

MONSOON-INDUCED SEASONAL VARIABILITY OF SHELTERED VERSUS EXPOSED BEACHES ALONG THE WEST COAST OF INDIA

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(Received February 3, 1986; revised and accepted July 29, 1986)

Abstract

Shenoi, S.S.C., Murty, C.S. and Veerayya, M., 1987. Monsoon-induced seasonal variability of sheltered versus exposed beaches along the west coast of India. *Mar. Geol.*, 76: 117–130.

Changes in profile configuration of the beaches at different locations along the west coast of India have been quantitatively compared by means of Empirical Orthogonal Function (EOF) analysis. These beaches, though exposed to similar monsoonal forcings, respond through variable changes depending on their individual geographical/geomorphological setting. The analysis suggests that, for the period of study, the beaches are stable as revealed by the temporal dependence of the first eigenfunction. The second function reveals the significant erosional/accretional phases with a well defined cyclicality of one year associated with monsoonal wind and wave climate. The second spatial function efficiently expresses a "pivot point" for the seasonal shore-normal movement of sand. The depth at which this pivot point occurs is inversely related to the width of the beach. The differential energy environments, even over short distances, are found to be the prime factors that determine the magnitude of temporal beach variability. Unprotected beaches showed higher magnitudes of variability. These results suggest that the second eigenfunction and the variance of the data set are more useful than the other order eigenfunctions for a comparative study of this kind.

Introduction

Almost the entire stretch of the west coast of India from Gujarat to the southernmost Cape has had a relatively similar geological and climatological history. This has been especially true of the extensive region along the Western Ghats during the last 18,000 yrs. Significantly, no major river system that could have substantially influenced the course of evolution of the beaches, or of the coastal configuration as such, discharges sediments into the coastal seas of this zone. Thus, most of this coastline today is comprised of a diverse border of beach sands variably backed by either dunes, lagoons, low-lying plains or

marshy lands. Most of the beaches exhibit variations in their geometric form over different time scales in response to monsoonal wind and wave climates excluding short periods of weather associated with cyclonic activities (Murty, 1977; Murty et al., 1982). Typically, these changes over periods of one year or so are examined quantitatively by estimating the volumes of beach material under certain measured profile configurations (assuming a unit width of 1 m). This approach, while serving some limited purpose, fails to provide information on the nature of these variations over different time scales owing to spatially varying energy environments. An alternative method that utilises Empirical Orthogonal

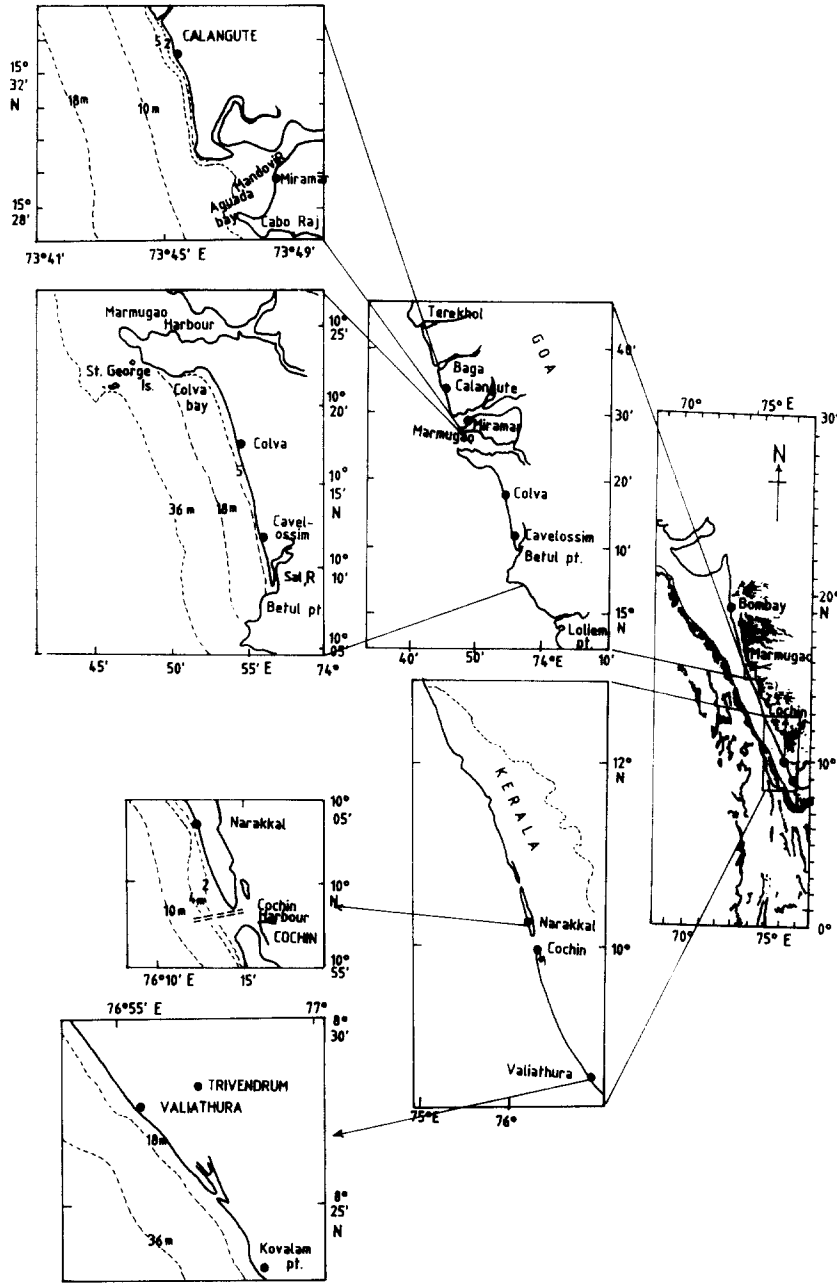


Fig.1. Map showing the locations of study.

Functions (EOF) (Winant et al., 1975) has been adopted towards this end. Following this approach, the presentation of beach profile changes becomes amenable to easier interpretation and, hence, more useful when one tries

to compare different locations for data sets spanning different durations (Winant and Aubrey, 1976; Aranuvachapun and Johnson, 1979; Aubrey, 1979; Aubrey et al., 1980).

This paper uses EOF to deal with the nature

of changes occurring at several beaches bordering the coasts of Kerala and Goa along the west coast of India (Fig.1). It is also intended to identify the energy environments of these beaches and to examine their seasonal changes under different regional settings and sediment characteristics. These beaches (Kerala and Goa) differ in their genetic types, viz.: (1) barrier beaches; and (2) mainland beaches interspersed with rocky headlands, rock outcrops, bayside beaches, etc. In a broader sense, they are subjected to similar climatological forcings.

Environmental setting

Previous conventional studies of the Goa beaches have indicated that they are fairly stable, in contrast to the barrier beaches of Kerala, which are migratory and susceptible to severe erosion and accretion (Murty, 1977; Murty et al., 1982). Along the Kerala coast, the beaches are, in general, characterised by step-like features at the foot of the subaerial beach, with their constituent sediments distributed in a linear manner. In the central part of the coast of Kerala, the appearance of mud banks in the nearshore regions during the southwest monsoon season is a conspicuous and unique feature. In contrast, the presence of rock outcrops and, in some areas, small offshore islands are common along the coast of Goa.

An examination of the existing bathymetric charts for the nearshore regions along the west coast of India indicates a gradually sloping sea bottom. The width of the continental shelf tapers from north to south (Fig.1). The nearshore sea bottom is composed of unconsolidated sediments — mainly sands — which occupy a well-marked zonation with regard to their spatial distribution. Silty clays or clayey silts occupy the inner shelf while clayey sands/sands cover the rest of the shelf (Nair and Pylee, 1968).

Monsoons control the climate in this region. Apart from the variability of winds from month to month, a complete reversal of the general wind system during the year is associated with these monsoons. Considering the orientation

of the shoreline, waves approaching the shore from directions 170° to 350° from north are significant in shore processes here. The predominant periods of the swell waves approaching the coastline under study lie between 5 and 14 s, with deep water directions between 240° and 320° from north (Fig.2). These waves have their predominant heights from 0.3 to 1.0 m during non-monsoon months (October to May) and attain as much as 3.0 m during southwest monsoon months (June to September). Occasionally, waves exceeding these heights prevail for about 20% of the time during these months (Tables 1 and 2). During the southwest monsoon, the predominant direction of wave approach lies between west-southwest and west-northwest (Varkey et al., 1982). The tides in this area are of the mixed semidiurnal type. The coast of Kerala falls within the microtidal range (≤ 1.2 m), while the coast of Goa experiences tides in the mesoscale range (≈ 2.2 m).

Study sites

Six locations were selected for this study — four along the Goa coast and two along the Kerala coast (Fig.1). The coast of Goa extends from Loliem Point ($14^\circ 55'N$, and $74^\circ 02'30''E$) in the south to Terekhol ($15^\circ 43'30''N$, and $73^\circ 42'E$) in the north while the Kerala coast extends from $12^\circ 50'N$ to $8^\circ 15'N$. These beaches constitute a wide variety of grain sizes, and range from open ocean beaches to partly sheltered ones by rocky promontories (Table 3).

Goa coast

Calangute. Calangute beach is a straight sandy beach, about 7.5 km in length backed by rows of sand dunes of varying heights (0.5–10 m). Very coarse to fine sands with occasional boulders constitute the sediments of this beach (Veerayya and Varadachari, 1975; Veerayya, 1978). The Mandovi and Chapora rivers to the south and north of the Aguada and Baga promontories, respectively, drain into the adjoining sea. The bathymetry contours are nearly parallel to the shoreline, with an average slope of 1.5 m km^{-1} (Veerayya, 1972).

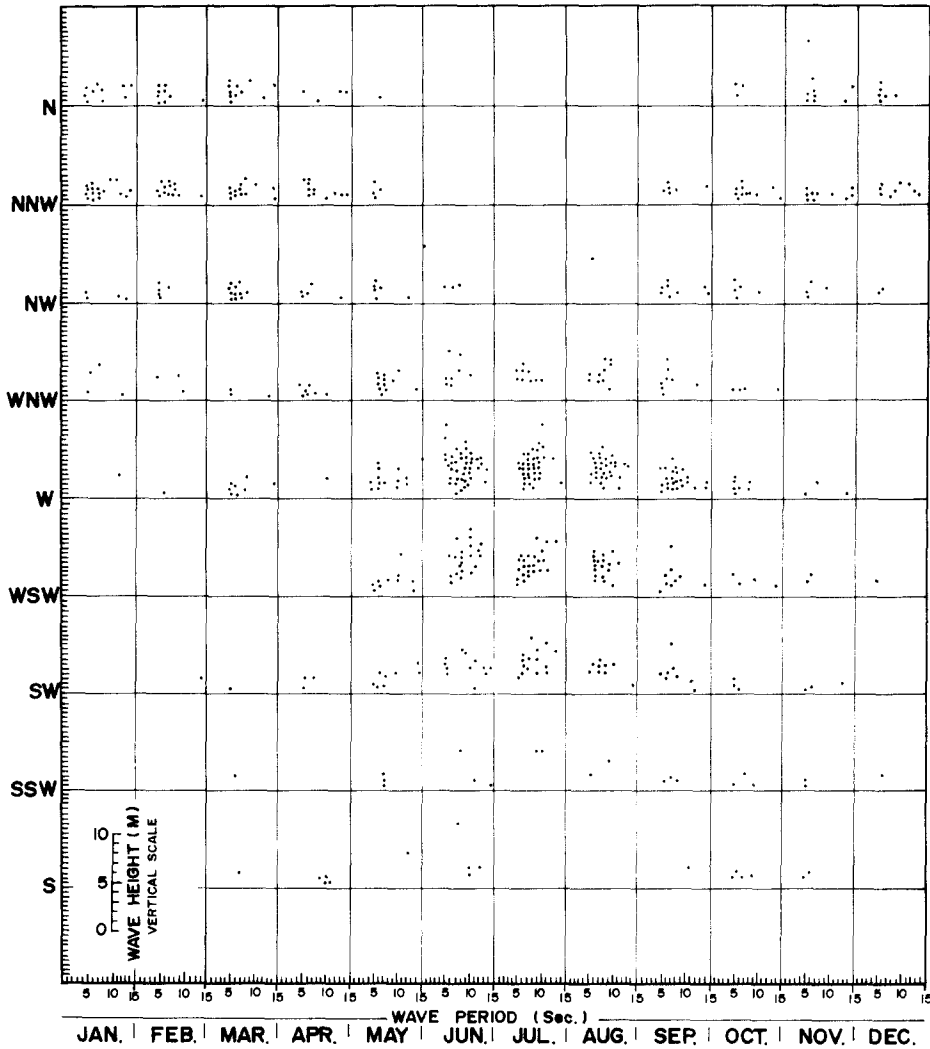


Fig.2. Swell-wave climate off the west coast of India.

Miramar. This is a bay-side sandy beach in the Aguada bay confined between two headlands — Aguada and Cabo Raj on the northern and southern sides respectively. Immediately north of this beach, the Mandovi river joins the bay. The Aguada Bay is open to the swells from the prevailing southwest, west and northwest directions. The beach foreshore slope varies from 10° to 5° . The sediments are medium- to very fine-grained sands.

Colva and Cavellissim. These locations are on the 30 km long straight sandy beach, com-

monly called Colva beach, between Betul point and Colva bay. In general, the beach foreshore is wide, and steep at its extreme ends. The beach is low with mild offshore gradients. It is backed by well-developed sand dunes. The beach is composed of medium- to fine-grained sands and moderately to very well sorted sediments. The sediments in the offshore region of the beach show the presence of sands adjacent to the beach, followed by silty sands or sandy silts, beyond which clay occurs (Veerayya, 1978). The waves propagating towards this beach often break offshore, dissi-

TABLE 1

Percentage frequency of swell-wave periods

Period (s)	5	6	7	8	9	10	11	12	13	14	calm
Month											
January	44.0	11.5	8.5	5.0	4.5	1.5	1.0	0.5	2.0	5.5	16.0
February	40.0	15.0	7.0	4.5	2.0	1.5	2.0	3.0	5.5	3.0	16.5
March	29.0	17.0	8.5	8.0	4.0	2.5	3.0	2.5	3.5	4.0	18.0
April	39.5	13.5	8.0	5.0	1.0	4.5	3.0	4.5	3.0	5.0	13.0
May	36.5	15.5	9.5	7.5	6.5	5.0	1.5	2.5	4.0	5.0	6.5
June	20.0	17.0	15.0	19.0	13.0	6.0	3.0	3.5	2.0	1.5	0.0
July	8.5	15.5	14.5	25.0	12.5	11.5	4.5	4.0	2.5	1.5	0.0
August	11.5	16.0	15.0	22.0	14.0	8.0	3.5	5.5	3.5	1.0	0.0
September	24.0	16.0	17.0	14.0	5.5	9.0	2.0	2.0	1.0	7.5	2.0
October	30.0	16.0	6.5	6.5	3.0	3.5	3.0	1.5	3.0	11.5	15.5
November	37.0	13.0	10.5	3.0	2.0	3.0	2.0	3.0	4.0	3.5	19.0
December	41.5	13.0	5.5	2.0	1.5	2.5	1.0	4.0	2.5	8.5	18.0

TABLE 2

Percentage frequency of swell-wave heights

Height (m)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	calm
Month													
January	21.0	27.0	23.0	9.5	1.5	1.0	0.5	0.5	-	-	-	-	16.0
February	23.5	27.5	15.5	11.5	3.0	1.5	1.0	-	-	-	-	-	16.5
March	21.0	34.5	15.5	8.0	2.5	0.5	-	-	-	-	-	-	18.0
April	29.5	38.0	10.5	3.5	2.5	0.5	1.0	1.0	0.5	-	-	-	13.0
May	9.5	28.0	32.0	11.5	6.0	4.0	1.0	0.5	0.5	0.5	-	-	6.5
June	2.5	6.0	10.5	15.5	16.0	19.5	9.0	11.5	6.5	2.5	0.5	-	0.0
July	0.5	2.0	3.5	9.0	14.0	17.0	11.5	17.0	7.0	9.0	2.5	3.5	0.0
August	3.5	9.0	10.0	16.0	16.5	20.0	7.5	9.5	5.5	1.0	0.5	0.5	0.0
September	13.0	21.0	23.0	13.0	9.5	10.0	3.5	2.5	2.5	-	-	-	2.0
October	22.5	40.0	15.5	4.5	0.5	0.5	0.5	0.5	-	-	-	-	15.5
November	21.0	30.5	17.0	9.5	1.0	0.5	0.5	0.5	0.5	-	-	-	19.0
December	16.0	35.5	21.0	5.5	2.5	1.0	0.5	-	-	-	-	-	18.0

pating much of their energy over a wide surf zone through multiple breakers.

Kerala coast

Narakkal. This station is about 8 km north of the Cochin harbour entrance channel. The offshore bathymetry slopes gently. During the southwest monsoon season, this beach receives some protection from the high monsoonal

waves owing to the presence of transient patches of highly turbid waters called mud banks. Fine- to medium-grained sands constitute the sediments of this beach (Shenoi, 1984).

Valiathura. It is a straight beach 6 km north of Kovalam point, composed of medium-grained sands. The nearshore bathymetry shows even topographic features. In the nearshore region, the sediments are mostly sands that extend

TABLE 3

Details of beach profile sites and beach survey data used in the analysis

Site	Duration		Mean grain size (ϕ)	Mean beach width (m)	Remarks
	From	To			
Calangute	Sept. 1969	Mar. 1972	2.30	50	Mainland beach, situated between two rock promontories. Open to ocean waves from offshore quadrants. Backshore narrows towards north
Miramar	Sept. 1969	Nov. 1970	2.50	80	Bayside beach situated between two headlands. Receives partial protection from the direct influence of ocean waves
Colva	Mar. 1971	Oct. 1973	2.75	105	Mainland, straight sandy beach. Direct exposure to ocean waves
Cavelossim	July 1970	Sep. 1973	2.50	55	As for Colva
Narakkal	Nov. 1964	Nov. 1966	2.40	40	Barrier beach. Protected by seawall groin assemblies; also receives protection from mud banks during SW-monsoon season
Valiathura	June 1967	May 1968	1.50	65	Exposed to a wave field from all offshore quadrants. Straight sandy mainland beach. Exposed to the ocean waves from all possible offshore quadrants

over the shelf, unlike the areas to the north. This region, experiencing tides in the microtidal range (≈ 1 m) is free from any natural or man made structures, with the exception of a 230 m long pier.

Data acquisition and analysis

The beach profile data collected under the programme on land-sea interaction studies at the National Institute of Oceanography, covers the period April 1964–February 1969 for the Kerala coast and September 1969–December 1973 for the coast of Goa. Monitoring of the profile changes was at a time interval of about 12–20 days. Table 3 shows the duration of the data utilised for this study. The beach profiles were measured at low tide

(at depths of about 1–3 m below MSL) using the level and surveyor's rod at all of the locations. At Valiathura, the profiles were measured at depths up to 4 m below MSL by sounding with the help of a lead line, and making use of the existing pier.

In the present study, the beach profiles were represented in terms of their empirical eigenfunctions (Empirical Orthogonal Functions, EOF). This decomposition is quite efficient in that the first few eigenfunctions provide information on most of the data variability. Moreover, the eigenfunction decomposition allows use of the entire profile to detail the beach changes, rather than considering just one point along the profile. In other words, this analysis objectively represents the variation in the beach profile configuration in terms of

distance from fixed data points, and in terms of temporal changes in the profile over the period of study. The EOF approach is, briefly, as follows.

The data set is denoted by a matrix, H , with each of the rows containing a time series of the elevation at a particular point along the profile and each column representing the beach profile at a particular time. Following Lawson and Hanson (1974) the data matrix H is represented as a product of three matrices in the form:

$$X = H/(mn)^{\frac{1}{2}} = U \Gamma V^T \quad (1)$$

where m is the number of rows and n is the number of columns of the data matrix H , the matrix U is of size $(m \cdot r)$ and V is of size $(n \cdot r)$ and Γ is a $(r \times r)$ diagonal matrix, with diagonal elements β_i , $i = 1, \dots, r$, $r [\leq \min(m, n)]$ is the rank of the matrix X . V^T is the transpose of V . The column vectors of U and V are orthonormal, i.e.:

$$U^T U = I, \text{ and: } V^T V = I \quad (2)$$

where I is the identity matrix. From eqs.1 and 2 we obtain the eigenvalue problem:

$$(B - \lambda_i I) V_i = 0 \quad (3)$$

$$(A - \lambda_i I) U_i = 0 \quad (4)$$

where $B = X^T X$, $A = X X^T$, V_i and U_i are the column vectors of V and U , respectively, and $\lambda_i = \beta_i^2$.

In the characteristic eqs.3 and 4 V_i , U_i and λ_i ,

recognised as the eigenvectors and eigenvalues of the real symmetric matrices B and A are evaluated on a ND-520 computer using the program developed by Fernandes and Mahadevan (1982).

Thus, the variability in the beach-profile configuration has been quantified by a set of eigenvalues, λ_i , and their eigen functions. Eigenfunctions are curves that best fit the beach profiles in the least-squares sense, and each eigenvalue defines the importance of the eigenfunction.

Results and discussion

The results of eigenfunction analysis from each site are summarized in Table 4. The functions are ranked according to the percentage of the mean square value of the data they explain. These percentages as accounted for by each function, enable evaluation of the relative importance of each function in explaining the observed beach variability. Since the first three functions account for more than 98% of the total mean-square value (TMSV), emphasis is laid on these functions. To express the changes in the mean profile directly, the sample mean has not been removed from the data set initially.

Before examining the modes of beach variability it may be noted that the data considered in this study were not uniformly sampled in time. The sampling intervals varied from 12 to

TABLE 4

Total mean-square value (TMSV) and the percent of the mean-square value of the data explained by the first five eigenfunctions. Numbers in brackets are the percent variance of the demeaned data set

Site	TMSV (m ²)	Variance (m ²)	1st function	2nd function	3rd function	4th function	5th function
Calangute	6.117	0.267	95.97	2.97(68.87)	0.40(15.04)	0.29(6.86)	0.14(3.10)
Miramar	1.219	0.119	93.67	4.92(67.83)	0.51(20.12)	0.31(4.96)	0.17(1.73)
Colva	2.091	0.160	93.47	4.66(76.42)	0.70(9.48)	0.40(7.07)	0.22(3.08)
Cavellossim	3.286	0.154	94.01	4.26(75.47)	0.85(11.54)	0.30(5.91)	0.19(2.28)
Narakkal	1.796	0.076	97.00	1.65(59.11)	0.83(19.71)	0.18(9.58)	0.13(3.94)
Valiathura	7.152	0.492	94.84	3.11(51.60)	1.13(26.34)	0.51(14.96)	0.22(3.61)

20 days and were occasionally slightly more at certain locations. To check this aspect, we analysed the data set for Miramar, selecting only the monthly sampled beach profiles, and compared the results with the irregularly sampled profile data. If the eigenfunctions are to accurately represent the beach variability, they should exhibit similar features for both of the data sets. Figure 3 illustrates the results of this analysis. The first spatial and temporal function for both of the data sets do not indicate any distinguishable departures, thereby showing the lack of dependence of these functions on data sampling. The configuration of the second spatial function remains almost the same in both of the cases, with identical time dependency characterizing a distinct seasonality. The third spatial function conserves its shape barring minor variations in its magnitude. The temporal dependence of this function shows identical trends, except for an accretional event noticed during April (Fig.3a). This event was smoothed in the case of evenly sampled data (Fig.3b). The primary information derived from the profiles in this study is the magnitude of beach variability, and its seasonality. From Fig.3 it is apparent that the seasonal signal is very clear for both uniformly and non-uniformly sampled beach-

profile data. The percentage of total mean-square value explained by each eigenfunction also remains the same — within 5% for the first three functions (Table 5). These results allow adoption of the EOF technique to non-uniformly sampled beach data without losing much information. Thus we assume that the non-uniformity in the sampling interval at certain locations has not contaminated the results.

The first eigenfunction (Figs.4 and 5) shows similarity in its shape for all of the six beaches and provides information on beach gradients. Apparently, the first function expresses the mean beach profile. Similarly, the temporal structure of the first eigenfunction (V_1) shows the near-stable nature of the beaches (Figs.6 and 7).

TABLE 5

Percent of the mean-square value of the data explained by the first five eigenfunctions for regularly and irregularly sampled data set for Miramar beach

Interval	First	Second	Third	Fourth	Fifth
regular	93.67	4.73	0.54	0.41	0.23
irregular	93.67	4.92	0.51	0.31	0.17

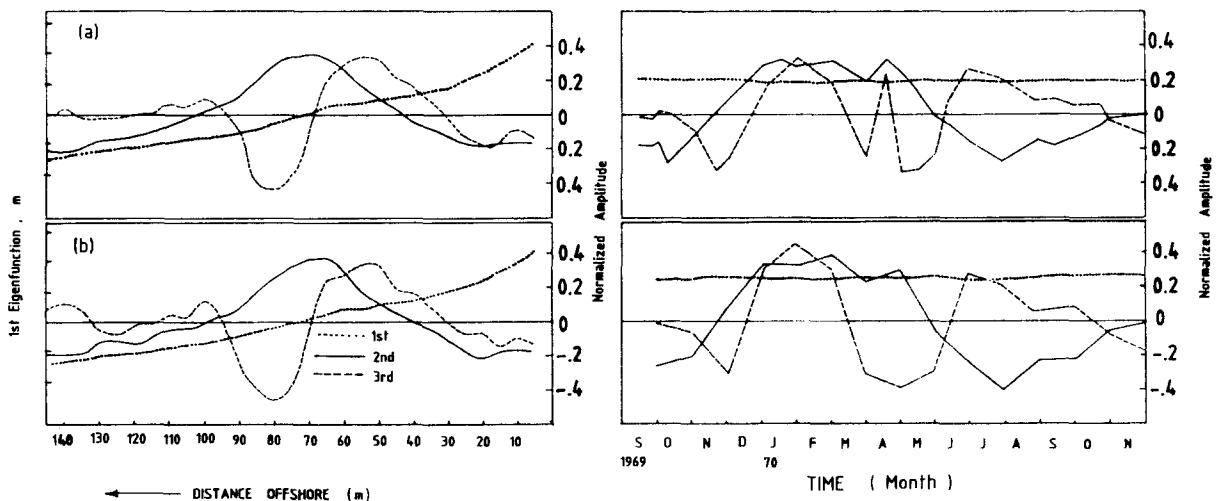


Fig.3. Spatial and temporal dependence of the eigenfunctions for (a) irregular and (b) regular data sets for Miramar beach.

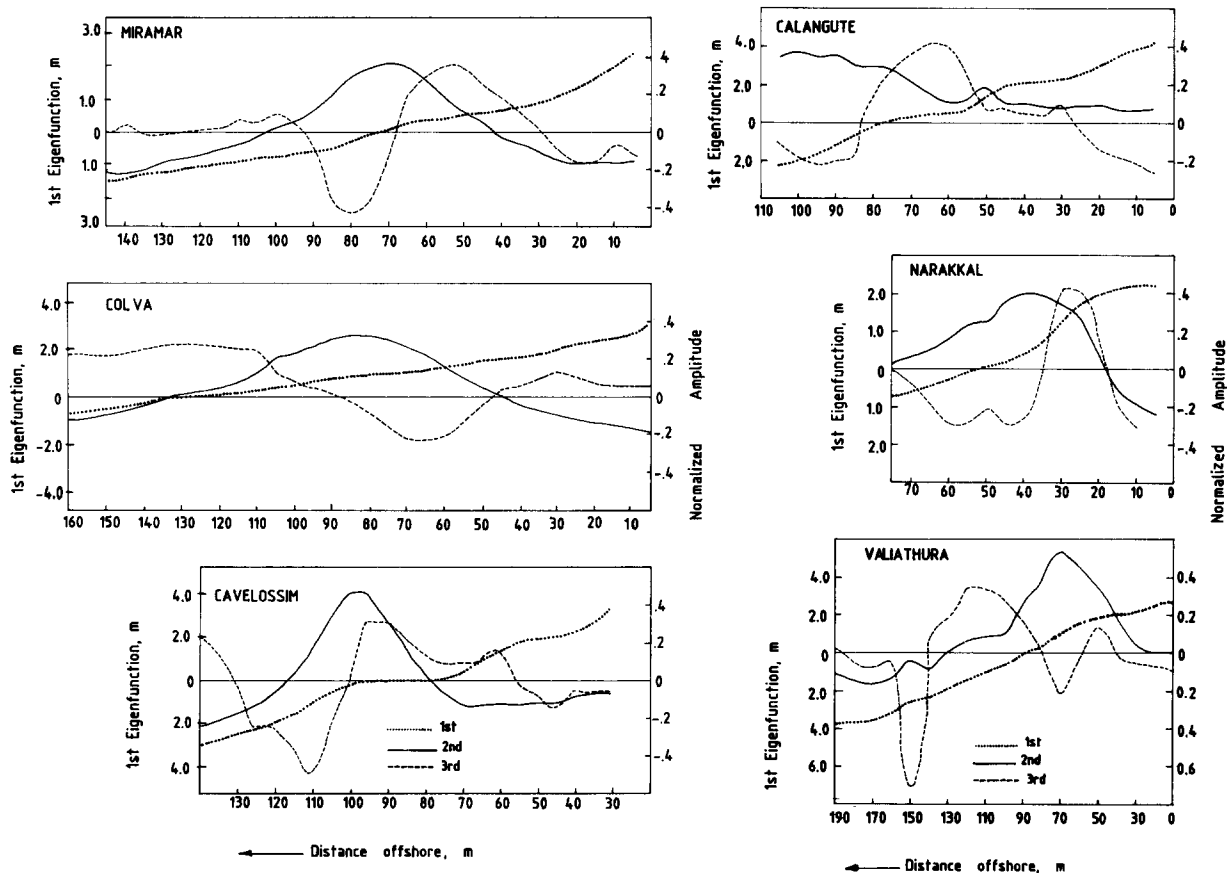


Fig.4. The spatial configuration of three eigenfunctions for Miramar, Colva and Cavelossim beaches.

Fig.5. The spatial configuration of three eigenfunctions for Calangute, Narakkal and Valiathura beaches.

The spatial configuration of the second function (U_2) shows similar patterns for the beaches at Miramar, Colva and Cavelossim (Fig.4). It shows the spatial location at which the major amount of beach variability occurs along the profile line. For Miramar and Cavelossim, it shows an extreme near the MLW (Fig.4), whereas for Colva it is shifted slightly towards the berm. These are the three mainland beaches among the six under study with low-energy environments and it is quite natural that the behaviours of the spatial dependence of the seasonal beach function (U_2) are alike. The second function of the other three beaches shows different configurations (Fig.5). Even though, these beaches have a direct

exposure to ocean waves, they differ greatly in their constituent sediments and regional settings. In the case of the high-energy environment beach at Calangute (Goa coast) with the coarsest sediments, the second eigenfunction (U_2) shows only positive values, with a maximum beyond the MLW (Fig.5). For the beaches at Narakkal and Valiathura (Kerala coast), however, this maximum appears at the lower foreshore with an identical configuration (Fig.5).

The cyclical nature of the erosion/accretion taking place along these beaches is well indicated by the time dependence of the second eigenfunction (V_2) (Figs.6 and 7). In general, it shows that all of the beaches under study show

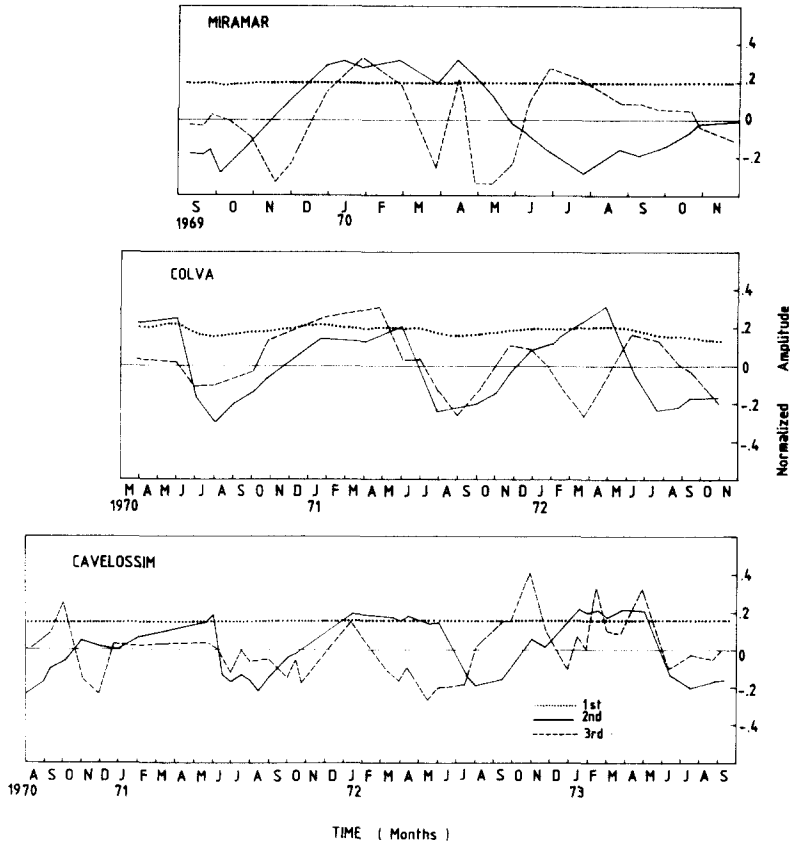


Fig.6. Temporal dependence of the eigenfunctions for Miramar, Colva and Cavelossim beaches.

a cyclical pattern in erosion/accretion, with a periodicity of approximately one year. The beaches attain their maximum sediment storage by about March–April. With the onset of southwest-monsoonal waves, by the end of May, the beaches are subjected to rapid rates of erosion till the end of July, when the beaches have the minimum sediment storage. Thereafter, with the changing wave climate the beaches recover to their normal March–April conditions after passing through occasional minor erosional events. However, this seasonal signal is not that pronounced for Calangute beach in comparison to the other beaches (Fig.7). In the latter cases, the apparent departures from cyclicity could be due to the alongshore flows that result from waves approaching from directions other than near-normal (Murty et al., 1975).

The third spatial function (U_3) shows a more complex shape and varies considerably between the six profiles (Figs.4 and 5). Similarly, the time-dependent function (V_2) does not show any distinct periodicity (Figs.6 and 7). It has a weak seasonality with superimposed short-period changes. The pattern of this function may be related to the irregular changes of the beach, and is possibly a result of the intermittent accretion that occurs when the beaches are being severely eroded. This feature is more conspicuous during lulls (breaks) in the southwest-monsoon activity (Murty, 1977). This, however, may not be as important as the first two functions in the understanding of beach-profile changes on a seasonal scale.

The configuration of the second spatial function gives an idea of the locations at which the fluctuations occur over a seasonal cycle.

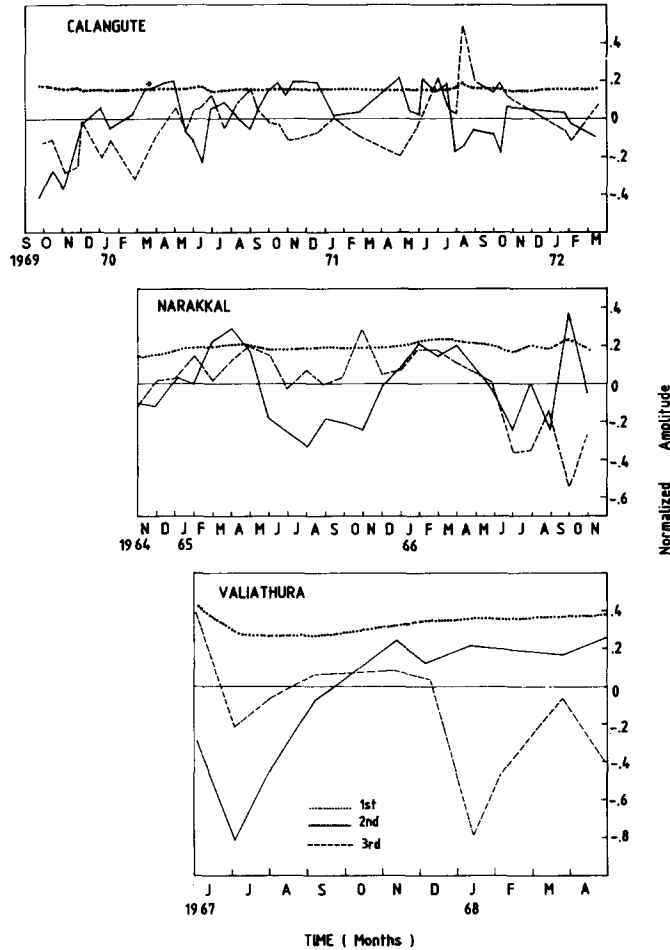


Fig.7. Temporal dependence of the eigenfunctions for Calangute, Narakkal and Valiathura beaches.

The extreme in the second spatial function (U_2) shows the segment of the beach which undergoes maximum fluctuations over a seasonal cycle, and the low values indicate the near-stable segment of the beach (Figs.4 and 5). Thus, the zero values of the second eigenfunction represent the most stable points along the beach profile when it undergoes changes over this time scale. Figure 4 shows the two most stable points along the beach profiles at Miramar, Colva and Cavelossim, with one located in the subaerial portion of the beach and the second one at a depth of about 1 m for Miramar beach, 0.2 m for Colva beach, and 2 m for Cavelossim beach. The spatial structure of

the second function for the Calangute beach does not show such stable points along the part of beach profile analysed in this study (Fig.5). However, its decreasing trend after peaking suggests the possibility of such a point at a location further offshore. This aspect could not be shown as the present data set does not extend sufficiently offshore. The same has happened in the case of Narakkal beach, but for this profile the second spatial function shows one zero value at a point 18 m seaward of the reference point (R.P.). The configuration of the second function at Valiathura clearly shows a stable point at a depth of about 2 m below the MLW.

Similar observations have been reported in the case of the beaches of Torrey Pines (Aubrey, 1979), where the stable point has been termed a "pivot point" that clearly identifies the seasonal movement of sand in onshore-offshore direction. However, the fluctuations shown by the third- and higher-order functions at this point can not be neglected. As an example and to clarify the pivot point aspect, we plotted two extreme profiles (July 1967 and April 1968) together with the mean beach profile (Fig.8). The figure clearly shows the existence of such a pivot point at a depth of about 2 m below the MLW (130 m from the R.P.). This feature, in a way, clarifies the near-equilibrium conditions prevailing at this location. The alongshore flows might lead to departures from these equilibrium conditions. Under these conditions, the nearshore sediment movement would be impeded by the presence of promontories (Calangute, Colva) and groins (Narakkal). This would result in recirculation of the sediments within the beach with a feedback from the offshore regions.

The variance estimate provides information on the variability in the data per spatial sampling point and per time sample (Aubrey, 1983). For this purpose a new data set, called the demeaned data set, has been generated by subtracting the arithmetic means of each row from the corresponding elements. In other words, the mean of the processes, here the

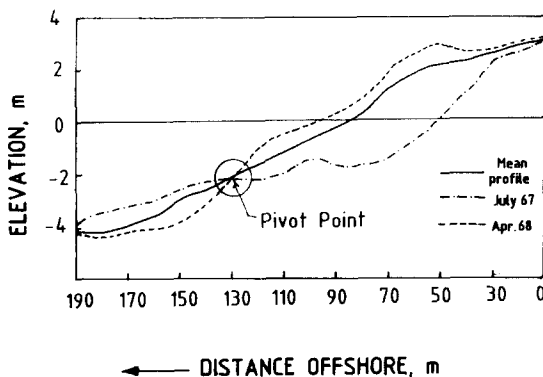


Fig.8. Plot of the mean and two extreme beach profiles at Valiathura.

mean profile, has been removed from the data set. In this case, the sum of the eigenvalues represents the variance of the data set, instead of the mean-square value. The results of this analysis are also summarized in Table 4. Since the data set refers to the beach elevations, the variance mentioned reflects that of elevations. To compare the variance of one beach to another we have applied the empirical correction for active beaches (Aubrey, 1983).

Table 4 shows a variation of 0.492 to 0.076 m^2 in the variance estimates for different beaches. Among the mainland beaches of Goa the highest variance of 0.267 m^2 , observed at Calangute, clearly confirms the higher energies prevailing at this location, in contrast to Colva and Cavelossim. The latter two beaches which are situated under similar energy environments prevailing along the 30 km long continuous stretch of Colva beach show near-equal values of the variances. At Miramar the variance is lowest (0.119 m^2) and indicates the degree of shelter this beach receives. The Narakkal beach shows a variance of 0.076 m^2 . This low value is suggestive of the greater protection received by this beach from the southwest monsoonal waves. Even though this beach has an open exposure to the ocean waves, it receives protection from the quasi-static mud banks active off this beach during the rough-weather months of the period of study. The waves propagating across these mud banks are strongly attenuated (Shenoi, 1984). Moreover, as mentioned in Table 3, this beach receives protection from the existing artificial structures, where the alongshore movement of the material is restricted to limited zones between the groins. The Valiathura beach, which is directly exposed to ocean waves and free from promontories or artificial structures, exhibits the maximum annual variability (0.492 m^2). Thus, the beaches which are free from any kind of protection from the impinging ocean waves show high variability. In other words, the beaches with high variability are those associated with higher wave energy. Unfortunately, lack of wave data at these coastal sites preclude quantitative exam-

ination of the true relationship between beach variability and wave energy.

Conclusions

The behavioural pattern of the beach-profile changes at six different locations analyzed along the west coast of India, using Empirical Orthogonal Functions have been summarized below.

(1) The first three eigenfunctions sufficiently describe the major beach changes along this coast.

(2) A comparison of the results of the analysis with both regularly and irregularly sampled data sets suggests that the non-uniformity of the sampling in time introduces very small errors (<5%) over the first three functions.

(3) The stability of the beaches under study is shown by the temporal structure of the first eigenfunction (V_1), whereas the second temporal function (V_2) well documents the annual cyclical trend in erosion/accretion associated with the southwest-monsoon wind and wave climate. The configuration of the second spatial function shows similar patterns for the low-energy mainland beaches — Miramar, Colva and Cavelossim. However, the subtle differences prevailing within these low-energy environments could be identified by the peak in the distribution of U_2 at Cavelossim (Fig.4).

(4) This analysis has identified a most stable point, the "pivot point" along the beach profile, about which the seasonal movement of sand in the onshore-offshore direction takes place. The depth of this point has been found to depend on the width of the beach. At Colva (wide beach) this point occurs at 0.2 m below MLW, whereas at Valiathura (narrow beach) the same is noticed at 2 m below MLW. This pivot point thus appears to be an important parameter for describing the spatial variability.

(5) The variance analysis has revealed that the beaches exposed directly to the ocean waves have the highest beach variability while those with flat offshore bottom topography and

lesser exposure show low variability — reflecting on the prevailing energies. The open ocean beach (Narakkal), confined between a seawall and groin assembly and also protected by an offshore mud bank during the southwest-monsoon season, shows the least variability (0.076 m^2) among the six beaches. These results point out the close relationship between the beach variability and the degree of exposure of the beaches to the ocean waves.

(6) The study has also revealed that the estimation of variance and the second eigenfunction, as compared to other order eigenfunctions, are the best indicators of beach changes in space and time.

The close relationship between the beach variability and the nature of shelter to the beaches from the ocean waves suggests the need for detailed observations on nearshore wave climate through the use of wave recorders and directional spectra, for the purpose of predicting beach profiles. Such a set of observations would help in quantifying the magnitude of beach changes in response to wave forcings, and provide the basic information desired for structural designs to protect the shorelines.

Acknowledgements

The authors are thankful to Dr. H.N. Siddiquie, Director, for providing the facilities and to Dr. J.S. Sastry, Head, Physical Oceanography Division for his interest and encouragement. They are also grateful to the reviewers for their critical comments and their useful suggestions.

References

- Aranuvachapun, S. and Johnson, A.J., 1979. Beach profiles at Gorleston and Great Yarmouth. *Coastal Eng.*, 2: 201-213.
- Aubrey, D.G., 1979. Seasonal patterns of onshore/offshore sediment movement. *J. Geophys. Res.*, 84: 6347-6354.
- Aubrey, D.G., 1983. Beach changes on the coasts with different wave climates. In: A. McLachlan and T. Erasmus (Editors), *Sandy Beaches as Ecosystems*. Junk, The Hague, pp.63-85.
- Aubrey, D.G., Inman, D.L. and Winant, C.D., 1980. The

- statistical prediction of beach changes in southern California. *J. Geophys. Res.*, 85: 3264-3276.
- Fernandes, A.A. and Mahadevan, R., 1982. Factor analysis of multivariate data. Tech. Rep. No. 2/82, National Institute of Oceanography, Dona-Paula.
- Lawson, C.L. and Hanson, R.J., 1974. Solving Least Squares Problems. Prentice-Hall, Englewood Cliffs, N.J., 340 pp.
- Murty, C.S., 1977. Studies on the physical aspects of shoreline dynamics at some selected places along the west coast of India. Ph.D. Thesis, Univ. of Kerala, Kerala, 149 pp.
- Murty, C.S., Veerayya, M. and Varadachari, V.V.R., 1975. Littoral and rip currents off Calangute beach, Goa. *Ind. J. Mar. Sci.*, 4: 1-4.
- Murty, C.S., Veerayya, M. and Varadachari, V.V.R., 1982. Morphological changes of the beaches of Goa. *Ind. J. Mar. Sci.*, 11: 35-42.
- Nair, R.R. and Pylee, A., 1968. Size distribution and carbonate content of the sediments of the western shelf of India. *Bull. Natl. Inst. Sci. India*, 38: 411-420.
- Shenoi, S.S.C., 1984. Studies on the littoral processes in relation to stability of beaches around Cochin. Ph.D. Thesis, Univ. of Cochin, Cochin, 145 pp.
- Varkey, M.J., Kesava Das, V., Swamy, G.N., Joseph, P.S. and Sastry, J.S., 1982. Wave (swell) atlas for Arabian sea and Bay of Bengal. Tech. Rep. National Institute of Oceanography, Dona-Paula.
- Veerayya, M., 1972. Textural characteristics of Calangute beach sediments, Goa coast. *Ind. J. Mar. Sci.*, 1: 28-44.
- Veerayya, M., 1978. Studies on the geological aspects of the beaches of Goa, in relation to some meteorological and physical oceanographic factors. Ph.D. Thesis, Andhra Univ., 240 pp.
- Veerayya, M. and Varadachari, V.V.R., 1975. Depositional environments of coastal sediments of Calangute, Goa. *Sediment. Geol.*, 14: 63-74.
- Winant, C.D., Inman, D.L. and Nordstrom, C.E., 1975. Description of seasonal beach changes using empirical eigenfunctions. *J. Geophys. Res.*, 80: 1979-1986.
- Winant, C.D. and Aubrey, D.G., 1976. Stability and impulse response of empirical eigenfunctions. Proc. 15th Coastal Eng. Conf., Am. Soc. Civ. Eng., New York, N.Y., pp.1312-1325.