominują osady czwartorzędowe. Biorąc pod uwagę geomorfologię i budowę geologiczną wyróżniono trzy zasadnicze typy wybrzeży: klify o łącznej długości ok. 101 km, wybrzeża wydmowe (mierzeje) o łącznej długości ok. 380 km oraz wybrzeża nizinne typu Wetland o długości ok. 17 km.
Na wybrzeżach klifowych wyróżniono trzy typy ruchów masowych: obrywy dominujące na klifach, w których występujeglina zwałowa, zsuwy i osypiska dominujące na klifach zbudowanych głównie z osadów piaszczystych oraz typowe osuwiska występujące na klifach o złożonej strukturze geologicznej, gdzie główną rolę odgrywają warstwy ilaste będące powierzchnią poślizgu dla warstw wyżejległych.
Poważne zagrożenia związane są też z erozją niskich i wąskich mierzei, które łatwo mogą być przerwane w czasie sztormów. Nisko położone obszary zaplecza mierzei w takim wypadku zagrożone są powodziami sztormowymi. Podobne zagrożenia powodziowe istnieją też na zapleczu mierzei relatywnie stabilnych — szerokich z wysokimi wałami wydmowymi. Powodzie mogą wystąpić w przypadku wysokich stanów wody spowodowanych spiętrzeniami sztormowymi i barycznymi, dochodzącymi maksymalnie do 2 m ponad średni poziom morza, kiedy dochodzi do wlewów wód morskich do Zalewów i jezior przybrzeżnych.

Słowa kluczowe: klify, mierzeje, erozja brzegu, ruchy masowe, powodzie sztormowe, południowy Bałtyk.

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INTRODUCTION

During the Atlantic Period, due to the presence of the permanent connection of the Baltic with the ocean, the dominant role in coastal development was played by glacio-eustatic sea level rise. Effects of glacio-eustatic vertical crustal movements on evolution of the southern Baltic coast diminished in that time. In Late Holocene, the importance of glacio-eustatics in the Baltic Sea declined along with the reduction of its importance at the global scale. During the last 8500 years, the water level rose by *c.* 28 m, and the shoreline moved southwards over a distance ranging from about 60 km in the Pomeranian Bay, to about 5 km in the Gulf of Gdańsk. The shoreline location reached the present state at the final phase of the Atlantic Period. Late Holocene was a period when coast developed under conditions of ceasing transgression, the shoreline becoming gradually closer and closer to its present setting.

When sea level rise is slow, more important for coastal processes became morphological and geological characteristics of the coast, lithologic properties of rocks building the seafloor and the coast, as well as sedimentary material erosion, transport and accumulation. Those characteristics and properties may very substantially affect the rate, and sometimes also the direction, of changes taking place on the shores.

At present, the southern Baltic coast seems to enter a new developmental stage. For about 50 years, the entire coast has been showing an accelerated sea level rise as well as an increasing frequency and force of storms (e.g. Dziadziuszko, Jednorał, 1996; Rotnicki, Borzyszkowska, 1999). Those phenomena bring about accelerated erosion of the shores both cliffs and dunes, and have been described in numerous publications.

GEOLOGICAL SETTING

Polish coast of the Baltic Sea has a total length of 498 km (without internal lagoons coasts). Coastal zone, similar to central and northern Poland, is built of Quaternary deposits; Pleistocene tills, clays and sands on morainal uplands, and Holocene muds and sands on lowlands. Thickness of Quaternary deposits in the coastal zone changes, in general, from *c.* 50 to *c.* 100 m, in some places up to 300 m. The main parent formation of the marine clastic sediments are glacial and fluvioglacial deposits. Holocene marine sediments are residual or are the products of multiple redepositions of eroded Pleistocene deposits. Thickness of marine sand and gravel in the coastal zone varies from 0 m in some places in front of cliffs, to dozen meters in the barriers. Only very locally, on the western coast of the Gulf of Gdańsk, Tertiary (Miocene) sandy and sandy-clayey deposits are cropped out in the cliffs.

According to morphology and geological structure, three types of coast are distinguished: cliffs, barriers and coast similar to wetlands (salt marshes). Cliffs builds *c.* 101 km of the Polish coast. Barriers are the most common type of the coasts with a length of 380 km. Wetlands are not very common; occur on the north-western coast of the Gulf of Gdańsk (*c.* 17 km in Puck Bay and Lagoon) and other lagoonal coasts, only, not directly influenced by marine processes (Fig. 1).

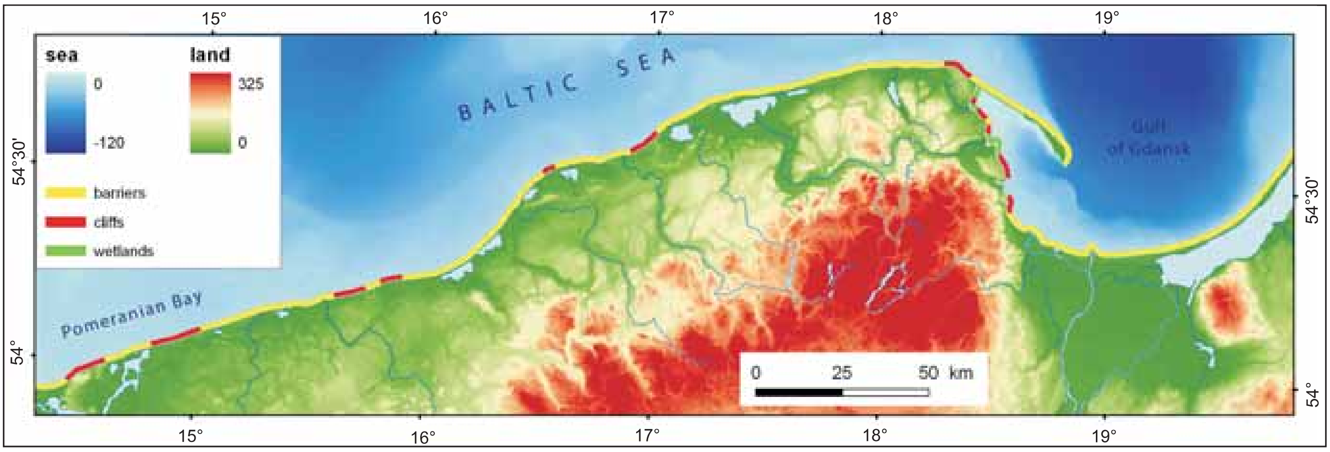

Fig. 1. DTM model of the Polish coastal zone and main types of the coasts

GEOLOGICAL STRUCTURE AND RELATED HAZARDS

Main types of hazards on the Polish coasts are related to coastal zone morphology and geological structure, including lithology and amount of sediments. Main factor of the hazards is coastal erosion caused by sea-level rise and climate changes; in that the most important is increased frequency of heavy storm surges. For example, for the last 100 years, the average sea level rise in Gdańsk was *c.* 1.5 mm/y. Beginning from the 1950s this rate increased to 5 mm/y. The frequency of storm surges increased in the Gulf of Gdańsk from 11 in the 1960s to 38 in the 1980s. (Dziadziuszko, Jednorał, 1996). Because of those factors, many parts of the coast, which were inactive (cliffs) or persisted in equilibrium state (barriers), became activated during the last decades.

CLIFFS

Cliff on the Polish coasts is built mainly of Pleistocene glacial tills, clays and fluvioglacial sands. The highs of the cliffs are generally between a few m to 20–30 m, in some places higher, up to 52 m at Rozewie Cape and 70 m on Wolin Island.

The rate of coastal cliffs retreat depends on its geological structure and is related to types of mass movements. Rate of coast retreat depends of course also on regional/local hydrodynamic activity. Long-term average rate of coastal cliffs retreat, for the period of 1875–1979, was 0.23 m/year on western Polish coast and 0.55 m/year for the eastern part. The cliffs retreat rate increased in the last decades (1971–1983) to 0.78 m/year on the western and to 1.49 m/year on the eastern part of the coast (Zawadzka, 1999).

Most dangerous for hinterland are catastrophic events related to mass movements. Generally, three types of mass movements can be distinguished on Polish coast: eboulements (rock falls) dominated on the cliffs built mainly of tills (Fig. 2), talus and landslip dominated on sandy cliffs (Fig. 3) and typical landslides occurred on cliff stretches with a complex structure, where the main role play clay layers being initial slide layers for other deposits. Landslides are most hazardous on the coast because, opposite to eboulements and taluses, affected sometimes zone of hundreds metres away from the cliff edge.

Jastrzębia Góra Cliff is the best-known example of landslide risk on the Polish coast. The cliff is located *c.* 10 km west of Władysławowo, and surrounds the north-western part of

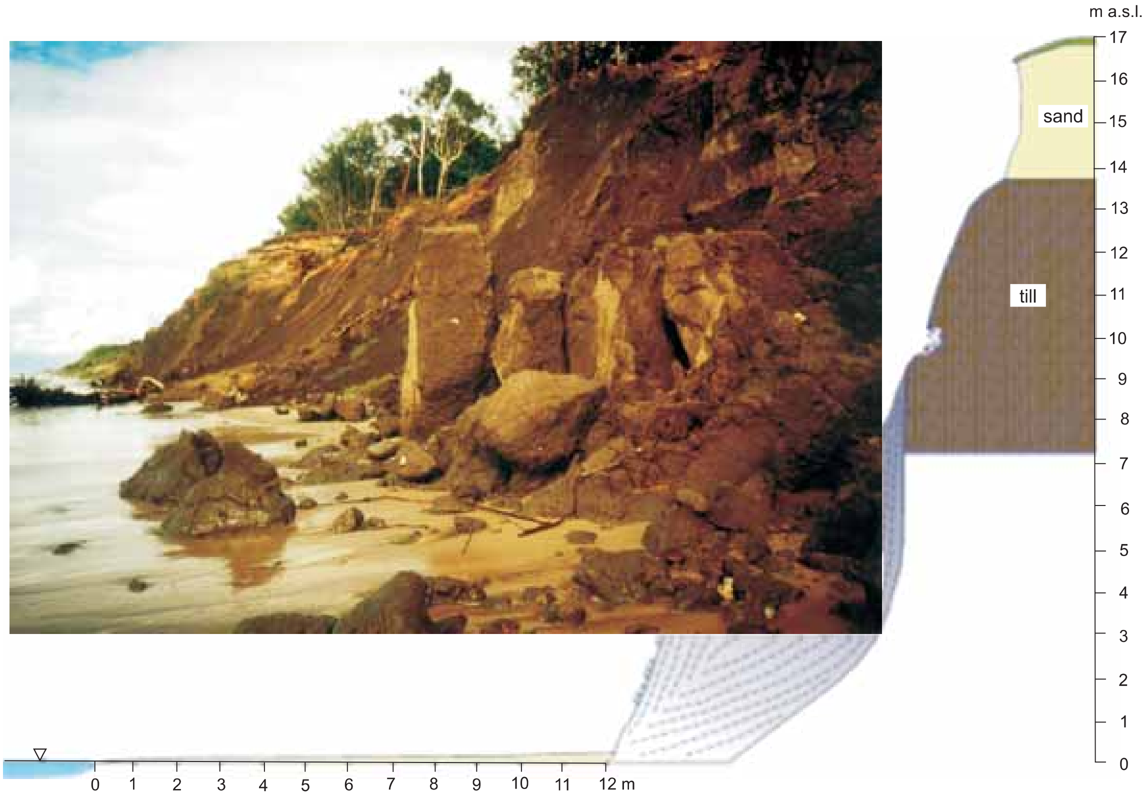

Fig. 2. Geological profile of the cliff dominated by tills and eboulements (rock falls) near Dębina (middle Polish coast)

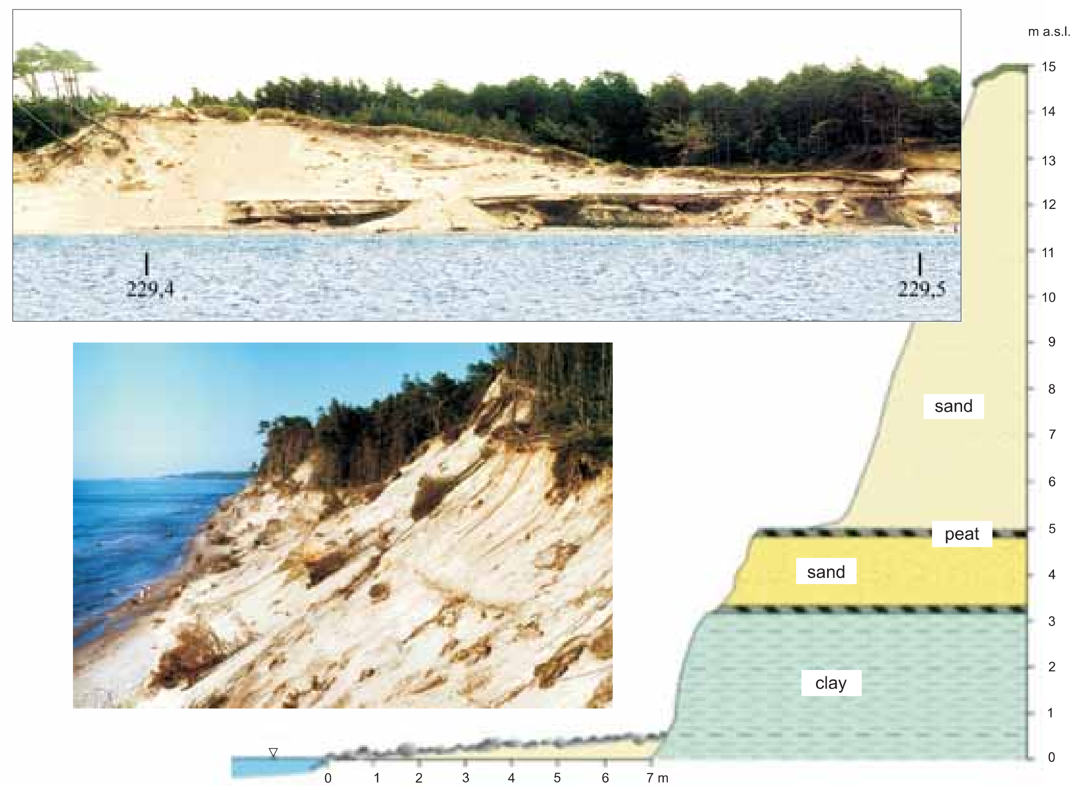

Fig. 3. Geological profile of the cliff dominated by sandy layers east from Ustka (middle Polish coast) and taluses and landslips

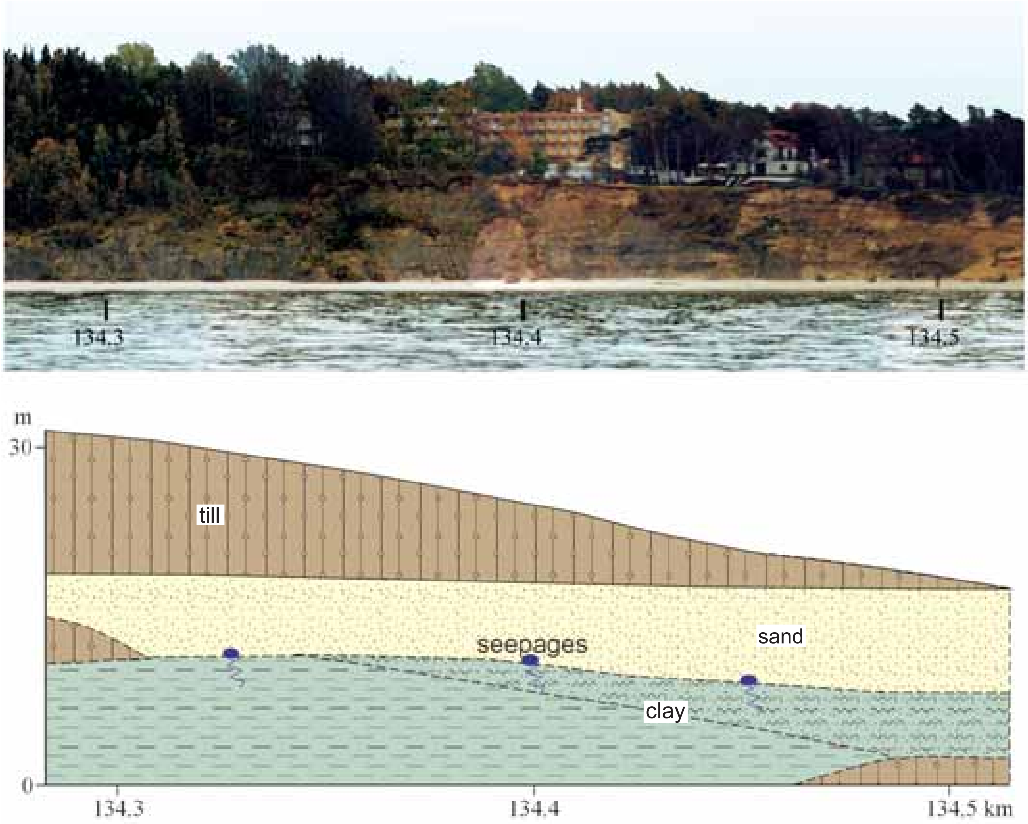

Fig. 4. Panoramic photo and geological cross-section of the Jastrzębia Góra Cliff in 1995
(*Photo. and cross-section by L. Zaleszkiewicz*)

Fig. 5. Landslide on Jastrzębia Góra Cliff, January 1999 (*Photo. by Sz. Uścinowicz*)

Fig. 6. Seawall built in 1994 for protection of the cliff, partly destroyed by landslide in January 1999 (*Photo. by Sz. Uścinowicz*)

the Gulf of Gdańsk. The stretch of active cliff coast is *c.* 2 km long and up to 30 m high. In geological structure appear mainly deposits of Vistulian Glaciation. Except for three levels of till, and dividing them intermorainal formations represented mainly by fluvioglacial sands, glacilimnic varved clays are worth a special attention. The intermorainal sands laying on the varved clays are watered. The occurring groundwater appears on the cliff wall in the form of seepage springs (Fig. 4). The geological structure, together with marine erosion of the foot slope of the cliff, is the main factors responsible for formation of landslides and other mass movements. The landslides reached as far as several dozen meters inland. The average rate of colluvium erosion at the cliff foot slope, for the period of 1977–1990, was 0.94 m/year. Till to 1994, the cliff in Jastrzębia Góra was not protected by any hydrotechnical constructions or other methods. In 1994, a sea wall was constructed for protection the of the cliff's foot slope against the marine erosion. The marine erosion was stopped but mass movements on the cliff still have occurred. A large landslide took place in January 1999 (Fig. 5). And sea wall was partly destroyed (Fig. 6). During the year 2000, a stepped stony wall was built for protection of the cliff's slope (Fig. 7). The open question still is: is it the best solution for all the eroded cliff's sections on Polish coast?

Fig. 7. Stepped stony wall protecting of the Jastrzębia Góra cliff's slope, built in 2000, and new landslide behind the wall (*Photo. by P. Domaradzki, 2001*)

BARRIERS

Two basic barrier types, differing in morphology and of the processes governing their evolution, can be distinguished: stationary barriers (accreted) and the ones migrating landward. The first barrier type, wide and carrying a well-developed dune system, emerged in areas where large amounts of sandy material was supplied. Typical for that type are Vistula Spit, and Łebsko and Sarbsko Barriers reaching the width up to 1.5 km, with dune height up to *c.* 50 m. The other type of barriers, narrow and with poorly developed dune systems, frequently limited to a fore dune only, evolved in areas, which experienced a deficiency in sandy material. The width of those barriers are in some places 100–200 m only, and dunes are very often not higher then 5 m. Typical examples for those type barrier on Polish coast are barriers separating Lakes Jamno and Bukowo from the Baltic Sea, as well as the north-western part of Hel Peninsula. There are, of course, intermediate formations between the two basic types.

Long-term average rate of barrier retreat, for the period of 1875–1979, was 0.09 m/year on the western Polish coast and 0.06 m/year for its eastern coast. The barrier retreat rate increased during the last decades similarly to the cliff coast. During the 1971–1983 years, barriers on the western Polish coast retreated in average by 0.55 m/year and on the eastern part by up to 1.37 m/year (Zawadzka, 1999). In some places, where barrier was low and narrow, coastline retreated by up to 12 m/year.

The first type of barriers: wide and covered by well developed high dune system, dominated on the Polish coast, and even when the accelerated erosion occurred there was no direct, short terms risks for the coastline stability, nor for the hinterlands. Serious risks are related to erosion of the second type of barriers: low and narrow, which could be easy broken during storm surges (Fig. 8). Storm floods in case of the barrier being broken threaten lowlands behind the barriers. Similar flood hazard exist also in lagoonal coasts located behind large and relatively stable barriers. It is caused by barographic high water stands, which in extreme cases reach up to 2 m above the mean sea level (Majewski, 1987), and by back flow into the straits connected lagoons with the sea. Such events occurred on the Polish coast during the last two decades.

The best-known case of destroying the barrier system is the Hel Peninsula. The length of Hel Peninsula is 36 km and its width is between 200 m and 3 km. The western (root) part of the peninsula is narrow and relatively flat. Terrain height is there 1–2 m above sea level. Higher stand only tops of coastal dunes, which only at some places attain the height of 7–13 m above sea level. The seaward coast of the Peninsula is badly eroded by the sea. During the historical times, western, narrow part of Hell Peninsula was broken and over flown several times. Protection works started in 1946. A system of groins and in some places also seawalls was constructed. However, the shore erosion was limited for some years, only, after the protection system has been built. In the years 1957–1991, the shore retreated in some places by 55 m. The average rate of dune erosion was up to 1 m/year. Last catastrophic overflowing took place during the heavy storm in February 1983. At the beginning of 1980s, not only coastal dunes but also underwater sandbar system was almost destroyed. In 1989, large-scale beach reinforcement started. During 1989–1994, the *c.* 20 km of beaches were fed with *c.* 6 mln m^3 of sand.

Much bigger is long-term risk related to erosion of barrier coast. If recent trends will persist, barriers with high dunes could also be eroded and large areas in Vistula Delta Plain, areas around the Szczecin Lagoon and many others places around the lagoons could be threatened by storm floods. Similar risk occurs for the less common type of coasts, like wetlands type coasts (Zeidler, 1995; Rotnicki *et al.*, 1995).

One of the most vulnerable place for possible storm flooding is Gdańsk city. Gdańsk is located on the southern coast of the Gulf of Gdańsk, in the south-eastern part of the Baltic Sea, very closely to the Vistula river mouth. It is one of the oldest ports on the Baltic Sea. At the present time, the area of Gdańsk is 262 km^2, and its population - about 460,000 inhabitants. The landscape of Gdańsk and the surrounding area is very diverse, consisting of moraine upland built of glacial till and sand, low lying (<2.5 m) sandy coastal terrace, and also low laying (partly below sea level) Vistula Delta Plain with muddy and sandy deltaic sediments, locally with peat. In the Gdańsk region occurs the land subsidence of average magnitude at *c.* 1–2 mm/year. The 880 ha of urban and industrial area in the city are located below 1 m a.s.l., and 1,020 ha — between 1.0 and 2.5 m a.s.l. Three groundwater intakes, important for water supply to Gdańsk, are also located in the areas endangered by flooding — on coastal terrace and on Vistula Delta Plain. There are serious flood hazards for low lay-

Fig. 8. Braking of Dziwnów Barrier (western Polish coast) during the storm in November 1995 (*Photo. by P. Domaradzki*)

in the Vistula coinciding with the spring high water stages and superposing with strong, lasting, northern winds generating storm surges and causing invasion of Baltic waters into Vistula mouth. In unfavourable conditions, the rise in sea level may exceed 1.5 m. The last catastrophic flooding in Gdańsk occurred in April 1829, when 75% of the contemporary city area was under water. Up to the present days, five marks of the highest water stand survived on the walls of buildings in the Old Town indicating high water at 3.36 m above mean sea level and c. 1.5 m above the ground (Fig. 9). Also after the Second World War, a part of the city was flooded because of damages of dykes and dams in the area of Vistula Delta Plain. In the near future, the flood hazard would increase because of accelerated sea level rise and increased frequency of heavy storms. The large and important parts of the city, like port facilities, urban districts, industry, warehouses, transportation routs, sewage and drainage water system and sewage plants as well as groundwater intakes are vulnerable to accelerated sea-level rise and endangered by flooding. Some historic buildings in Gdańsk in the low laying part of the Old Town and some of groundwater intakes are threatened directly. During the last years, there were observed rise of groundwater level. For example, water appeared at the cellars of several buildings. Also intrusion of salt water into the fresh water aquifers was observed.

Fig. 9. Mark of the highest water stand on the wall of old granary, indicating 3.36 m above the mean sea level

CONCLUSIONS

Main factor causing the hazards is coastal erosion connected with sea-level rise and climate changes; in that the most important is an increased frequency of heavy storm surges. Because of those factors, many parts of the coast, which were inactive or persisted in equilibrium state, became activated during the last decades. The type and range of risks on the coast depends mainly on morphological and geological features of the coast. Therefore, detailed knowledge of the coast geology is strongly needed. The first step was done by producing the Geodynamic Map of the Polish Coastal Zone in scale 1:10,000 by the Polish Geological Institute, but actualisation of the map as well as permanent monitoring and actual information fed into the databases are needed.

The future projects should also focus on the socio-economic and environmental assessment of climate change in the Polish Baltic Sea coast, especially on the sea level rise, increased coastal erosion, changing runoff patterns of rivers and groundwater contamination. These can lead to better understanding of major flooding events having severe impacts on the spatial development of cities and regions as well as to sustainable development of the entire Polish coast.

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