

MODELLING LARGE-SCALE DYNAMICS OF HEL PENINSULA, PL

Marek SZMYTKIEWICZ, Ryszard B. ZEIDLER, Grzegorz RÓŻYŃSKI
& Marek SKAJA¹

Abstract

Two-stage methodology of shoreline prediction for long coastal segments is presented in the study. About 30-km stretch of seaward coast of the Hel Peninsula was selected for the analysis. In 1st stage the shoreline evolution was assessed ignoring local effects of man-made structures. Those calculations allowed the identification of potentially eroding spots and the explanation of causes of erosion. In 2nd stage a 2-km eroding sub-segment of the Peninsula in the vicinity of existing harbour was thoroughly examined including local man-induced effects. The computations properly reproduced the shoreline evolution along this sub-segment over a long period between 1934 and 1997.

Introduction

The study presents the methodology of shoreline change analysis, which was developed for large scale modelling of shoreline evolution of potentially eroding coastal segments. Results of the study are intended to optimise shore protection activities. A case study of the Hel Peninsula (Fig. 1) is used to demonstrate the concepts of such an approach.

The observed shoreline changes are induced by a number of mutually correlated hydro-meteorological and lithodynamic factors. They can be roughly divided into two basic groups:

- external factors encompassing spatial and temporal distribution of wave energy, followed by similar distribution of longshore currents and sediment transport, coupled with bed topography and granular diversification of sediment;
- local factors attributed to the presence of man made constructions, such as groins, seawalls and harbour breakwaters, which intensify coastal processes in their vicinity.

Shoreline changes are modelled in two steps. The first step takes account of the whole coastal segment ignoring the existing constructions and hypothetically assuming that all variations of shoreline positions are caused solely by external factors. The

¹ Snr Res Assoc., Prof, Snr Res Assoc & Eng, resp., Polish Academy Sciences' Inst Hydro-Engng IBW PAN Gdańsk. Phone: (+48) 58 552 20 11, Fax: (+48) 58 552 42 11, E-mail: mareksz@ibwpan.gda.pl

calculations identify potentially eroding coastal sub-segments and explain main causes of erosion.

In the second step calculations are executed for shorter, eroding sub-segments, which must be protected for various reasons. These calculations include the effects of all local factors; the existing shore constructions in particular and the results from 1st step are utilised to determine boundary conditions of 2nd step.

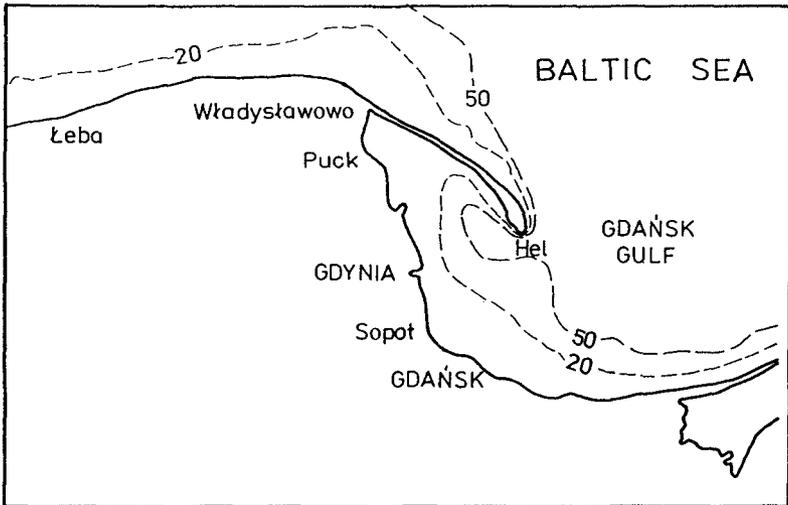


Figure 1. Layout of Hel Peninsula

For Hel Peninsula this procedure was applied in the following manner.

- For 1st step shoreline change computations for a 22-km seaward stretch of Peninsula's coastline were carried out. It was assumed that with exception of the harbour at Władysławowo, situated at the root of the Peninsula, the shore could be treated as a free segment without any artificial structures. A numerical model SAND94 was developed to analyse the possible diversification of wave energy, longshore currents and sediment transport rates. The computations allowed for identification of potentially eroding locations and were done for the period between 1991 and 1995. For that period detailed bed topography was used. Simultaneous comparative shoreline change computations were also obtained with the UNIBEST computer package.
- For 2nd step a 2-km long sub-segment lying in the vicinity of Peninsula's root, in the close proximity of the Władysławowo harbour was selected. The harbour was erected in the 30-ties and the computations were aimed at long-term shoreline evolution between 1934 and 1997. The evolution of this area has been controlled by local factors *i.e.* the construction of harbour breakwaters in 1936-37 followed by shore protection structures on the lee side of the harbour, which were built after 2nd world war. Shoreline change for step 2 was computed with four models: UNIBEST, GENESIS, LITPACK and SAND94. Currently, extensive artificial beach nourishment is conducted in this part of the Peninsula, so practical objective of the study was to predict the future shoreline evolution with proper reproduction of local effects, followed by optimisation of future beach fills.

Hel Peninsula and Władysławowo harbour

Being a fairly narrow, 35-km barrier separating the Gulf of Gdańsk from open waters of the Baltic Sea, the Hel Peninsula is an important segment of the Polish coast. Its area measures 32.4 km² and its width varies from 200 m to 3 km. The western part of the Peninsula is narrow and rather flat, with heights ranging from 1 to 2 m above mean sea level (MSL), higher dune crests up to 13 m above MSL. The south-eastern part is much wider (1-3 km) and higher (between 3 and 5 m above MSL). Hel Peninsula is a holiday place for thousands of people. There are two towns and three villages.

Władysławowo harbour construction was started in early 1936 and completed in late autumn of 1937. The length of the western breakwater is 763 m, while its eastern counterpart is only 320 m long. Immediately after construction they reached some 400-m offshore. In 1937, because of the anticipated shore erosion east of the harbour, the shore there was protected with a heavy seawall, which was 250 m long. The seawall is a massive, concrete wall, resting on wooden piles and a bulkhead. It was elongated by 300 m in 1952, to prevent scour east of the initial seawall.

The first group of groins at the root of the Peninsula, east of the harbour, was built after heavy storms in February and March 1946, which severely hurt the Peninsula on the first 3 kilometres of its stretch. The first groins were completed in August 1946 and until 1949 another group of 44 groins was built from km H 0.02 to km H 4.45 of Peninsula's chainage. They were made of wood in form of a single palisade, each 100-m long. The span between them was 90 m, doubled to 180 m between the last four. The groins were intended to be perfectly impermeable to sand, but in reality they exhibit cavities on some 20%÷30% of the length. The groins were being gradually destroyed, mainly by ice phenomena.

Protection work had been continued in the next years. Currently, there are 162 groins between Władysławowo and Kuźnica and 1500 m of sand dike with seaward slope jointly protected by rubble mound and concrete sleepers in the Kuźnica region.

The dredging, primarily at the harbour entrance, started in 1948, and in total 2.217 million m³ was dredged until 1975. Artificial nourishment of the Peninsula was started at the end of 70-ties and was associated with the maintenance of the navigation channel of the Władysławowo harbour. Before that time, the sediment was deposited offshore. Later, it was being dumped closer to the shoreline, at depths of 3÷5 m. In 1984 the sediment was dumped at about km H 3.4÷3.5 in the surf zone at depths 2÷3m. Since 1989, the sediment has been dumped directly onto the beach.

Shoreline change during and after harbour construction

Before the harbour construction, the zone up to 300m offshore exhibited two longshore bars. The inner one was smaller and was usually situated some 150m offshore. The outer one was greater, the average distance to that bar was 200÷250m. The average depth over crest of the outer bar was 2m. The depth of trough between that bar and the shore reached some 3÷4m. Outside the outer bar the depths were increasing gently and steadily. Distinct bottom movements occurred at depths up to 7 m; the comparison of hydrographic maps implies that at greater depths the bed is either stable or its movements are insignificant.

During and after the harbour construction, bathymetric surveys were executed twice a year. They covered a stretch of some 1000-m west and east of the harbour. The construction of the harbour triggered bed movements, whose intensity was coupled

with increasing breakwater lengths. Figure 2 illustrates the early construction stage, where underwater part of breakwater body was nearly completed, and shows a developing shoal running west and far east of the future harbour. The shoals are very distinct and run along the whole surveyed area and further east. Outside western breakwater they formed a sand bank. Natural depths at the harbour entrance were 6 m.

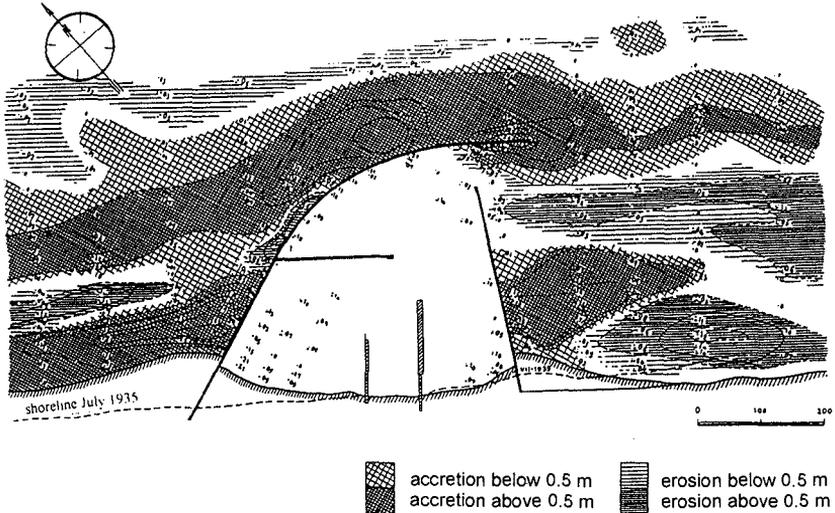


Figure 2. Depth changes at Władysławowo harbour from May 1936 to March 1938

The completion of the harbour at Władysławowo started the accretion of sand west of the western breakwater. This effect appeared rapidly (Adamski 1938), and the rate of deposition became the basis of longshore sediment transport assessments in the harbour area. The transport rate for the period between spring 1936 and spring 1938 was calculated at $70,000 \text{ m}^3$ per year, upon the assumption that no bypassing occurred during that period. Gradual beach accretion west of the harbour led to such bed configuration that the bar, which was cut by the breakwater, surrounded it and maintained the 2+3 m depth over crest (Szopowski 1958). This fact gave a clue that the longshore sediment transport, which was initially interrupted by the breakwater, was restored at the time the bar appeared in front of it (Hueckel 1968, Mielczarski 1984, Szopowski 1958, Tubielewicz 1957). Restoration of longshore sediment transport due to beach accretion updrift of the breakwater was also reported in many other cases (Zenkowicz 1962). The appearance of the main bar in front of the breakwater led to gradual shallowing of the harbour channel. Therefore, dredging became indispensable as early as in 1948.

Upon the analysis of shoreline changes along the Hel Peninsula and along the whole Polish coast, it can be assumed that the existence of breakwaters has only a local influence on shoreline evolution, so the changes become insignificant 2 km west and east of the harbour (Basiński, Szmytkiewicz. 1990).

Description of forecast model SAND94

With a realistic evaluation of the factors controlling the decadal evolution of the Polish

coast, a single-line numerical model SLineR has been formulated with IBW's package SAND94.

The computer package SAND94 was developed at IBW PAN. SAND94 is the software package intended for computations of waves, wave-induced currents, sediment transport and shore evolution. Deep-water wind wave parameters for SAND94 are computed on the basis of wind speed, direction and fetch, stemming from Krylov's quasi-spectral forecast method, which involves semi-empirical equations of the following form:

$$\frac{g\bar{H}}{W^2} = f_1\left(\frac{g}{W^2}, \frac{gt}{W}\right) \quad (1)$$

$$\frac{g\bar{T}}{W} = f_2\left(\frac{gX}{W^2}, \frac{gt}{W}\right) \quad (2)$$

where:

g - gravity acceleration, \bar{H} - mean wave height, W - wind speed, \bar{T} - mean wave period, X - wind fetch and t - time of duration.

This approach takes account of the arbitrary shoreline layout and bathymetric variability along each directional spectral component. The directional energy distribution in terms of $\cos^2 \alpha$ in the range $\pm \pi$ from wind direction is assumed, each directional sector comprises 22.5° while the radii in all directions are divided into the segments of constant depth maximum 40 Mm long. For each segment, the average depth is determined for the stripe 20 Mm wide. The compliance between measured and post-dicted deep-water wind wave parameters is good for the conditions of open sites, undisturbed by headlands, harbour breakwaters etc. The model yields wave parameters at the offshore deep-water boundary of a coastal zone.

Coastline evolution package is based on a standard one-line model. The single-line routine can be run either for sediment transport rates determined from wave input given in chronological order or for net sediment transport computed for the entire analysed period. In the first (full run) option the transport is computed at each time step and for each cross-shore profile, taking account of instantaneous wave-shoreline angle. In the second (simplified run) option the net transport rates for each transect, treated as the representative ones for all period, are computed and then are modified in all time steps as functions of changes of shoreline angles determined in the previous step. It should be noted that only longshore-related routines have been used in the SAND94 full run, to match the general objective of the project, dealing with coastal evolution due to longshore transport variability.

Hel Peninsula shoreline change modelling

As mentioned before, the 22-km seaward stretch between Władysławowo and Jastarnia was chosen for 1st step of the analysis. For simulation the period between 1991 and 1995 was selected, because detailed bed topography from 1991 and measurements of shoreline positions in 1991 and 1995 provided real data for model input and testing.

Distribution of wave energy, velocity of longshore currents and intensity of sediment transport along the Peninsula were computed with numerical model SAND94. The computations embraced spatial change of wave field including refraction-diffraction effects in a strip of 40 km from Rozewie (first mainland locality west of Władysławowo) to Hel town. The width of that strip varied between 9 km for Rozewie and 38 km for Hel town. Bed topography for those computations, recorded in 1991, is shown in Figure 3. It can be seen that the bed topography along the Peninsula is featured by two distinct troughs, surrounded by shallow waters in direct proximity of the coast. The first one is situated between Władysławowo and Chałupy (km H 4.0), the second one lies in the vicinity of Kuźnica (km H 12-13).

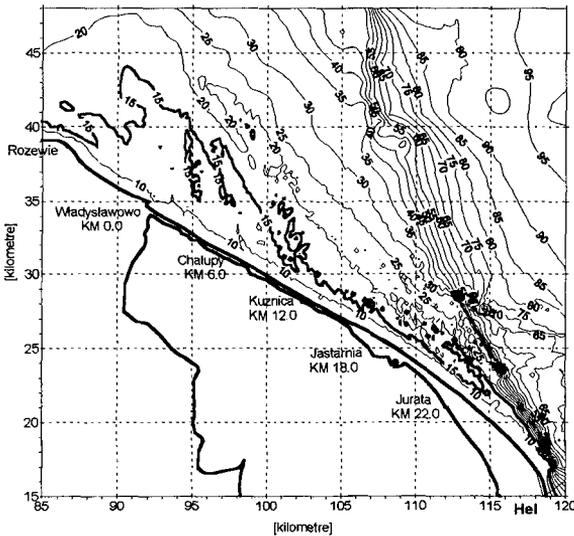


Figure 3 Bathymetry along Hel Peninsula

Assuming the computed wave climate parameters *i.e.* significant wave height H_s , wave period T_p and angle of wave incidence θ as boundary conditions, dissipation of wave energy was calculated together with change of wave height along profiles approximately perpendicular to average shoreline configuration in the wave transformation zone and the surf zone. The spacing between consecutive profiles was set to 100 m.

On the basis of wave height change velocities of longshore currents were computed, which were used as the input for Bijker-type routine for longshore sediment transport calculations.

For long-term assessment of Peninsula's vulnerability to erosion, the conditions of average statistical year were chosen. In order to properly discretise the conditions of that year, the wind rose of all seaward winds from W to SE was thoroughly examined with the 22.5° resolution. Wind speed ranged between 1 and 20 m/s with 1m/s step. Exemplary fields of significant wave heights and azimuths of wave ray for 10 m/s of wind speed and the most frequent westerly winds are shown in Figs. 4a and 4b.

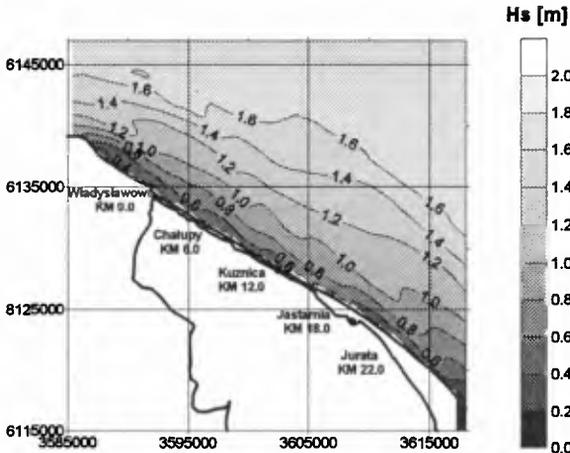


Figure 4a Distribution of wave significant height H_s along Hel Peninsula; wind direction W , speed 10 m/s

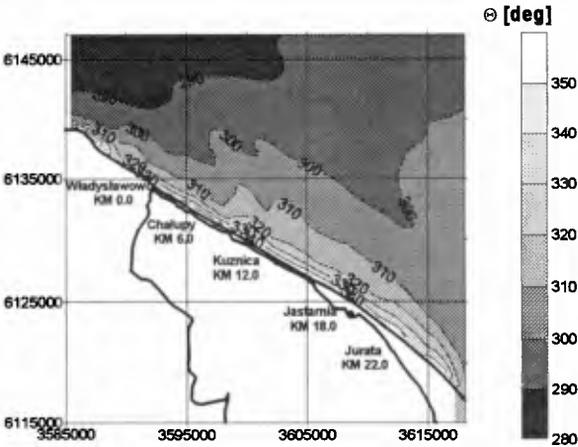


Figure 4b Distribution of wave approach Θ along Hel Peninsula; wind direction W , speed 10 m/s

Wave ray azimuth represents the direction of wave approach. For sake of computations the average azimuth of shoreline was assumed to equal 121.5° (equivalently 301.5°). The isolines of wave heights and wave ray azimuths indicate spots of intensive wave energy, reaching the vicinity of coastal zone. Upon thorough scrutiny of individual stormy situations, the following conclusions can be drawn:

- for westerly winds (W) the amount of wave energy reaching the shore is fairly evenly distributed along the Peninsula and the angle of wave incidence equals some 40° with respect to a shore normal direction, waves come from the western sector (Figure 4a and 4b);

- for north westerly winds (NW) high concentration of energy was identified on a short, 1 km long, sub-segment between Władysławowo and Chałupy and in the proximity of Kuźnica, the angle of wave incidence is 40° and is identical to the case of westerly winds;
- for northerly winds (N) spots with higher energy concentrations are scattered all over the Peninsula, the incidence angle is between 75° and 80° with regard to a shore-normal direction, winds come from the western sector;
- for north easterly winds (NE) energy concentrations were found in the vicinity of Kuźnica and locally close to the Władysławowo harbour, the incidence angle is equal to some 85° to a shore normal direction, waves arrive from the eastern sector;
- for easterly winds (E) the Chałupy region absorbs most of the energy, whose distribution then gradually declines heading east along the Peninsula, waves come from the eastern sector at 50° to the shore-normal line;
- for south easterly winds (SE) energy distribution is fairly uniform; it only gently grows east of Jurata, waves reach the shore from the eastern sector at 20° to the shore normal direction.

The computed, resultant sediment transport curves for average statistical year is plotted in Figure 5. It can be seen that the littoral drift is directed eastwards and is characterised by two distinct areas where it grows. The former is well pronounced and lies on first four kilometres of the Peninsula between Władysławowo and Chałupy. The latter, less conspicuous but still clearly visible, is situated between Kuźnica and Jastarnia. The sediment transport pattern thus has a positive gradient in those two areas, so it can be expected they are exposed to erosion. The computational results comply well with the observed spots of local erosion. They show that the most heavily eroded segments are 2 km stretch just east of Władysławowo harbour breakwaters, the zone at km H 4.0, the Chałupy region and the area between Kuźnica and Jastarnia.

Artificial beach nourishment between 1991 and 1995 was being executed at the following locations:

- 1991: KM H 0.0-0.8, 3.2-3.7, 10.3-13.6, 16.3-16.5, 18.2-19.2
- 1992: KM H 0.145-4.6, 10.0-10.9, 15.8-17.2, 22.1-22.5
- 1993: KM H 0.0-2.0, 4.1-4.56, 9.55-12.45, 14.45-17.15, 21.5-22.8
- 1994: KM H 0.2-2.75, 9.6-11.0, 16.3-17.2
- 1995: KM H 0.1-0.5, 3.1-4.4, 10.0-10.7, 15.2-16.25, 22.1-22.7

The amounts of sediment deposited on the beaches and nourishment periods were precisely quantified in SAND94 input files. The hindcast input wave data, was assumed constant in each 24-hour interval, being the computational time step for the whole simulation. The depth of closure was also constant and set to 7 m.

The mean grain size diameter used in the computations varied from 0.18 to 0.26 mm. The lower limit stems from extensive field studies of the Peninsula, carried out since 1983, the upper one – from the data collected recently. The latter data are distorted by artificial nourishment, which has been carried out eastwards of Władysławowo since 1990.

Results obtained by SAND94 were verified with UNIBEST, which requires only one cross-shore profile assumed to represent the entire modelled coastal zone. Upon detailed analysis of all transects from 1991 year the one of km H 10.0 was chosen.

The results of shoreline change computations along the Peninsula by SAND94 and UNIBEST for 1995 are jointly presented in Figure 6. The comparison shows that both models yield very similar results, which are fairly consistent with measurements done in 1995. Certain discrepancies can be attributed to local effects, which were deliberately ignored on this stage of the analysis.

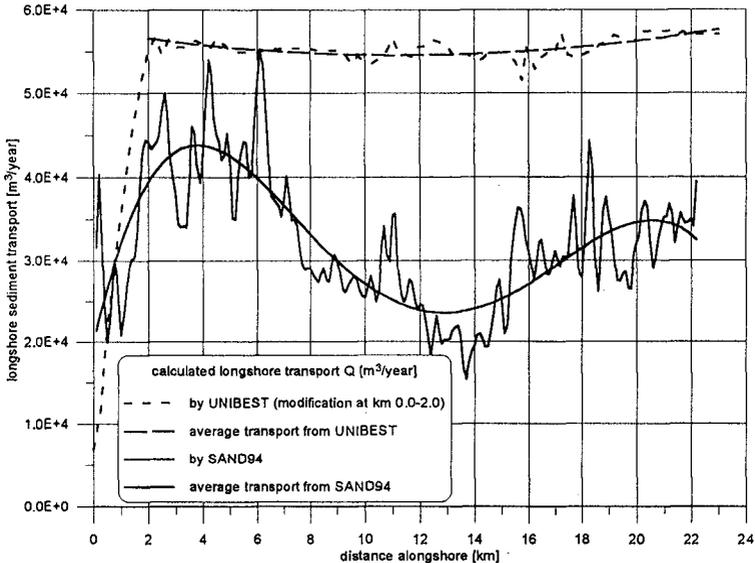


Figure 5 Net longshore sediment transport rates computed along Hel Peninsula by UNIBEST and SAND94 without beach fills

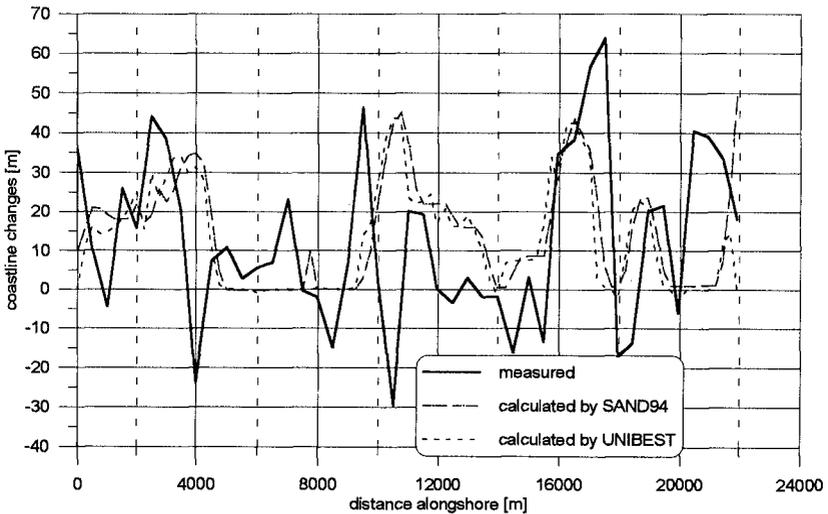


Figure 6 Computed and measured coastline changes along Hel Peninsula in 1991-1995; beach fills included

Modelling of the Władysławowo harbour effect

The 2nd step of shoreline change modelling takes into account local effects. Such modelling is aimed at detailed examination of local effects on small sub-segments of the area analysed in the 1st step. Man-made structures locally disturb natural processes, so special attention should be paid to properly reproduce the effects they cause. Hence, the vicinity of Władysławowo harbour, and the relative abundance of data acquired over decades, gives an excellent opportunity for analyses of coastal phenomena as well as extensive model testing.

Shoreline evolution in the proximity of the Władysławowo harbour was modelled by four models (GENESIS, LITPACK, SAND94 and UNIBEST) in the long-term time scale, for the shore segments stretching 2-km westwards and 2.3-km eastwards of the harbour. The initial conditions for computations were set to the year before the harbour construction (1934) and the simulation period covered more than 60 years until 1996/1997. The computations were designed to provide proper representation of the long-term shoreline migration in the close vicinity of the harbour on its both sides. The available model options were used to arrive at the most accurate reproduction of shoreline positions. The tests were carried out with wave input based on the representative meteorological annual chronology, retrieved for the period 1952-1990. The analysis of statistics of the meteorological data for each of those years revealed that the year 1970 was the most similar to the mean statistical year. The meteorological record of this year was then assumed as typical in determination of wave input for the modelled shoreline changes in 1934-1996/97. Hence, the offshore wave conditions were calculated from the actual wind measurements taken in 1970, with the time step of one day, and were assumed to be valid for the entire analysed period of 62 years. Wind parameters were assumed constant during each 24-hour interval. In all tested models the depth of closure in the single-line models was set to 7 m. Artificial beach fills on the lee side were included into consideration for the period in which detailed records of fills are available, i.e. 1991-1996.

Apart from LITPACK, the tested models assume the same sediment grain size in the entire region modelled; GENESIS uses a median grain size only. The median grain diameter used in the computations varied as in the 1st step from 0.18 to 0.26 mm. The sensitivity tests for all models except for LITPACK show a very weak response of the modelled shoreline to the variation of grain diameter.

Most groins east of Władysławowo are damaged and their influence on coastal processes was found to be negligibly small. The efficiency of these groins in the past is reported as very doubtful, so their existence in the modelling processes could be neglected. The simplified run option of SAND94 was used. The transport of 1934 was computed from the model of Bijker, yielding net value of 50000 m³/year at average for the analysed shore segment. This transport was directed eastwards. The harbour was represented in the modelling procedure by two jetties closed by an offshore breakwater. The seawall was defined in its actual location, as well as beach fills in accordance with the actual records of nourishment.

In order to include the harbour impact, the longshore transport was modified and the blocking percentage was assumed, varying gradually from 20 % in 1936 (harbour appearance) to 1% in 1965-1997. The modified transport distributions for consecutive three sub-periods is shown in Figure 7. It can be seen that both spatial and temporal trends of sediment transport were reproduced satisfactorily. The sediment transport

variability has produced the reasonable shoreline evolution, which is presented in Figures 8. It can be seen from the plot that the model result for west side of the harbour is proper, while the erosion at the close east side is underestimated. The latter results from beach fills of 1991-1996, which apparently are not in model balance with erosive processes. Further eastwards of the harbour, the model shoreline changes are correct for the entire analysed period.

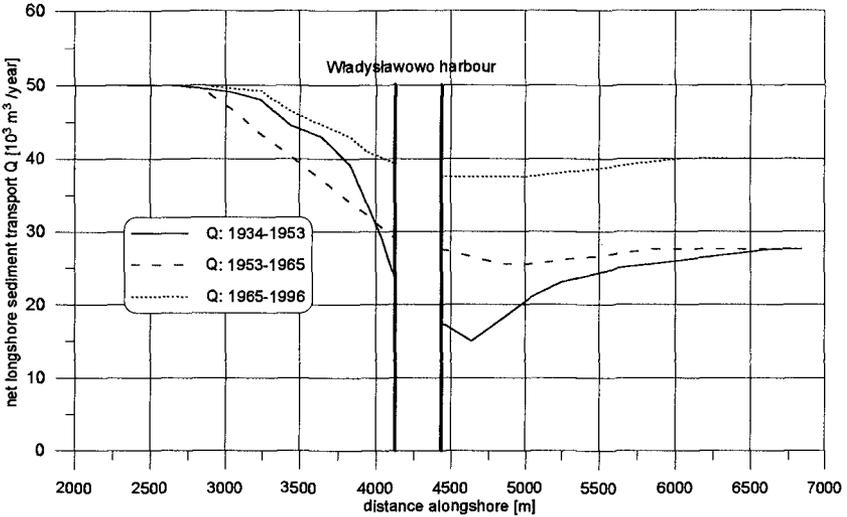


Figure 7 Net longshore sediment transport rates computed from SAND94 in 3 consecutive sub-periods

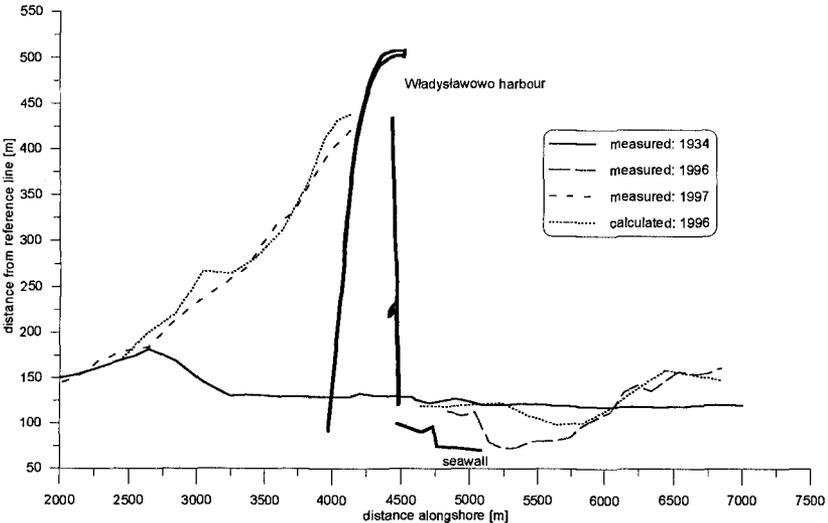


Figure 8 Shoreline positions nearby the harbour measured and computed from 1934-1996/97 from SAND94

The above results have been compared with the output provided by the other three models (GENESIS, LITPACK and UNIBEST). The comparison of final measured and computed shoreline positions is given in Figure 9. It can be seen that the long-term accretion westwards of the harbour are well represented. Almost the same accuracy of hindcast in the long time scale has been achieved at the lee-side of the harbour. It can be concluded that UNIBEST produced at least satisfactory shoreline positions in all sub-periods of the analysed period. The modelled transport rates also look very realistic.

In general it can be seen that all outputs are at least satisfactory. Westwards of the harbour, the outputs produced by all models are acceptable. The most accurate shoreline representations have been obtained from UNIBEST and LITPACK. Eastwards of the harbour, however, LITPACK clearly underestimates the lee-side erosion effects, while the shoreline retreats produced by GENESIS and UNIBEST are quite satisfactory.

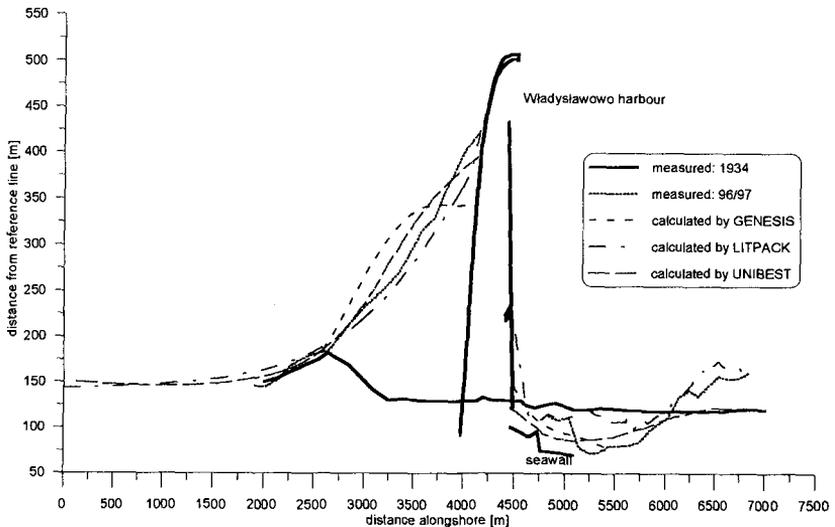


Figure 9 Shoreline positions nearby the harbour computed for 1934-1996/97 by GENESIS, LITPACK and UNIBEST

Conclusions

Two-step shoreline change modelling for the case study of the Hel Peninsula is presented in the study.

In the 1st step the large-scale calculations done for the vast portion of the Peninsula allowed for identification of potentially eroding spots and gave way to explain the causes of erosion.

In the 2nd step the vicinity of the Władysławowo harbour was thoroughly examined including local man-made effects. Long-term shoreline evolution was properly modelled and thus prediction of future evolution can easily be simulated. This in turn

modelled and thus prediction of future evolution can easily be simulated. This in turn facilitates and optimises future beach fills design and other shore protection activities in this region.

The following detailed conclusions for 1st step can be drawn:

- bed topography along the Peninsula, featured by two distinct troughs in the shallow water zone results in local concentrations of wave energy that reaches the shore in two regions adjacent to troughs;
- the 1st region of high energy concentration is situated between Władysławowo and Chałupy (km H 4.0), the 2nd one lies near Kuźnica (km H 12.0 – 13.0);
- analogously to wave energy, the calculated resultant longshore sediment transport is characterised by two zones of increasing intensity, one between Władysławowo and Chałupy and the other between Kuźnica and Jastarnia, such configuration implies that increasing transport rates are driven by high wave energy concentrations;
- energy concentrations occur mainly for north westerly winds, energy distributions for other winds is far more uniform;
- shoreline change computations comprising beach fills were done for the period between 1991 and 1995 by means of SAND94 and UNIBEST; the selection of that period guaranteed extensive background information in form of detailed bed topography and measurements of shoreline positions, a fairly good compliance with final shoreline configuration was achieved, certain discrepancies between computational results and measurements can be ascribed to local effects, which were ignored on this stage of analysis.

Results of computations in the 2nd step indicate that:

- thorough mapping of local conditions around Władysławowo harbour helped to properly model shoreline evolution history between 1934 and 1996/97;
- computations were executed with four models (GENESIS, LITPACK, UNIBEST and SAND94), the compliance with final shoreline positions is excellent for them all on the updrift (west) side of harbour breakwaters, good compliance on the lee side was achieved for GENESIS, LITPACK and SAND94, UNIBEST reached even better fit after tuning in with available user defined options;
- the results allow for accurate forecasting of future shoreline evolution and can be used for optimisation of artificial beach fills.

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