Journal of Coastal Research	SI 39	351 - 354	ICS 2004 (Proceedings)	Brazil	ISSN 0749-0208

Application of the Empirical Orthogonal Functions for the Analysis of Southern Brazilian Beach Profiles

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ABSTRACT

BARLETTA, R. C.; FRANCO, D.; MELO, E.; PEREIRA, P.; TOZZI, H. and CALLIARI, L. J., 2006. Application of the empirical orthogonal functions for the analysis of southern Brazilian beach profiles. Journal of Coastal Research, SI 39 (Proccedings of the 8th International Coastal Symposium), 351- 354. Itajaí, SC, Brazil, ISSN 0749-0208.

In an attempt to improve data treatment and interpretation, Empirical Orthogonal Function statistical analysis was performed for southern Brazilian beach profile data. The efficiency of the method for analysing the data was evaluated and compared with previous similar works. The analysis separates temporal and spatial dependences of the data allowing the description of beach changes as a linear combination of time and space functions. Irregulary time sampled seasonal data yielded worse results than the more regular daily profile observations. Most of the variations in profile configuration were explained by the first three eigenfunctions corresponding to the three largest eigenvalues. The largest eigenvalue corresponded to an eigenfunction which represented an average profile. The second eigenfunction showed a maximum at the berm location and tended to have a minimum towards the lower terrace and bar location. The third eigenfunction showed a minimum at the berm, tending to have a maximum near the terrace location. Results indicated that the method can be usefull tool for analysing south Brazilian beach data. It provides a way of interpretating profile variation behavior and the governing physical processes.

ADDITIONAL INDEX WORDS: *Beach profiles, volume changes, eigenfunctions, eigenvalues.*

INTRODUCTION

Continuous sediment volume changes in beaches are a characteristic behavior of most sandy coastlines around the world. Beach profile shape responds to meteorological and oceanographic processes, especially wind waves, on time scales that range from hours to years.

Several statistical techniques for describing beach changes have been used since the 70's. WINANT *et al.*(1975) pioneered the use of empirical orthogonal functions (EOF) to study variations in beach profiles in time and space. ARANUVACHAPUN and JOHNSON (1979) used this technique to analyse a 10 year data set from Gorleston and Great Yarmouth beaches, Norfolk. PRUZAK (1993) showed the EOF's ability to describe the evolution in time of beach profiles located in Poland and Bulgaria. HSU *et al.*(1994) proposed a beach change prediction model, based on EOF, reinforcing the statistically prediction ability of the method.

Most beach dynamics studies performed in southern Brazil were basically descriptive, consisting in data sampling and basic statistical analysis. Some of them applied the Australian beach classification models to those Brazilian beaches

Geological studies realized by CALLIARI and KLEIN (1993), TOZZI (1999), TOZZI and CALLIARI (2000) and BARLETTA and CALLIARI (2001) revealed seasonal sand migration patterns for beaches in Rio Grande do Sul (RS), the southernmost state of Brazil. These studies showed that sediment transport towards the beach prevails during spring and summer, resulting in steeper beaches and higher berms at the end of summer, whereas in fall and winter, waves generated by storms cause beach cuts and offshore sediment motion that gives rise to well developed system of bars off the surf zone. In a recent work, PEREIRA *et al*. (2003) sampled daily morphodynamic variations at Cassino Beach, south shore of RS state for beach safety purposes.

This preliminary study deals with the implementation, use and evaluation of the empirical orthogonal function statistical analysis for south Brazilian seasonal and daily beach profile data sets referent to some of the works cited above. The EOF method applied to beach profiles was used to determine their variation through time and along the beach.

METHODOLOGY

Seasonal and daily behavior of southern Brazilian beach profiles were analysed using the methodology described by WINANT *el al.* (1975) and DEAN and DALRYMPLE (2002). Beach profile data was used to generate sets of empirical eigenfunctions. The data represents depth elevations (h), as a function of distance normal to the beach (x) and time (t). The concept of the method is to describe changes among different beach profiles by the smallest number possible of functions, called eigenfunctions. Each of these eigenfunctions consists of a contribution to the water depth given as a function of the distance along the profile. The first eigenfunction is selected so that it accounts for the greatest possible variance of the data (defined as the mean square of the depths). The successive eigenfunctions, which are orthogonal to the previous ones, are selected sequentially such that they represent the greatest

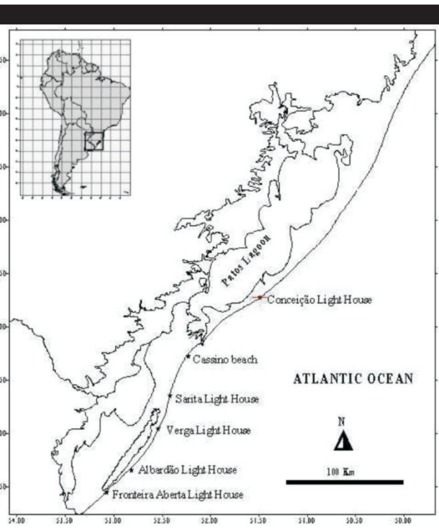

Figure 1. The smaller map shows the southernmost Brazilian state, Rio Grande do Sul. Main map shows the seasonal and daily beach profile measurement locations.

amount of variance not yet explained. The advantage of EOF analysis is that it provides a compact description of the spatial and temporal variability of data sets in terms of theirs orthogonal functions or statistical "modes". Although physical interpretations often are been given to EOFs, they are a purely statistical entity which represent the variance and covariance in an optimal manner, and therefore, no physical cause-effect relationships are established in the analysis. However, a previous knowledge about the behavior of coastal morphological system when combined with the analysis results often allows one to interpret the most representative EOFs in terms of physical mechanisms.

The seasonal EOF analysis was performed on beach profile data sampled at stations located north and south of the Patos Lagoon inlet, in the RS state coastline. The sample station 80 km north of the inlet is the Conceição Light House, which data set was sampled between 1996 and 1999 for geological study of BARLETTA and CALLIARI (2001). Southward from the inlet, the stations were: Sarita, Verga, Albardão and Fronteira Aberta Light Houses, located at 60, 100, 150 and 170 km from the inlet, respectively. The data for these stations was collected during the year of 1996 by TOZZI (1999).

The daily EOF analysis was applied to profile data sets obtained at Cassino beach on a site known as Touristic Terminal. They were sampled during the summer season of 2002 (48 days) and explored by PEREIRA *et al.* (2003). The sites are shown in figure 1.

We point out that the existing data was originally planned for geological studies and not for the type of statistical analysis we intended to do. As a result, data sets had different time lags and were not sampled regularly in space and time. That turned out to be a limitation since the EOF analysis assume the data to be equidistant in time and space. In order to make possible the EOF application, we had to arbitrarily re-sample the seasonal data to equal space and time intervals. Other limitation lies in the fact that most of the data included only a small part of the submerged part of the profile (surf zone), where sand motion is more intense. As a result an important compartment of the beach where the variability is high is not covered by the data sets, especially the seasonal ones.

RESULTS

Empirical eigenfunctions were calculated for all data sets. The results for the seasonal data (Table 1) shows that the eigenfunction with the largest eigenvalue dominate almost completely the variance. Eigenfunction 1 reflects the mean beach profile level and was previously called the "mean beach function" by WINANT *et al*. (1975). It also explains most of the variations (>99%) for all seasonal beach profiles analyzed and shows a very weak time variation, which means that the mean beach profiles analyzed don't change too much. Interestingly enough, Conceição Light House data shows an abrupt variation in time for this first eigenfunction. This change in the function matched a strong storm that occurred in April 1999. This event affected the beach morphology to a level that changed it's mean eigenfunction (Figure 2).

The second eigenfunction explains the rest of the residual variance that are not related to the mean function. Time variations were not taken into account because irregularity in sampling resulted in measurements with variable time lags for most locations, as mentioned before. A general characteristic of this second function related to seasonal data is that they showed a maximum at the berm and at the subaerial beach face. The third eigenfunction chosen explains even less variations than the second one.

EOF technique was also applied to the daily data sets. These series were sampled in a more regular way in time and they included a portion of the first subaquous sand bar. Due to this fact, we concentrated our efforts in this data set. The 2002 summer data for Cassino Beach was the best data set available (Figure 3a). Eigenfunctions percentuals are displayed in figure 3c.

The first eigenfunction explained more than 99% of the variation with a small time variation (Figure 4a). The second eigenfunction, despite explaining only a small percentual of the variance, showed good accuracy in revealing berm and beach

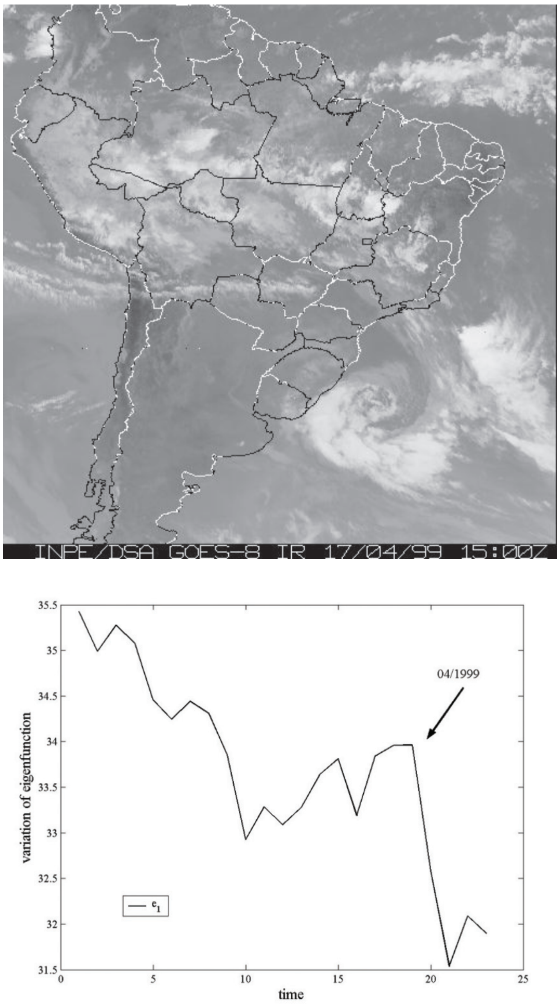

Figure 2. Severe storm in April 1999 were able to change the Conceição Light House mean beach function. Observe the drop in the curve to a lower level.

Table 1. *Results of Empirical Eigenfunction Analysis for Seasonal Data.*

	Conceição	Sarita	Verga	Albardão	Fronteira Aberta
Eigenvalue 1	99,39	99,02	99,61	98,57	99,27
Eigenvalue 2	0,48 (79,39%)	0,89 (92,7%)	0,18 (45,53%)	0,88 (61,31%)	0,3 (41,09%)
Eigenvalue 3	0,06 (10,13%)	0,038 (4%)	0,069 (17,70%)	0,26 (17,86%)	0,22 (30,85%)
Eigenvalue 4	0,03 (4,75%)	0,015 (1,6%)	0,06 (15,23%)	0,16 (11,41%)	0,13 (17,89%)
Eigenvalue 5	0,01 (1,85%)	0,011 (1,2%)	0,029 (7,43%)	0,062 (4,31%)	0,037 (5,09%)

The numbers in parentheses represent the percentage of the variance from the mean beach function associated with each eigenvalue. Other numbers represent the percentage of mean square value of the data associated which each eigenvalue.

face sand motions (Figure 3b). It presented a maximum at this compartment, tending to go to a minimum near the terrace zone, which is not well defined because of the lack of offshore data. There's also a minimum above the dune zone. Time series of visually observed wave height was used to check on the time variation of this function. Volume changes were also calculated for the beach above and below datum. Both pieces of information confirmed that the second eigenfunction has a periodicity that follows that of wave events associated to fair weather and/or cold front passages during the sampled period (Figure 4b and c).

The third eigenfunction explains a percentage of the variations smaller than the second one, having a maximum at the dune-toe zone and tending to have a maximum over the terrace zone. A broad minimum exists above the berm. A small secondary maximum under the berm suggests that some of the level variation under this feature occurs in phase with the second function. Time dependence variations doesn't show any remarkable pattern.

The second and third eigenfunctions are phase-shifted. In periods of fair weather combined with small wave action, berm and terrace motions kept stable, and these functions stayed inactive (constant) having a near a zero value, as shown in figure 4 b (day 23 trough 32). The high variance localized at the dune-toe zone was captured by both the second and third eigenfunctions and resulted from a waste material deposited at this place during the sampling period (antropic action).

DISCUSSION

Due to the irregularity in time of the available data, seasonal data sets were not sufficient for more precise interpretations. Sampling without the required periodicity are known to cause problems in EOF methodology. Therefore, for the seasonal data, time dependence variations were not investigated. It seemed more appropriate to search for the main spatial features and main functions influences in terms of variance, without evaluating them in time. Also, the underwater beach topography data was poor, and did not cover most of the subaquous beach features. To search for an insight about the sand exchange between the berm and the bars with such limited data did not seem plausible.

An improvement for this type of analysis would require EOF techniques designed to non-regular sampling. Nevertheless, this fact emphasises the importance of planning well the data sampling before going to field. Such effort would yield regularly sampled data sets that would allow robust numerical and statistical treatments pushing the state of the art into a next level, where prediction and hindcast are the purposes.

The highlight of this work was the application of the EOFs to daily beach profile data sets. The time regularity of the data yielded fairly good results and allowed consistent physical interpretation of EOFs. The 2002 summer season was marked by regular periods of high wave action together with periods of minor activity (Figure 4c). Those were well captured by the second eigenfunction's time evolution along the beach features (Figure 4b). Time variation of this function followed the scale of a few days and matched well with the periodicity of atmospheric low pressure systems that acted in Cassino beach during the studied period.

Comparing our second eigenfunction with Winant's "bar-berm" function it became clear that we were observing the same sand exchange process between subaerial and subaquous portions of the beach, but in different time scales. As we did not have the bar features measured, we were not able to define these eigenfunction as the Winant's "bar-berm function", but at least the "berm function" was detected. In fact, whenever the time periodicity coefficient is positive (Figure 4b), it accounts for the berm construction and reflects periods of small wave action and fair weather. The inverse is also true. The third eigenfunction was related to terrace movements and was much less active then the second one, most of the time having a coefficient near zero (Figure 4b).

Once again, to comparate our results with those of WINANT *et al.* (1975), we had to extrapolate our interpretations by regarding that the same beach compartments that are measured in both works show similar tendencies. The main difference between the beach data is that ours cover the more subaerial beach including the dunes, whereas their data cover the berm, beach face, terrace and the underwater bars in detail, revealing that sand exchanges takes place between the subaerial beach and subaquous depths up to 6/8 meters for Californian beaches. As shown by these authors, with better data sets, the distance where important sand exchanges take place inside the water could be determined for RS coastal beaches, including the determination of a closure depth. This may be a quest for the next years.

The EOF method applied for Brazilian southern beaches was a good chance to improve beach data treatment techniques in

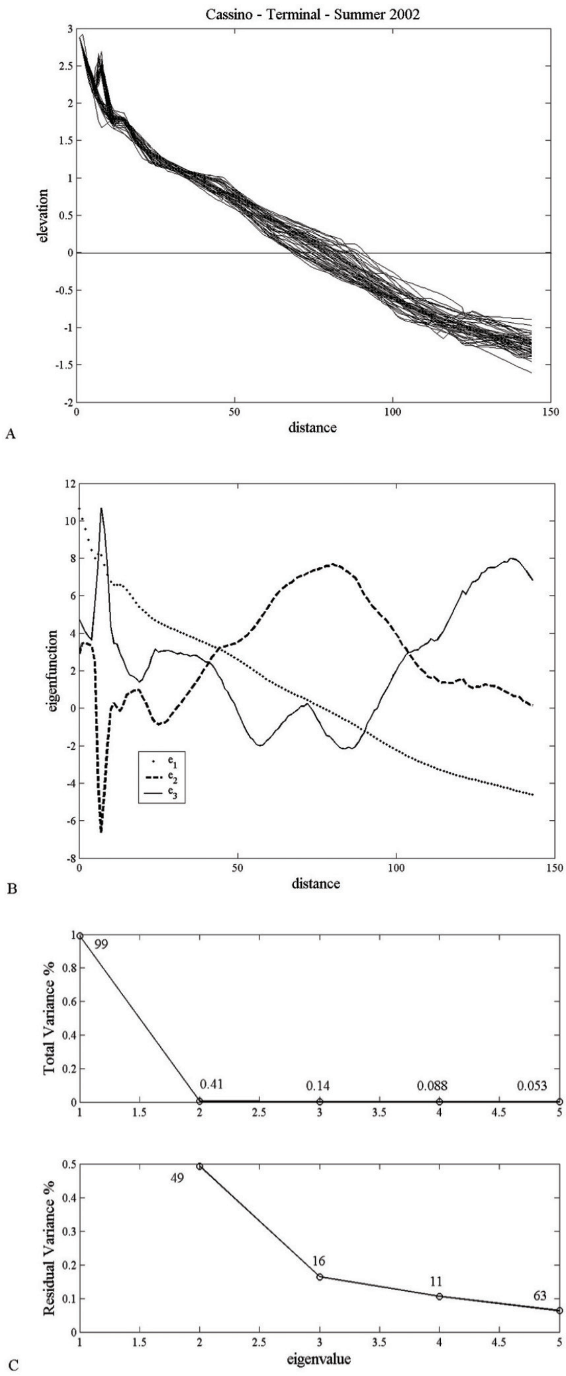

Figure 3. All Summer profiles measured at Cassino (a). Dotted line, mean beach function; dashed line, second eigenfunction; solid line, third eigenfunction (b). Eigenfunctions percentuals (c).

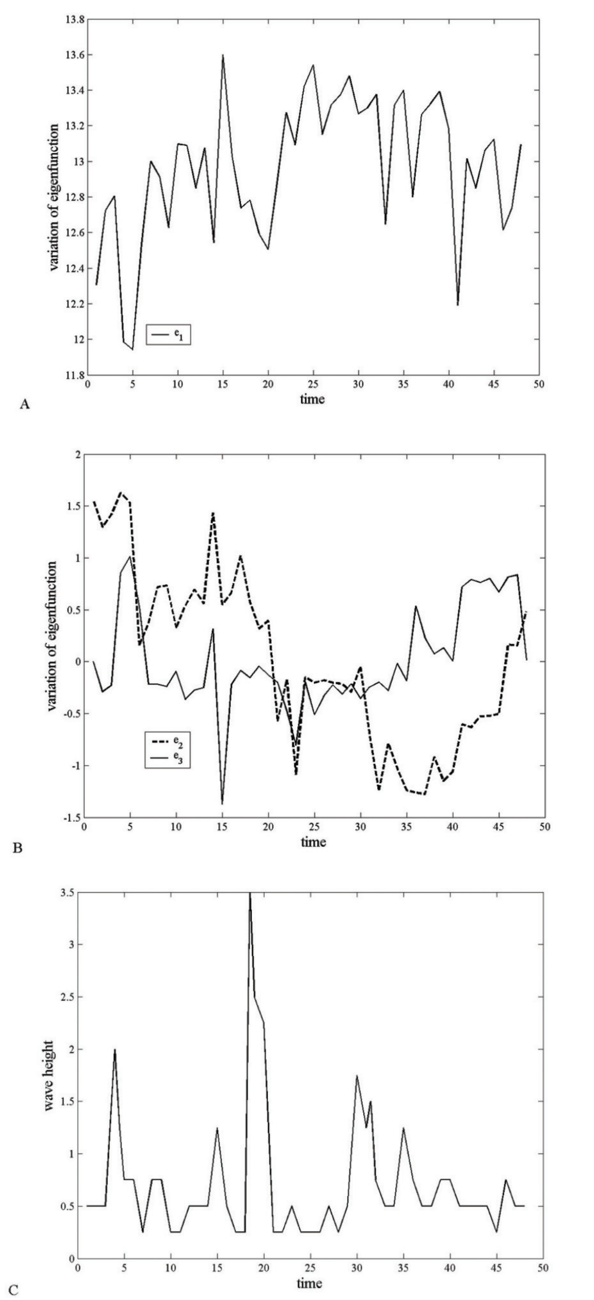

Figure 4. Time series of the mean beach function (a). Second and third eigenfunctions time variation (b). Visual observation wave height data at the sample station during the studied period (c).

Brazil. The method was valuable in showing changes in beach profile configuration that may have significance in the response of the profile to wave regime variation. It can improve the interpretations given for the processes acting at the beach. The variations captured by the method in the dune-toe zone were not explored in the interpretations, taking into account that the physical agent that rules most variance in this beach portion is the wind and rarely the waves.

CONCLUSIONS

Statistical EOF analysis of beach profile data from southern Brazilian beaches has produced valuable results by showing the changes in profile configuration as a function of time and space. Daily data produced better results than seasonal data due to more time regular and extensive space sampling. That shows data quality to be a limiting factor to this type of analysis.

Most of the variation in beach profiles can be acounted for or explained by the three first eigenfunctions which have the highest eigenvalues. The eigenfunction with the highest value is the mean beach function which indicate the mean profile position. A second eigenfunction, that in our case can be called the berm function, shows a large maximum at the location of the beach berm. A minimum tendency towards the subaquous first bar location is also observed. The time dependence of this function shows near week periodicity indicating that it should be related with weekly onshore/offshore movement of sand controled by waves associated with fair weather and/cold front period alternations. A third eigenfunction shows a maximum tending towards the beach low-tide terrace, however, it´s time dependence doesn't show any periodicity.

The results of this preliminary study points out to the great possibilities of this statistical treatment can have when applied to brazilian beach data, since the derived functions have shown direct relation to the natural processes.

ACKNOWLEDGEMENTS

The authors of this article wish to thank the National Research Council of Brazil (CNPq) for the financial support. We also thanks the Geological Oceanography Laboratory of FURG, for gently making available and permitting the use of the data.

LITERATURE CITED

ARANUVACHAPUN, S. and JOHNSON, J.A, 1979. Beach profile at Gorleston and Great Yarmouth. *Coastal Engineering*, 2, 201-213.

BARLETTA, R.C. and CALLIARI, L.J., 2001. Determinação da intensidade das tempestades que atuam no litoral do Rio Grande do Sul, Brasil. *Pesquisas em Geociências*, 28(2), 117-124.

CALLIARI, L.J., and KLEIN, A. H. F., 1993. Características morfodinâmicas e sedimentológicas das Praias Oceânicas entre Rio Grande e Chuí, RS. *Pesquisas*, 20 (1), 48-56.

DEAN, R.G. and DALRYMPLE, R.A., (eds.), 2002. *Coastal Processes with Engineering Applications.* New York: Cambridge University Press, 471p.

HSU, T.W.; OU, S.H. and WANG, S.K., 1994. On the prediction of beach changes by a new 2-D empirical eigenfunction model *Coastal Engineering*, 23(4), 255-270.

PEREIRA, P; CALLIARI, L. J.; AREJANO, T. B. and CARON, F., 2003. A morfodinâmica praial como ferramenta para a segurança dos banhistas da praia do cassino: estudo de caso da temporada 2002. *IX Congresso da Associação Brasileira de Estudos do Quaternário, ABEQUA.* (Recife, Brasil). CD press.

PRUSZAK, Z., 1993. The analysis of beach profile changes using Dean's method and empirical orthogonal functions. *Coastal Engineering,* 19(4), 245-261.

WINANT, C.D.; INMAN, D.L. and NORDSTORM, C.E., 1975. Description of seasonal beach changes using empirical eigenfunctions. *Journal of Geophysical Research*, 80: 1979-1986.

TOZZI, H.A.M., 1999. Influência das Tempestades Extratropicais sobre o estoque subaéreo das praias entre Rio Grande e Chuí, RS. Campanha do Outono e Inverno de 1996. Porto Alegre, Rio Grande do Sul: Instituto de Geociências, UFRGS. Dissertação de Mestrado, 115 p.

TOZZI, H.A.M. and CALLIARI, L.J., 2000. Morfodinâmica da Praia do Cassino, RS. *Pesquisas em Geociências*, 27(1), 24-33.