CHAPTER 159

MULTI-SCALE NEARSHORE & BEACH CHANGES

by
R.Ostrowski, Z.Pruszak & R.B.Zeidler[1]

ABSTRACT

Empirical orthogonal functions in one- and two-dimensional formulation are employed to identify the variability of longshore and cross-shore features in different scales, ranging from days to years. The prototype topographic data was measured in coastal zones of the Baltic and Black Seas. Conspicuous features such as berms, bars, salients and cusps can be identified through e_{2x}. Temporal variation of cross-shore transport is reflected in c_{2t} and e_{3x} while linkage of c_{3t} to coastal factors remains unspecified.

1 Introduction

Beach transformation processes are usually dealt with in categories of longshore and cross-shore sediment transport. Both modes are discussed in this paper. At the same time one distinguishes different spatial and time scales. For the purposes of this paper, we identify short-term, meso-scale and long-term beach changes. The former include changes ranging from days to weeks, the meso-scale transformation encompassing changes from days to seasons, the seasonal yearly and multi-yearly variation being placed in the category of long-term changes.

We are in possession of a bulk of data for shore transformation along the Polish coast of the south Baltic, the Bulgarian coast of the Black Sea, and some other sites. For illustration, Fig. 1 shows excerpts from bathymetric charts compiled for the years 1967, 1975 and 1987 in the central part of the Polish coastline. It is seen that some parts of the coastal profile undergo very intensive changes while some other display a node-type behaviour with very minor variations. Together with the obvious need for more exploration of coastal processes, that finding has inspired us to undertake the investigation of nearshore and beach changes reflected in this paper.

2 Field Measurements

Field measurements provide the most obvious tool for analysis of nearshore transformation. We have collected data basically at two coastal research stations, one at Lubiatowo on the south Baltic Sea, some 75 km to the west of Gdańsk and the other at Shkorpilovtsi, some 50 km south of Varna, on the Bulgarian Black Sea. The two sites differ in many

[1]all Polish Academy of Sciences' Institute of Hydro-Engineering IBW PAN, 80-953 Gdańsk, Kościerska 7, PL

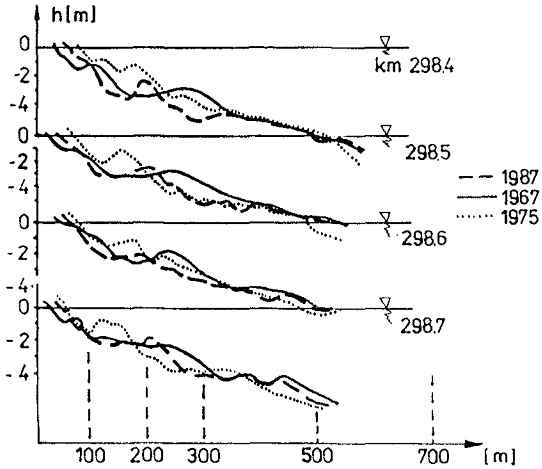

Fig. 1. Examples of shore profiles measured on Polish coast

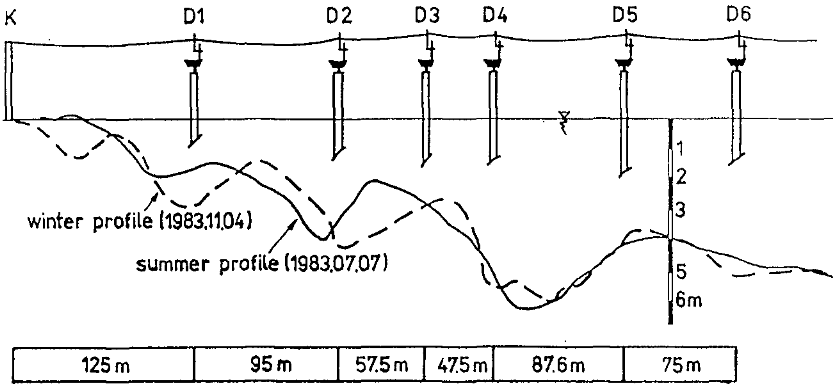

Fig. 2. Shore profile and measuring posts at IBW PAN Station at Lubiatowo (PL)

respects. The coastal zone at Lubiatowo is of dissipation type, with multiple bars, the inclination of bed being about 1%, and the sediment consisting of medium sand having $D_{50} \approx 0.22$ mm. The Bulgarian site is rather reflection type, with average bed slope about 1.5-2%, with one or no bar, its bed consisting of sand with $D_{50} \approx 0.4$ mm.

Fig. 2 depicts typical summer and winter profiles at Lubiatowo while Fig. 4 provides a rough idea of the Shkorpilovtsi environment. Data for short-term and meso-scale changes provided in this paper originate primarily from the Shkorpilovtsi station while the long--term variation is mostly based on measurements at Lubiatowo.

3 Empirical Orthogonal Functions (EOF)

Most of our analysis for bed changes is based on the method of empirical orthogonal functions, see Winant et al. (1975) for reference.

An one-dimensional approach, the variation of depth in time t and across shore, in the direction x can be given as the following linear series:

$$h_{xt} = \sum_n c_{nt} \cdot e_{nx} \tag{1}$$

in which the index x varies from 1 to n_x, the total number of points along the profile where data is taken, while t is contained between 1 and n_t, the total number of times at which profiles were recorded.

If we require that the orthonormality condition is satisfied as:

$$\sum e_{nx} \cdot e_{mx} = \delta_{nm} = \begin{cases} 1 & m = n \\ 0 & m \neq n \end{cases} \tag{2}$$

then the quantities e_{nx} form a set of normal modes, or eigenfunctions. It is recollected that usual Fourier series also conform to the above condition. The value of EOF consists in the fact that a set of empirical eigenfunctions is selected to fit the data in the least squares sense.

The eigenfunctions e_{nx} are found from the empirical symmetric correlation matrix B having the following elements:

$$b_{ij} = \frac{1}{n_x n_t} \sum_{t=1}^{n_t} h_{it} h_{jt} \tag{3}$$

Any square matrix possesses a set of eigenvalues λ_n being found from the following determinant:

$$det\,[B(\lambda)] = 0 \tag{4}$$

and a set of corresponding eigenfunctions, which are found from the following matrix equation:

$$B \cdot e_n = \lambda_n \cdot e_n \tag{5}$$

The coefficients c_{nt}, which may be referred to as a temporal eigenfunctions, are all also orthonormal:

$$\sum_{t=1}^{n_t} c^*_{nt} c^*_{mt} = \delta_{mn} = \begin{cases} 1 & m = n \\ 0 & m \neq n \end{cases} \tag{6}$$

in which $c^*_{nt} = c_{nt}/\sqrt{\lambda_n n_x n_t}$.

The coefficients c_{nt} are found by analogy from:

$$c_{nt} = \sum_n^{n_x} h_{xt} \cdot e_{nx} \tag{7}$$

For the mean shore profile represented by the first mode ($n = 1$ in Eq. 1) one has

$$h_{xt} = c_{1t} \cdot e_{1x} \approx e_{1x} \cdot (\lambda_1 \cdot n_x)^{\frac{1}{2}} \tag{8}$$

The above one-dimensional description can be expanded to the two dimensions (longshore and cross-shore), cf. Hsu et al. (1986):

$$h(x,y,t) = \sum_k e_k(x,t) e_k(y,t) \tag{9}$$

The functions $e_k(x,t)$ and $e_k(y,t)$ are given by the following equations:

$$e_k(x,t) = \sum_n (\lambda_n n_x n_t)^{\frac{1}{2}} e^n_k(x) C^n_{kx}(t) \tag{10}$$

$$e_k(y,t) = \sum (\lambda_m n_y n_t)^{\frac{1}{2}} e^m_k(x) C^m_{ky}(t) \tag{11}$$

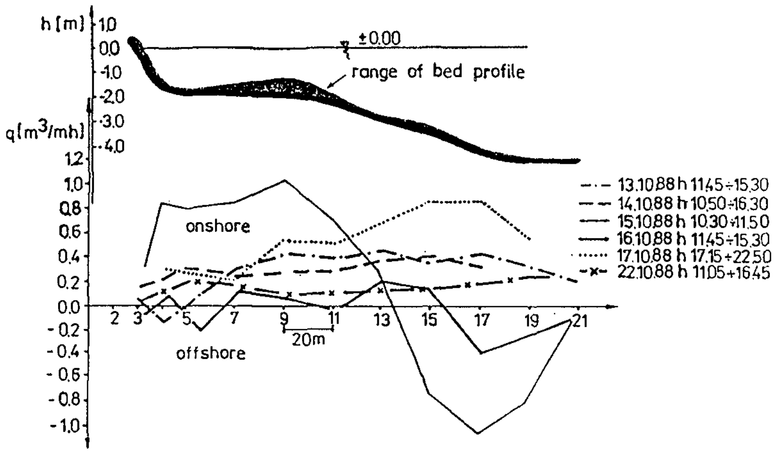

Fig. 3. Short-term bed changes measured at Shkorpilovtsi (Bulgarian Academy of Sciences)

in which:
k = two-dimensional mode of eigenfunction
λ_n, λ_m = eigenvalues for cross-shore and longshore direction, respectively
n_x, n_y, n_t = number of points measured across shore (x axis) and along shore (y axis) and profiles measured in time t, respectively
$e_k^n(x)$, $C_{kx}^n(t)$ = cross-shore (space and time) eigenfunctions
$e_k^m(y)$, $C_{ky}^m(t)$ = longshore (space and time) eigenfunctions.

4 Short-Term Bed Changes

The data for short-term bed changes have been collected at Shkorpilovtsi, where ultrasonic probes of 40-W power and 5° emission angle were deployed across shore in the years 1987 and 1988.

Fig. 3 illustrates the findings, from which it is clear that the most intensive changes occur again in the surf zone stretching between the underwater bar and shoreline. Since the longshore sediment transport did not exist for the particular configuration of shore, the cross-shore transport rates were computed from the continuity equation, as depicted at the bottom of Fig. 3.

The variability of bed prior to during, and after storm can be assessed from Fig. 4. Slow onshore transport is observed before storm. The dramatic changes towards offshore transport at a speed of 0.9 m/h are comparable with the estimates given by Birkenmeier (1984) (1.2 m/h) for waves $H \leq 2$m and $T \leq 4$s. During the recovery after storm the onshore transport occurs at a speed of 4 m/day, again somehow comparable with Sunamura (1989) who sites $v \approx 0.5$ m/day for a 1-m underwater bar and H_b=0.75 – 1 m; a quantity which is fifty times smaller than that during the storm !

5 Meso-Scale Changes

5.1 Single-Bar Profile

Multi-yearly measurements of meso-scale variation of shore profiles have been conducted in two regions of single bars and multiple bars. The range of bed changes observed was

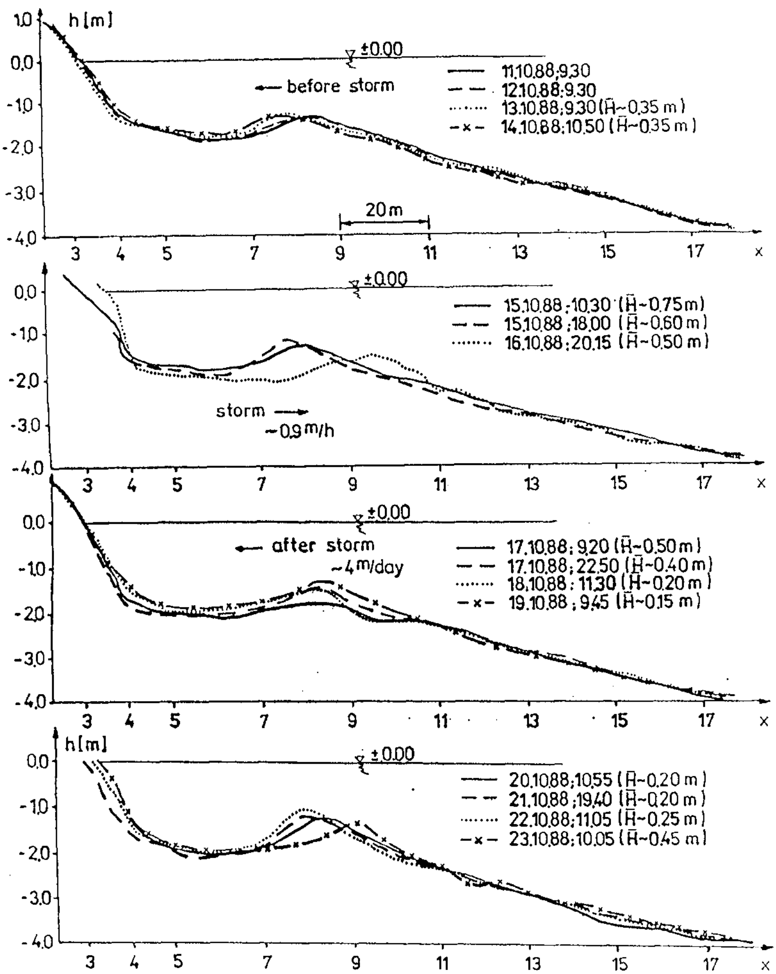

Fig. 4. Single-bar profile transformation in a storm at Shkorpilovtsi

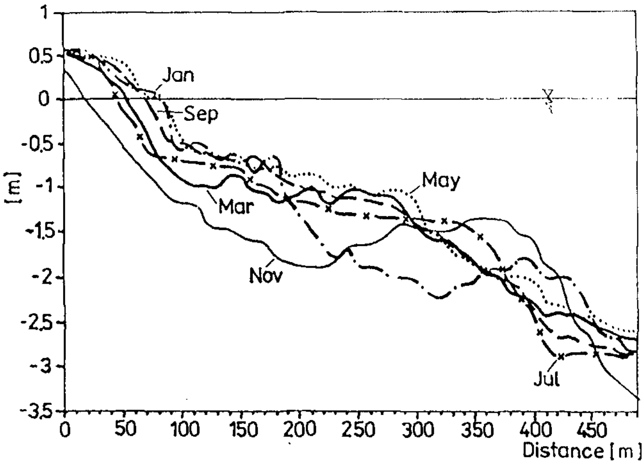

Fig. 5. Mesoscale single-bar profile transformation at Shkorpilovtsi in 1976

about 1 m, which is somehow visible in Fig. 5 for the Black Sea site of Shkorpilovtsi.

The meso-scale variation on single-bar profile was measured every month from 1973 to 1977.

One-dimensional EOF analysis for the profiles measured every month over the period of one year in the years 1974 and 1976 for the first three eigenfunctions e_{1x}, e_{2x}, e_{3x} has exposed certain relationships between them and pertinent coastal processes. An illustration is provided in Fig. 6. The following findings can be outlined:

- The first eigenfunction e_{1x} describes the average shore profile in which all underwater forms are smoothed out
- The second eigenfunction e_{2x} identifies the location of the underwater bar and berm in the summer (through its maxima). The minimum of the second eigenfunction identifies the location of bar in the winter season
- The third eigenfunction e_{3x} denotes the locations where accretion (maximum) or erosion (minimum) prevails.

The following can be said for the temporal eigenfunctions (the coefficients c_{nt} (Fig. 7):

- The first coefficient c_{1t} can be regarded as constant about $c_{1t} \approx \sqrt{n_x \cdot \lambda_1}$, in the range from 9 to 13
- The second temporal eigenfunction c_{2t} depicts the seasonal (yearly) predominance of cross-shore transport direction (offshore or onshore). It is confirmed that the onshore mode prevails in the summer versus the offshore direction in the winter (negative value in the drawing)
- The coefficient c_{3t} is most difficult to identify as it oscillates and varies quite strongly. It can be attributed to the instantaneous predominance of erosion or accretion processes, much as the third eigenfunction e_{3x}. The places where onshore and offshore transport prevails are shown by arrows.

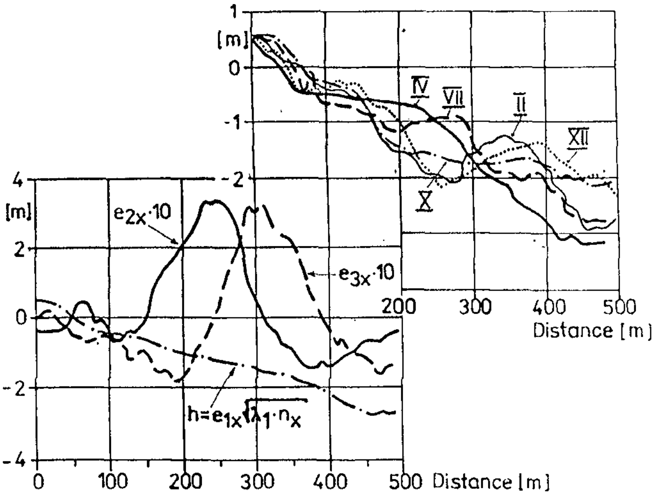

Fig. 6. Mesoscale changes at Shkorpilovtsi in 1974: bed profiles (top) and eigenfunctions (bottom)

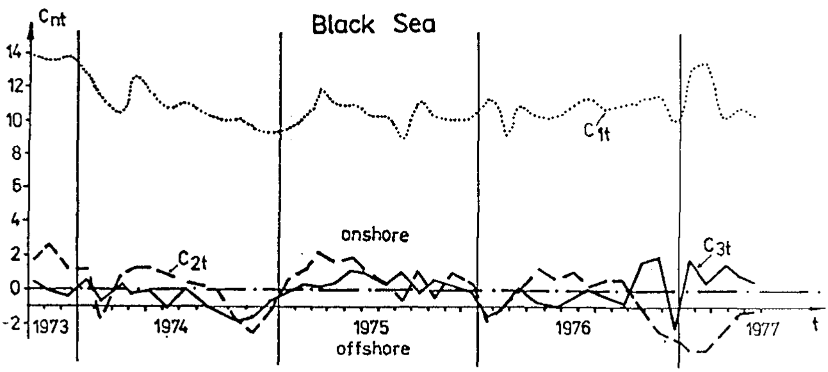

Fig. 7. Coefficients c_{it} at Shkorpilovtsi, 1973 - 1977

5.2 Multiple-Bar Profiles

5.2.1 General Observations

Analysis of the variability of topographical features measured on the multiple-bar profile of the Polish coastline (Lubiatowo) illustrated in Fig. 8 has provided the following findings:

- Seasonal variability of the multiple-bar profile largely depends on the direction of cross-shore transport, the regions of the second and third bars (counted from shoreline) displaying the most intensive bed changes;
- In the summer, the onshore sediment transport prevails, primarily as bedload. This holds particularly for the surf zone, so that the second and third bars and beach are subject to clear transformation;
- If more violent storms appear in the summer, a strong accretion in the central part of underwater profile is noted, particularly about the third bar, which is supplied under these conditions from both land and sea;
- During calm periods most transformations are confined to the zone about shoreline and the shallowest bars.

The variation of shoreline and dune toe, coupled with the above changes in the underwater profile are depicted respectively in Fig. 8 b, c. It is seen that the migration of shoreline exceeds 10 m, the widest beach being exposed in the summer, as anticipated. The variation of the dune toe is generally less pronounced as it is due to extreme storm events, which have not appeared in the period of measurements.

5.2.2 EOF Analysis

The analysis has been based on the measurements performed at Lubiatowo a few times in the period from mid–May to mid-October 1987, in about twenty cross-shore profiles stretching over 700 – 1000 m and spaced from 100 to 200 m. In the one-dimensional representation depicted in Fig. 9 one can see that the first eigenfunction e_{1x} again depicts the average shore profile with characteristic macroforms. The second eigenfunction e_{2x} is attributed to underwater bars, its maximum being associated with clear accretion and its minimum being associated with erosion. The peak of the function e_{2x} is proportional to the intensity of local bed changes. Sharp peaks are localized about crests or troughs while smeared shallow extrema denote local accretion or erosion. The third eigenfunction e_{3x} is correlated with the predominance of offshore or onshore sediment transport. The maximum of e_{3x} can be linked to periodic predominance of onshore transport, while the minimum denotes the offshore mode.

The characteristic features repeat in the cross-shore profiles deployed along shore.

Two–dimensional EOF analysis provides a deeper insight into the coastal phenomena, although very few findings are clear-cut and conclusive.

The prototype results for meso-scale variability measured at Lubiatowo are depicted for the cross-shore eigenfunctions and longshore ones in Figs. 10 and 11, respectively. The following features for the first mode deserve attention:

- The first eigenfunction $e_1^1(x)$ represents the cross-shore profile averaged over the entire area (x, y);
- The second eigenfunction $e_1^2(x)$ displays the location of underwater bars representative for the entire area as implied from analysis of the cross-shore profiles measured;

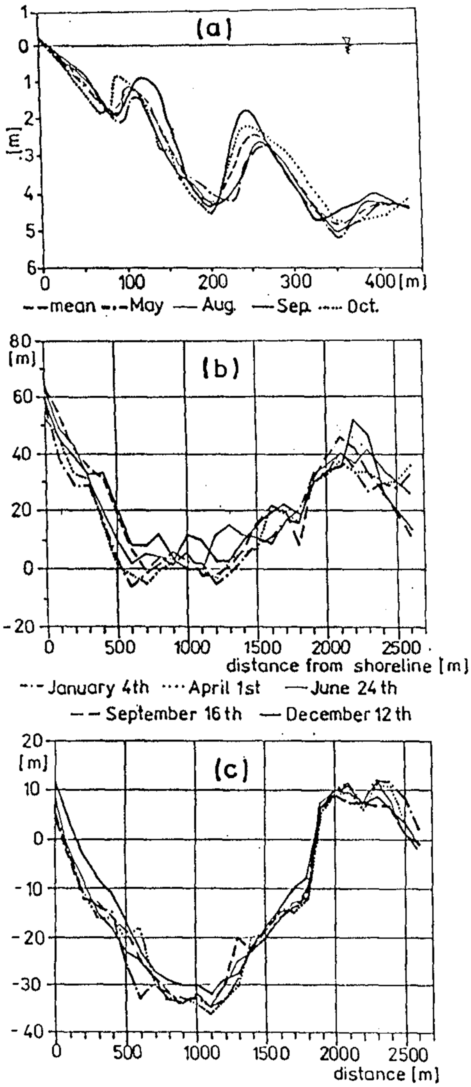

Fig. 8. Mesoscale changes in coastal topography at Lubiatowo in 1987: (a) bed profile; (b) shoreline; (c) dune toe

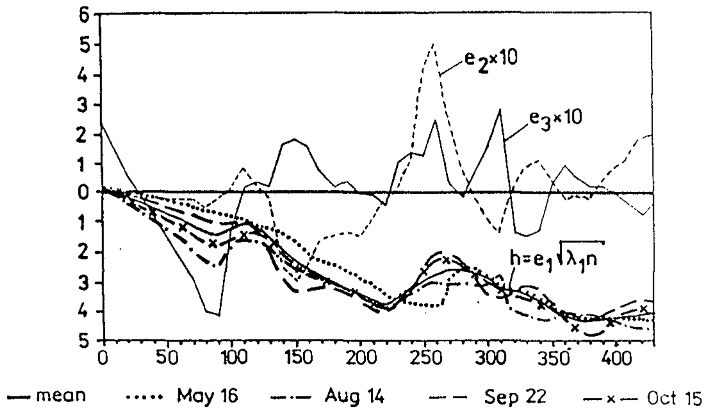

Fig. 9. Bed profiles and eigenfunctions at Lubiatowo in 1987

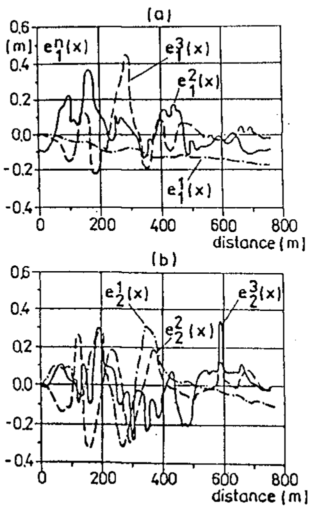

Fig. 10. Cross-shore spatial eigenfunctions (2–D) for modes k=1 (a) and k=2 (b); Lubiatowo 1987

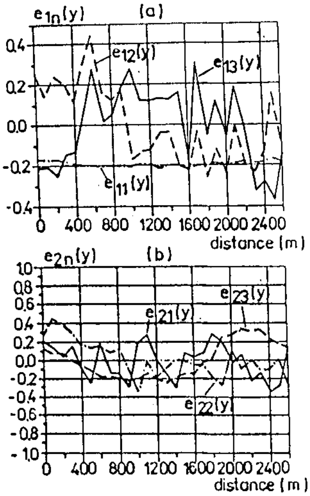

Fig. 11. Longshore spatial eigenfunctions (2-D) for modes k=1 (a) and k=2 (b); Lubiatowo 1987

- The third eigenfunction $e_1^3(x)$ is linked to locations of predominant erosion or accretion, again averaged over the entire area (x, y).

It should be noted that the extremum values of the eigenfunctions e_{2x} and e_{3x} appear where the profile changes are maximum.

The findings for the second mode k=2, i.e. $e_2^1(x)$, $e_2^2(x)$ and $e_2^3(x)$ have not displayed any clear correlation with profile parameters, as shown in Fig. 10b. It should be stressed that the maximum changes in the function $e_2^n(x)$ are similar to those for $e_1^n(x)$ and appear in the zone of the most intensive profile transformation.

The respective longshore eigenfunctions $e_1^1(y)$, $e_1^2(y)$, $e_1^3(y)$ are illustrated in Fig. 11, for the first mode k=1 and second mode k=2 respectively, in parts a and b. The first eigenfunction $e_1^1(y)$ again characterizes the average feature, this time the allocation of shoreline. The second longshore eigenfunction $e_1^2(y)$ is difficult to identify. It is not excluded that its existence is associated with longshore forms, but more data is required to confirm this hypothesis. The third longshore eigenfunction $e_1^3(y)$ is associated with longshore changes in cross-shore profiles. The maxima of $e_1^3(y)$ point to the places of prevailing accretion while the minima are linked to erosion.

The longshore EOF for the second mode k=2, i.e. $e_2^1(y)$, $e_2^2(y)$, $e_2^3(y)$ do not show any clear correlation whatsoever with the coastal features except for the first function $e_2^1(y)$ which represents the average shape of shoreline (but not its location !).

The temporal eigenfunctions measured at Lubiatowo are depicted in Fig. 12 for cross-shore modes. The following observations can be made:

- The first function $C_{1x}^1(t)$ is constant, which implies that the average profile can be treated as time independent;
- The second function C_{1x}^2 is associated with the net cross-shore sediment transport, or processes of erosion and accretion, in good agreement with Winant et al. (1975) and Hsu et al. (1986);
- The third eigenfunction C_{1x}^3 seems to be uncorrelated with coastal features;

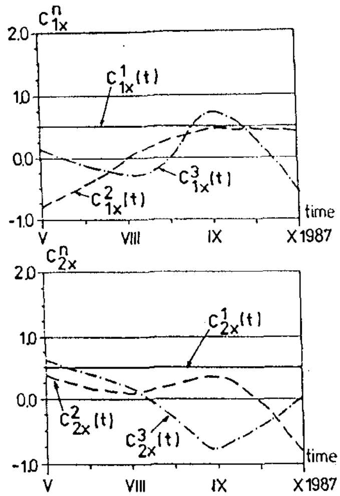

Fig. 12. Cross-shore coefficients c_{it} for modes k=1 and k=2; Lubiatowo 1987

- The cross-shore characteristics for the second mode k=2 do not display any clear-cut regularity or relationship to geometrical and dynamic characteristics.

The geometric and dynamical features of shoreline can be analyzed in terms of one--dimensional EOF. Some findings are illustrated in Fig. 13. For instance, the second eigenfunction e_{2y} indicates the places where the net accretion is the highest (maximum of e_{2y}) or erosion prevails (minimum of e_{2y}) along shore during the entire period of analysis. Oscillations about zero exhibit places of small net variation of shoreline.

The following remarks can be put forth for the temporal eigenfunctions c_{1t}, c_{2t} and c_{3t} (not illustrated):

- c_{1t} is approximately constant
- c_{2t} averaged over all shoreline locations shows a tendency towards accretion or erosion in consecutive time intervals. Positive values of this function point to the seaward advancement of shoreline while negative values indicate the landward retreat.

6 Long-Term Changes

6.1 Single-Bar or Smooth Shore Profiles

Our analysis of long-term single-bar profile changes has been based on multiyearly measurements carried out on the Black Sea coastline in the years 1974 - 1977. Fig. 14 illustrates the results obtained by one-dimensional EOF method. The findings are similar to those obtained for meso-scale changes, but it is because of the addition of multiyearly effects that individual functions are pronounced to a lesser extent. For instance, the average profile $h = e_{1x} \cdot \sqrt{\lambda_1 n_x}$ does not exhibit clear underwater bars and other forms, as they are smoothed out by individual profiles.

6.2 Multiple-Bar Profiles

These changes have been analyzed for the shoreline measured on the Baltic Sea in the years 1983 - 1989. Fig. 15a shows that the shoreline changes in the years 1983 - 1986 were

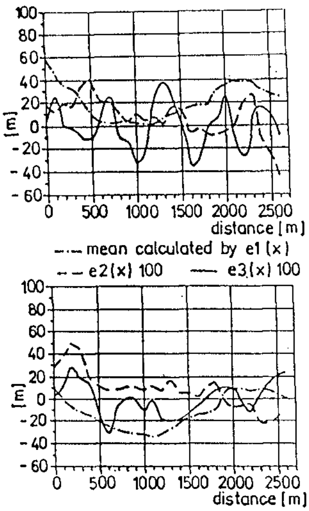

Fig. 13. Longshore empirical eigenfunctions (1-D); Lubiatowo 1987

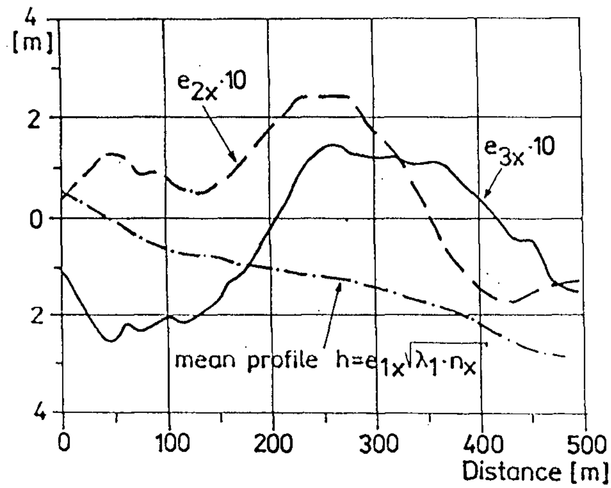

Fig. 14. Long-term variation of single-bar profile at Shkorpilovtsi, 1973 - 1977

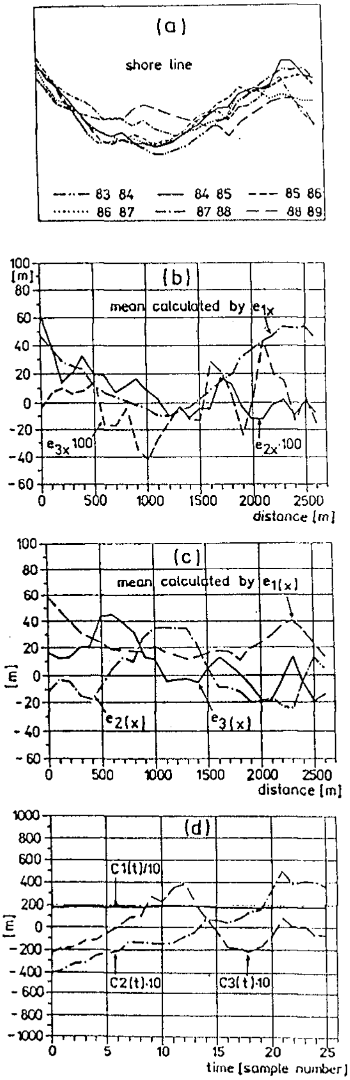

Fig. 15. Long-term variation of shore topography at Lubiatowo: shoreline from 1983 to 1989 (a); longshore EOF (1-D) 1983 - 84 (b); longshore EOF (1-D) 1987 - 89 (c); coefficients c_{it} (d)

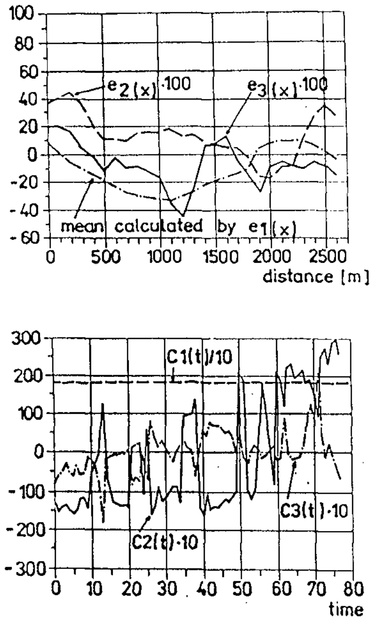

Fig. 16. Longshore empirical eigenfunctions (1-D) at Lubiatowo, for the entire period 1983 - 1989

by far less intensive than those in the years 1987 - 1989. This is also reflected in the second eigenfunction e_{2y}, cf. Fig. 15b vs. Fig. 15c. The coefficients c_{it} are depicted in Fig. 15d.

The interpretation of the eingenfunctions and the temporal coefficients is similar to that provided earlier for the shorter time scales. For comparison, Fig. 16 shows the EOF for the entire period 1983 - 1989.

In order to provide an expanded background for the shoreline changes we analysed the variability of shoreline back to 1890 for the central coastline mentioned in the introduction. Reliable precise bathymetric charts were retrieved for the period from 1967 to date. One interesting feature observed was that in long scales the seabed varied in the vertical range of 1.0 - 2.5 m about both inner and outer bar, although the changes at the outer bar occur in a wider strip. As already mentioned, quasinodes with insignificant changes were observed in between the bars, some 150 - 175 m from shoreline. Beyond the zone of bar migration another node appears 300 - 350 m from shoreline.

7 Conclusions

1. The use of EOF, in 1-D and 2-D formulation, for analysis of bed & shoreline changes in multiple scales, and in different barred environments has confirmed the adequacy of the tool.

2. Some earlier linkage of eigenfunctions to factors of coastal dynamics has been given an extensive experimental support, and some other relationships have been exposed.

3. The following association of eigenfunctions and coastal features have been confirmed:
   1st mode $e_{1x} \rightarrow$ mean profile and/or shoreline
   2nd mode $e_{2x} \rightarrow$ berm/bars and/or salients/cusps, etc.
   2nd time f. $c_{2t} \rightarrow$ temporal predominance of off/onshore transport
   3d mode $e_{3x\ 1-bar} \rightarrow$ intensive bed changes
   $e_{3x\ >1bar} \rightarrow$ predominance of off/onshore transport
   3d time f. $c_{3t} \rightarrow$ difficult to attribute...

4. 2-D EOF sometimes obscures data analysis due to excessive smoothing out, although permits identification of longshore features.

5. Further application of EOF in analysis of scale-model and prototype data is intended.

Acknowledgements
This study has been carried out under the program CPBP 02.12-2.3, which is gratefully acknowledged.

References

Hsu T.W., Liaw S.R., Wang S.K., Ou S.H. (1986) *Two-dimensional empirical eigenfunction model for the analysis and prediction of beach profile changes*, Proceed. of 20th Coastal Eng. Conf., Taipei

Winant C.D., Inman D.L., Nordsom Ch.E. (1975) *Description of seasonal beach changes using empirical eigenfunctions*, Journal of Geoph. Research, Vol. 80, No 15