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Short term morphological evolution of sandy beach and possible mitigation: A case study off Kadalur Periyakuppam

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This paper is a result of studies aimed at understanding morphological changes of a straight-sandy beach in response to the site specific coastal processes. Data collection includes beach profile surveys, bathymetry, and particle size distribution of sand in breaker zone, analysis of historical maps, satellite imageries, and tide and surface currents in the vicinity. Based on monthly beach profiling, the shoreline was observed to be oscillating over a distance of 30 m in normal climate conditions. However immediately after each cyclone passage, there was a major shore retreat within a matter of few days. Numerical model simulation and field data indicates that the cross shore sediment transport is significant. This understanding is essential and plays a major role in providing a sustainable shore protection measure to stabilize the site. The study further deals with the assessment of the efficacy of shore parallel submerged dyke using numerical models.

[Keywords: Cyclone, Beach profile, Morphology, Sediment transport, Submerged dyke]

Introduction

The short term morphological evolution of a straight sandy beach off Kadalur Periyakuppam (KPK) situated between two river mouths (Fig. 1) is studied. River Palar estuary is located at the northern boundary of the beach, while the site is bounded by Chinna Palar (creek) to the south. Both the rivers are rain fed and remain dry during most of the year with the mouth clogged and closed with sea sand. Closure of river mouths and creeks due to littoral sediment transport is typical of Indian east coast, wherever the monsoon fed river flow is absent. Estimated net littoral transport rate by various researchers[1-3] for the east coast ranges between 0.4 and 1.0 Mm^3 varying spatially and temporally. The littoral transport also manifests into sediment cells whose dimension and transport intensity depends primarily on the local configuration of coast and wave characteristics resulting in rapid changes in the coastal morphology due to erosion/accretion. In general it is found that the net effect of this evolution leads to loss of land and property situated along the coast.

The KPK site was reported to have been affected severely in the aftermath of cyclone *Thane* in December 2011. The beach started recovering till it suffered another cyclone passage (*Nilam)* during November 2012. Efforts have been put in by National Institute of Ocean Technology (NIOT) and State Fisheries Department to save some of the fisheries facilities that have fallen within the reach of wave run-up (Fig. 2). Lack of secondary information of the site except for satellite imageries precluded the assessment of trends in the evolution of beach front. Systematic observations by NIOT commenced from July 2012 onwards with periodic surveys and beach profiling. The observations included bathymetry, monthly beach profiling, seabed sediment sampling and measurements of tide and currents. Using the field observations, numerical simulations were carried out to reproduce the hydrodynamic and sediment transport processes to assess the beach evolution. The simulation exercise included 2D modeling using DELFT3D package and 1D modeling using MIKE-

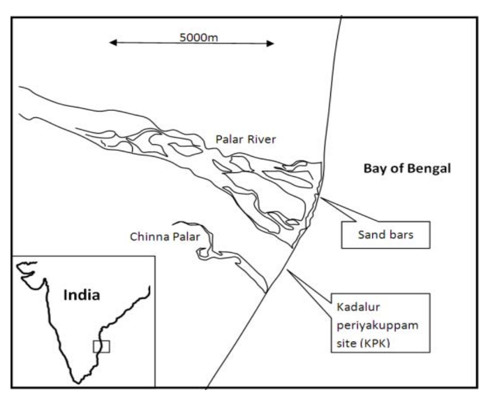

Fig. 1—Study site

LITPACK. Besides the model output, the field observations like sediment grain size and differential topography were used to characterize the changes in the coast over a period. While it is generally perceived that long-shore sediment transport is the predominant cause for morphological changes along the Indian coast especially on the east coast, observations at this site indicate that local phenomena like coastline orientation, bathymetry, land based discharges, proximity to cyclone prone areas etc., are likely have greater influence on the shoreline behaviour. Based on the information collected and inferences made from the model simulation, it appears that cross-shore transport of sediment could take prominence over long-shore transport.

Providing protective measure like seawalls, groins or revetments to safeguard an eroding beach without thorough understanding of the coastal phenomena is likely to aggravate the situation as has been the case of most of Kerala and Pondicherry coasts. In the light of such developments, it becomes more prudent to characterize the sediment transport trends before designing an appropriate protection measure. The solution sought here was to be environmentally friendly, cost effective and reversible if required. Seeking a 'reversible' measure is the result of uncertainties encountered due to paucity of historical data, model uncertainties and lack of confidence in implementing relatively new concept in the country. Hard structures installed for shore protection have failed in numerous locations, but reversing the situation is out of question due to huge cost involved in removal of stone dumps which is generally not attempted till date to our knowledge.

After considering options, it was decided to install a shore parallel submerged dyke made up of geosynthetic-sand-filled tubes. This solution is evaluated for functional performance and structural integrity. The final configuration consists of 1760 m long dyke in segments of 200 m long elements and gap of 60 m in 4m water depths. The dyke is to be made up of geosynthetic sand tubes of 25 m length and 3 m height laid in two rows. The installation of dyke is proposed to be carried out during January-march 2014.

Materials and Methods

The study site is a fairly straight sandy beach of about 1500 m long, terminated on either side by two rivers – Palar on the north and Chinna Palar on the south (Fig. 1). To the north of this site the River Palar estuary is situated over a spread of about 4000 m forming a transition for the regional coast orientation. To the south of this estuary (where KPK is situated) the coast is at an orientation of about 33º with respect to north while the coast to the north of Palar estuary is fairly straight at an angle of 8º. The coastal system was reported to comprise sand dunes, wide beaches and gentle intertidal zone until recently (~ 20 years). The river systems are fed by monsoon runoff and of late, they remain closed with sand bars round the year due to absence of sufficient rain water flow.

The region faces two spells of active wave climate – one during southwest monsoon and other during northeast monsoon. In the offshore areas, the wave approach is predominantly from south during the months of May to September (southwest monsoon) and it changes to east-northeast during the months of October-December during the northeast monsoon.

The Bay of Bengal is prone to cyclones especially during north east monsoon[4]. During cyclones the waves are reported to be in the order of >3 m (H_{max}) in the shallow area (~ 10 m), while the H_s is 1.5 to 2 m. Based on IMD data, it is observed this area has experienced only 10 landfalls due to cyclones, depressions and severe cyclonic storms between 1891 and 2012. However the Cuddalore region which is about 100 km south of this area is highly cyclone prone. The 'Thane' cyclone's landfall was near Cuddalore. The impact of these cyclonic storms therefore appears to impact the KPK site during the northeast monsoon.

The beaches of study site are devoid of vegetation or mangroves due to wave breaking on the shore. The regional geological mapping by Geological Survey of India (GSI) reveals rocky stretches particularly in this region at a distance of 3.5 km from the shoreline. Rocky outcrops are found along the Covelong beach located about 30 km north. The rocks are also expected to form underlying bed beneath the present beach thereby making the sediments loose/unconsolidated thereby transportable. The River Palar no longer brings sediments to this region due to negligible flows as also intense sand mining in the upstream areas thereby depriving the coastal areas of sand. The wave energy dominates this region and results in removal of sand during monsoons and cyclones. However it is observed that during fair weather the wave conditions are favourable for beach to accrete.

Kadalur Periyakuppam (KPK) site comprises three fishing villages immediately south of Palar River and north of a creek. A number of fisheries facilities have been developed by the Tamil Nadu Fisheries Department along the coastline of KPK. The facilities were initially located at a distance of 60m from the High Tide Line. Presently (2013) the fisheries facilities are under severe threat due to alternate erosion/accretion of the shorefront during monsoon and non monsoon respectively. The erosion has caused scour below the fisheries structures and beach

(a) Erosion after 'Nilam' cyclone November 2012

(b) Accretion during February 2013

(c) Erosion as of July 2013 (tilt of column is due to image orientation)

Fig. 2—Short term variations of beach level

loss which is further aggravated during the cyclones. Photographs (Fig. 2 a-c) indicate the short term oscillation of beach level and its implication on of the structures integrity.

Primary and secondary information

A summary of met-ocean parameters collected from secondary data sources is presented in Table 1.

Satellite imageries

Shoreline changes in KPK coast has been analyzed using various satellite imageries that are available. The approximate coastlines were demarcated on imageries and superimposed for comparison. The resolution of LANDSAT imageries is 30 m while that of Google Earth was 2.5 - 1.1 m. Google imageries showed an uncertainty in horizontal position of the order of 10 m. This was ascertained by comparing boundaries of test features over different time frames (like tank bunds and roads that are commonly available on compared imageries). The land-water interface as seen in the imageries was assumed to represent the coastline and was manually demarcated. The sequential overlay of coastlines were carried out using five snap shots obtained from LANDSAT (1990 and 2000) and Google Earth (2006, 2011 and 2013) covering a total span of 23 years. The portion of coastline comparison in the vicinity of KPK site with the background of fisheries buildings is presented in Fig. 3.

Beach profiling

Beach Profiling using RTK-GPS receiver was carried out once every full moon day of the calendar month from October 2012 for a distance of 3 km along shore with measurements being made at a distance of 200 m. These profiles cover the topography from -1 m to + 3 m (MSL).

Another detailed grid survey (5×5 m) for spot levels is being conducted in the vicinity of the structures. The grid points are maintained same for consecutive surveys operations with an aim for better comparison. Based on this data the Digital Terrain Models (DTM) were prepared on monthly basis. The 0m contours were extracted from DTM for comparison of shoreline variation.

Similarly a control area is demarcated in the study site covering an area over which the volume variation on monthly basis is computed using SURFER package taking MSL as lower surface

Table 1—Met-ocean parameters off KPK

Sl	Parameter	Description
1	Climate, Relative Humidity & Temperature	Tropical Climate with mean relative humidity around 75% reaching a maximum up to even 100%. March to June is the summer season with maximum temperature touching around 42^{o}C. December to February is the winter season with minimum temperature falling to around 18^{o}C
2	Rainfall	The annual rainfall is of the order of 1400mm, about 65% occurring from October to December which is the monsoon season for this part of the country.
3	Wind	The predominant wind direction is North East during October-December (NE Monsoon) and from South and south East during June-September (SW Monsoon) period. The average wind speed does not exceed 20 kmph for about 90% of the time in a year but during monsoon seasons, speeds exceeding 60 kmph can occur.
4	Tide	Semidiurnal with a range of 1.2 m
5	Currents	Currents during NE monsoon are directed southwards and during SW monsoon towards north. The current velocities are in the range of 0.1 to 0.5 m/Sec.
6	waves	Typical annual maximum ~2.8 m Annual mean 1.4 m Approach : Variable from North-east to south as given in Fig. 6

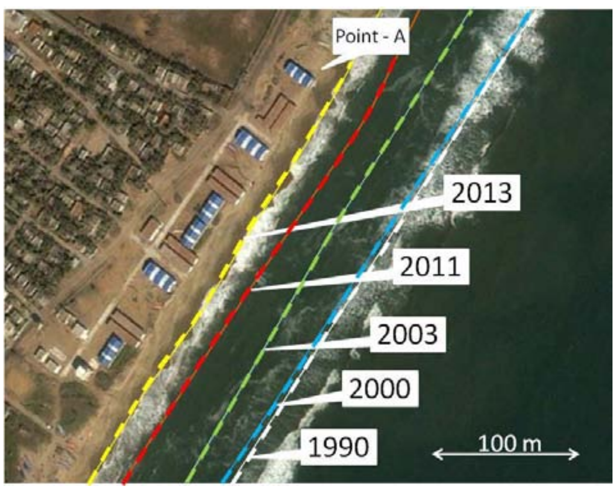

Fig. 3—Sequential overlay of Shorelines (1990-2013)

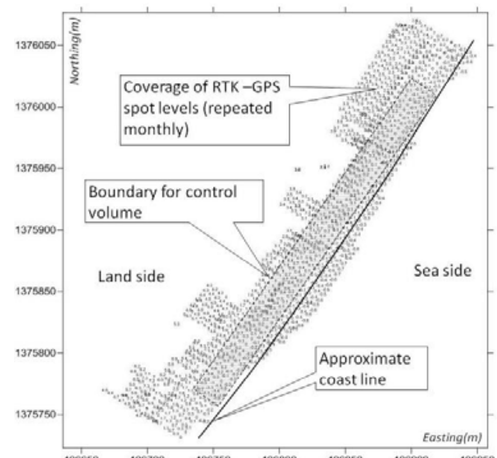

Fig. 4—Topographic survey coverage and definition of control volume

(Fig. 4). The control volume is defined to be the volume of sand found within the control boundary between MSL and the beach surface. The observed variation of the control volume from July 2012 to July 2013 is presented in Fig. 5.

Bathymetry

Bathymetric survey using single beam echo sounder was carried out over a stretch of 1.5km along the shore and 2 km offshore in September 2012. The survey was expanded into 20 × 10 km with 500 m spacing for improving the hydrodynamic model in May 2013. It is observed that the 4m contour is located at a distance of 300 m to 400 m from the shore. Water level changes were measured using tide gauge in the month of July for a period of 15 days. It was observed that there was no significant difference in water level and phase in the tide measured at KPK and Chennai, where long term tidal observations are available. For reduction of sounding, predicted tide of Chennai was used.

Geotechnical sampling

Grab samples were collected from 20 locations in grid fashion near shore (3 m to 10 m water depths) and 5 locations onshore along the shoreline. Sieve analysis was carried out on the samples to determine the grain size distribution. The mean particle size of the near shore samples varied from 106 to 243 microns while for the shore samples it varied from

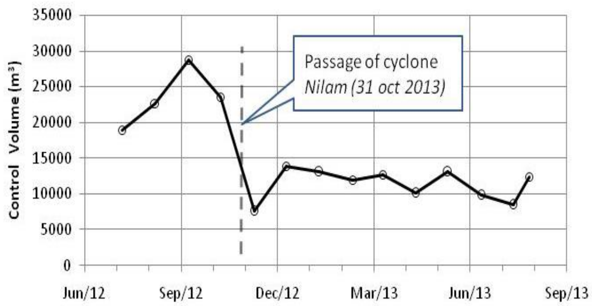

Fig. 5—Variation of control volume over one year period in KPK beach (observed)

540 to 610 microns. The grain size distribution shows that the near shore samples are poorly graded sand with 90% of fine sand while the on shore samples are poorly graded sand with 80% medium sand. The larger size material is found onshore.

Wave Data

Wave statistics were adopted from regional hind cast model set up at NIOT using MIKE21-SW (Spectral Wave) package. The model wind forcing is provided using QSCAT/NCEP blended ocean winds with a resolution of 0.5×0.5 degree at every six hour. The model output was validated with observed directional wave data off Panaiyur (~30 km south of KPK site) covering one year cycle. Due to similar shoreline orientation, bathymetry and proximity to study site, it was considered to be justified to use these statistics as valid for KPK site. The distinct variation of wave approach and intensity over different seasons is depicted in rose diagram in Fig. 6.

Model Simulations

Numerical model simulations were carried out in an attempt to reproduce the present sediment transport and morphological changes in the site with and without human intervention. The software package DELFT-3D-flow coupled with wave model was used to simulate the hydrodynamics and morphological response.

The model consists of two domains, i.e, an inner domain, with finer grid (15 m x 20 m), nested into an outer domain with coarser grid (70 m × 180 m) as shown in Fig. 7. Bathymetry survey carried out by NIOT had been used in the KPK area (inner domain) while GEBCO data had been used over the outer domain.

Wave conditions are based on the wave atlas developed by NIOT. Water level boundary condition

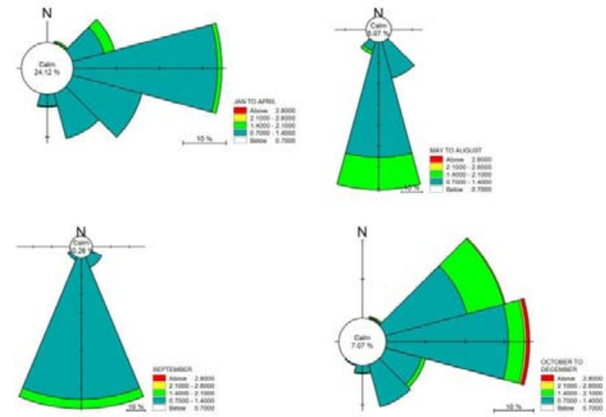

Fig. 6—Wave rose for KPK site(2012)

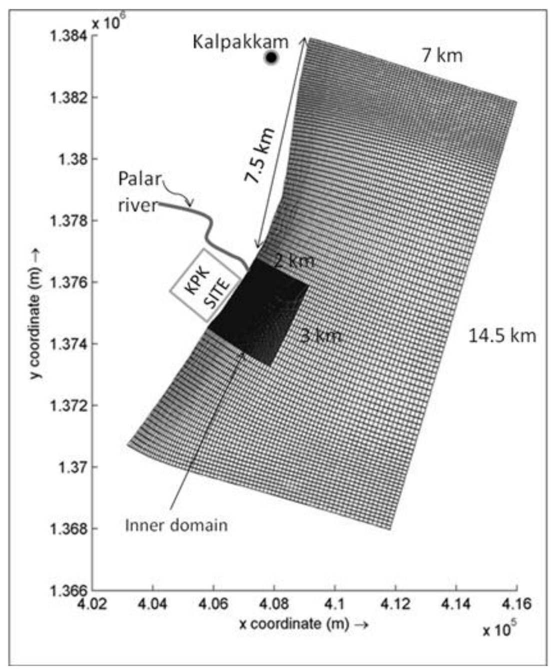

Fig. 7—Model Domain definition

is applied using Astronomical constituents along eastern boundary while Neumann conditions are applied along the northern and southern boundaries. The hydrodynamic model was calibrated using tide elevation data from predicted Indian tide table for Chennai. For sediment transport modelling, a representative size (D_{50} value) of 150 microns is given as input based on grain size distribution of 20 Grab samples collected from the area.

Cyclone condition The behaviour of the shoreline during Thane cyclone of December 2011 is simulated using wave coupled DELFT3D model. Data on *Thane* cyclone track, wind speed and pressure drop are used from the report published by Indian meteorological department. Based on this data, spider web file is generated and input to DELFT3D. The MORFAC value was taken as 1 and model was run for 1 week. (MORFAC is a user defined morphological acceleration factor that gives morphological change for a period equal to MORFAC times the simulation time of the model run). The response along a typical bathymetric profile is shown in Fig. 8.

The DELFT3D model has simulated the wave and surge conditions during the cyclone. A maximum wave height of 3 m was generated by the model.

Seasonal variation

Apart from cyclone induced short term changes, the coastal space also responds for seasonal variation in wave climate around the year. The study site was assessed for responses that account for monsoon, non-monsoon and transitional phases. This information is vital to assess the effectiveness of shore protection measure that may be proposed. The sediment transport (erosion/accretion) process representing one year period was simulated using one week equivalent model run. This was carried out in DELFT3D model by giving a MORFAC value of 52 as the software input for factoring the one week model to the entire year. The seasonal variation of wave conditions were schematised based on one year wave data scaled down to one week.

Results and Discussions

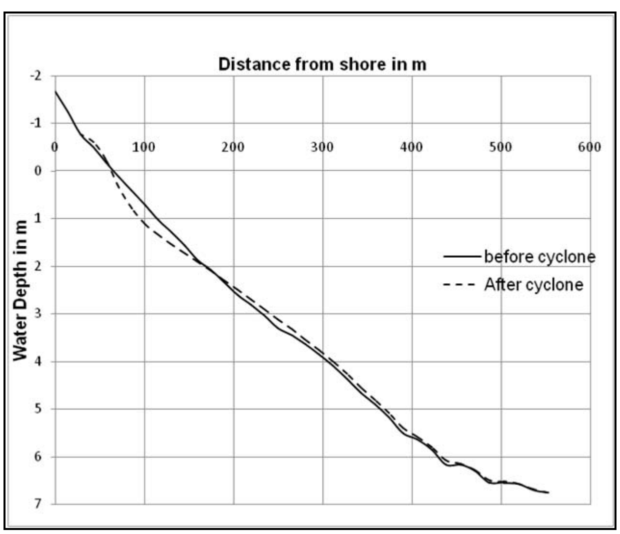

Fig. 8—Response of bathymetric profile for cyclone Thane off KPK site (DELFT 3D Model)

The results of all available studies have been considered to assess the trend in morphological evolution and to decide a suitable protection measure. With the technological improvements the present satellite imageries may be of higher resolution, yet analysis of imageries from 1970 onwards[5] provides a trend of the coastline behaviour. According to the IOM analysis the KPK coast has been defined as low to medium eroding coast. However the comparison in Fig. 3 indicates a total shoreline retreat of about 60 m. The erosion rate is highest from 2006 onwards.

The periodical beach profiling survey carried out by NIOT indicates the seasonal build up and erosional pattern. The trends indicate that there is accretion during fair weather (January to March), but the build up is not sufficient enough to overcome the erosion effect during cyclone/southwest monsoon, which can be of the order of more than 10 m in few days. The fact that a total of about 60 m beach is lost in about 20 years (1990 to 2013) itself may indicate that alternative build and erosion is taking place with a bias towards higher erosion.

From beach profile and the control volume variation, considerable loss of sand due to the passage of cyclone Nilam in October 2012 is observed. The rough weather during the passage lasted for three days. A weak recovery was observed in the months of January, April and July of 2013. However this build up could not compensate the loss suffered during single short duration event viz. Nilam cyclone.

Sediment transport trends

Based on model results (Fig. 8), it may be seen that in the aftermath of a cyclone, the beach slope gets impacted due to onslaught of high waves. The material lost on the beach (0-2 m depth) is seen to be depositing at deeper water (2-6 m), which is expected to be transported back during fair weather at least partially. It may be noted that cyclone *Nilam* had passed close to study site on 31 October 2012 causing severe erosion in a matter of three days. The loss of material indicated for November in Fig. 5 and photograph 2a confirms the effect of cyclone *Nilam*. The observed beach recovery up to February 2013 is indicated in Figs. 5 and 2b The changes in modelled beach profiles (pre and post cyclone conditions) Fig. 8 seen in conjunction with periodic beach recovery lend credence to assumption that cross-shore sediment movement is significant in the study site.

Evaluation of solution

Functional requirement:

Design of coastal protection measures needs to consider stabilizing the coastline in a long-term without causing changes or transferring the problem to adjacent areas. Long term studies indicate that conventional shore protection measures like groins, breakwaters, seawalls, revetments, bulkheads, beach-fill, etc., have certain disadvantages like blocking of longshore sediment transport resulting in severe erosion to the leeward side, scouring of revetments etc However, it is found that shore-parallel breakwater, placed at the shoreline or offshore are designed either to intercept a portion of longshore moving sediment or to protect a placed beach-fill, whilst absorbing the wave energy has the potential to significantly better for several coastal environments. The requirement at KPK site is to provide a sustainable solution to keep the shoreline stable and protect the fisheries facilities.

NIOT has evaluated several options like groins, seawalls, shore parallel submerged dyke etc. One of the options is to provide a submerged shore parallel offshore dyke over approximately a length of 1.5 km so that wave forces are reduced/absorbed and loss of material is prevented. The criteria for selection of shore parallel submerged dyke include evaluation of the site characteristics which indicates predominantly onshore-offshore sediment movement. Evaluation of various options for shore protection indicated that (i) Groins may deprive leeward side of the structure of sediments resulting in severe erosion thereby transferring the erosion issue to the northern side (ii) Sand nourishment whilst being a better option has prohibitively high costs involved and requirement of replenishment after every cyclone (iii) Shore parallel breakwaters may absorb the wave energy and result in sedimentation behind the breakwater over a long period of time without interfering much with the longshore transport. The sedimentation pattern would also be gradual thereby providing time for mid-project corrective measures to be taken if required.

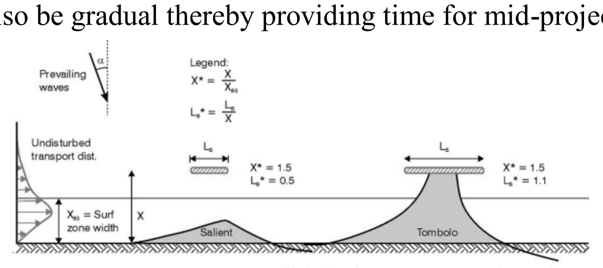

Fig 9—Definition of detached breakwater parameters (Source: Detached breakwaters coastal wiki.htm)

Analysis of various prototype structures cited in the literature[6] indicate that tombolos are formed when ratio of length of breakwater segment (Ls) to its distance offshore (X) is>1 i.e. Ls/X >1.0 as indicated in Fig. 9. for [7], Ls/X<1.0, tombola formation is prevented; for Ls/X >2.0, tombola is certain within surf zone.

These formulations are based on physical and laboratory model tests. It is observed that a salient is preferable to a tombola because the formation of salient takes significantly longer time than a tombola and also a salient does not alter the alongshore transport drastically. A salient formation therefore prevents any erosion to the upstream side as it does not radically interfere with the hydrodynamics.

A segmented structure enables water mass movement between the gaps thereby dissipating the discharge from overflow (over the submerged breakwater) within short intervals whilst also enabling movement of boats between the gaps. Numerical modeling has been carried out with varying segment lengths (Ls) and gap distances to evaluate the sedimentation/erosion patterns. The solution providing the most optimum salient formation with negligible upstream impacts has been considered for implementation.

For the submerged dyke construction, various options of materials, configuration and geometry have been evaluated. The options considered include stacked geosynthetic tubes, geosynthetic bags filled inside rope gabions, etc. All options have been evaluated against criteria such as ease of construction, requirement of marine spread, effectiveness in absorbing energy etc. It is found that construction of two layered geosynthetic tube requires large marine spread and equipments while gabions filled with small size sand filled bags is labour intensive and requires longer time. The other options like concrete blocks generally present irreversible solutions. Therefore geosynthetic tube installation has been considered for the stabilization.

Stability considerations

The design of geosynthetic tubes have been carried as per Liu, Goh and Silvester method provided in Pilarcyzk (2000). Two types of configurations were considered for the submerged dyke construction. Option one was a stacked two layered geosynthetic tube consisting of two layers of 1.8 m of bottom layer

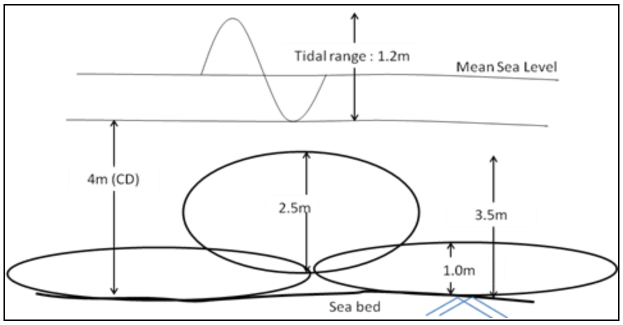

Fig. 10—Geosynthetic tube configurations for dyke construction (two layer stacked system)

and one geosynthetic tube on top measuring to a overall height of 3.5 m. Option two was a single layered geosynthetic tubes of 15 m circumference (each) forming a height of 2.5 m. The stability of these tubes were analyzed under wave loading conditions and checked for stability under sliding, overturning and bearing.

In order to assess the stability of the filled geotextile tube structure, current and wave forces have to be estimated. Though a definitive analysis technique has not been established, a modified Minikin[8] approach, as outlined in the Shoreline Protection Manual, provides a reasonable means to assess the stability of filled units under wave loading. The theoretical stability analysis employed is a 2-Dimensional hydraulic stability analysis, based on the linear wave theory and geotechnical stability analysis method. Several methods that can be pursued to address impact loading are addressed[9] using Hiroi's equation which is particularly widely used in Japan and the Asian region.

For the two layered stacked system, the top layer is found unsafe for the initially chosen dimensions against sliding under H1/10 and during cyclone (H_{max}). It was also not possible to establish the friction factor between the two geosynthetic layers. The single layer configuration was safe against bearing and sliding, overturning for wave loading (H_s and $H_{1/10}$). However the maximum height that could be achieved in this case is restricted to about 3.0 m, which is not sufficient. Hence a final configuration of two layer scheme with top tube of larger size (circumference of 15 m) is proposed as shown in Fig. 10. The lower layer is proposed to be of same circumference but to be filled with 50% of capacity to result in a flatter shape. The flatter lower layer enhances the stability of dyke, helps to achieve desired height and reduces reflection on seaward face resulting in lesser toe erosion.

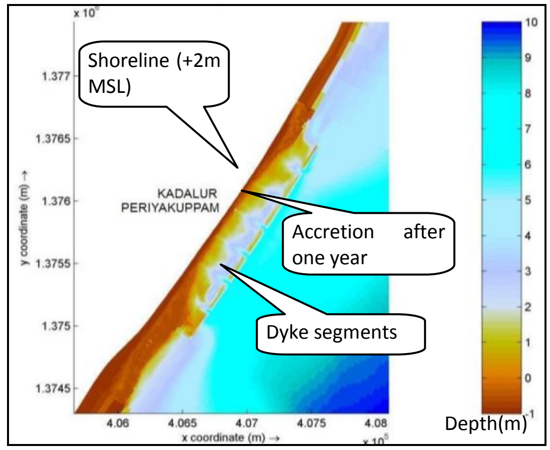

Fig. 11—Model result for beach accretion after one year simulation with dyke installed

The final configuration of dyke with 3.5 m height is implemented in the model as a bathymetry variation. The segment length is 200 m and the gap between segments is 60 m. The total length of dyke system is 1760 m. The model output showing the beach accretion after 1 year simulation period with dyke is presented in Fig. 11.

Conclusions

The shore term variation of beach erosion off Kadalur Periyakuppam village was studied over a period of one year. Analyses of field observations and available secondary information indicate that cross-shore sediment transport could be the predominant cause for shoreline changes at this location. Seasonal events like cyclones are observed to cause rapid depletion of beach sand in short time but calm weather conditions causes the beach to accrete. The net result is loss of beach width at a rate of about 6 m/year over last 10 years as observed from analysis of satellite imageries. As a remedial measure, shore parallel submerged dyke made up of geosynthetic tubes filled with sand is proposed to be installed. After model simulation and design exercise, a dyke length of 1760 m in 7 segments (200 m tubes + 60 m gap) has been finalised. The dyke is expected to be installed during January-March 2014.

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