Indian Journal of Spatial Science
Spring Issue, 10 (1) 2019 pp. 79 - 86

Indian Journal of Spatial Science
Peer Reviewed and UGC Approved (Sl No. 7617)
EISSN: 2249 - 4316 homepage: www.indiansss.org ISSN: 2249 - 3921

Effects of Tidal Range on the Digha Coast: A Geomorphological Investigation

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Article Info

Article History

Received on:
20 December, 2018
Accepted in *Revised Form* on:
28 February, 2019
Available *Online* on and from:
21 March, 2019

Key Words

Beach
Dimensionless Fall Velocity
Relative Tide Range
Surf Zone

Abstract

Coastal beaches are characterized by a well-defined set of wave and tide parameters. Accordingly the energy condition, tidal scenario, beach slope, and sedimentation environment together shape the geomorphology of the associated beach. The tidal effect is influenced by several variables, viz., breaker height, wave period, high tide sediment fall velocity and tidal range. This research paper deals with the morphodynamics of the Digha coastal beach and also makes a detailed study of the impact of tides on it. The tidal effect on beach morphology and morphodynamics have been quantified by two parameters, viz., dimensionless fall velocity and the relative tide range. The values of the various parameters of beach, tide and waves have been used to classify the tidal beach and also to extract information about the relative importance of swash, surf zone and wave shoaling.

Introduction

Being the transition zone between land and sea, beach is a coastal landform facing the open sea. It is a gently sloping flat plain between low water line of spring tide to the upper limit of wave action. Thus, the profile describes the littoral zone that may stretch from the landward limit of wave action (considerably higher than high tide level) to water depths of 10m to 20m at low tide (Komar, 1976). Naturally, it is the zone of accumulation on the shore of generally loose, unconsolidated sediment, ranging in size from very fine sand up to pebbles, cobbles and occasionally boulders, often with shelly material (Bird, 2008). Obviously, its profile is shaped by the actions of the coastal waves and tides.

Waves are undulations on surface water formed by the prevailing winds. The driving force behind almost all coastal process is the waves (Pethick, 1984). Wave height during breaking is an important factor that shape the beach profile. Tide is defined as the periodic rise and fall of sea level in the continental margin due to the differential gravitational attractions of Moon and Sun. The range of tide (the difference between tide and ebb) varies from place to place and also periodically from a maximum to minimum value (Mclellan, 1968). The beach morphology is certainly related to wave and sediment characteristics via the dimensionless fall velocity (Gourlay, 1968; Dean, 1973).

Study Area

Digha is an important tourist hub of West Bengal. It belongs to the Contai or Kanthi sub-division, Purba Medinipur. Geographically, it is a part of Kanthi coast that is about 45 km long stretching from the mouth of Subarnarekha river in west to the mouth of Rasalpur river in the east. It is divided into seven segments, viz., Junput coast, Shoula coast, Mandarmani coast, Tajpur coast, Shankarpur coast, Digha coast, and Talsari coast (east to west). The Digha coast extends from the mouth of the tidal river Champa in the east to Udaipur (West Bengal Odisha Border) in the west for about 7 km. It comprises 15 different parts and are known as Udaypur (80.3m), Jatranala (1632.9m), Police Holiday Home (304.7m), Larika (656.4m), Hospital (368.9m), Jagannath Temple (170.0m), Aparajita Cottage (342.0m), Blue View (161.6m), 1st Gate (260.3m), Saikatabas (154.5m), Hotel (362.5), Breack (260.0m),and Digha Mohana (1662.6m) from west to east.

Objective

The major objectives of this study are to quantify the effect of tide of Digha coastal beach, a part of Kanthi coast by the measurement of two prominent parameters:
1) the 'dimensionless fall velocity' and
2) the relative tide range.

Methodology

The present research is done based on both primary and secondary data. Primary data as wave height, trough, water depth, breaker height, sediment grain size, sedimentation etc have been measured and collected through the conventional survey equipment as dumpy level, GPS etc. Secondary data as the tide, tidal range etc is collected from Kolkata Port Trust Web Portal. In addition, other secondary data has been collected from NATMO, Survey of India, Digha Shankarpur Development Authority (DSDA), Academic Journals, Books etc. These data have been used to quantify the impact of tidal effect on beach profile. The indices are:

a) tidal range (Davies, 1964; Short, 1991),
b) wave steepness,
c) wave height during breaking,
d) breaking coefficient of onshore waves (Galvin, 1968),
e) relative tide range (Hayes, 1979; Davis and Hayes. 1984; Paul, 2002),
f) dimensionless fall velocity (Sonu, 1973; Wright and Short,1984; Sunamura, 1989; Lippmann and Holman, 1990), and
g) conceptual beach model (Clarke et al., 1984; Wright et al., 1986, 1987; Masselink and Short, 1993).

Tidal Range

The difference of sea levels between high tide and low tide is known as **'**tidal range**'**. It varies with time and also in different beaches. In coastal geography, it addresses two aspects:

i) the frequency of tide and water level, and
ii) the tidal range in the coastal region.

Both aspects are interlinked. The gravitational attraction of Moon and Sun is the main force to generate tide. In fact, the entire tidal system is controlled by the gravitational attraction of Moon. Despite the fact that the Sun is much bigger than the Moon, it is further away so that the Sun's tidal pull is just less than half that of the moon (0.46 times: Pethick, 1984).

The frequency of the tide denotes the continuous rise and fall of sea level at a location. Generally, there are two diurnal tides at a coastal location. Tide generates two types of waves:

i) progressive tidal wave, and
ii) rotating tidal wave.

The progressive tidal wave occurs in open sea while the rotating tidal wave occurs in bays, enclosed seas, and semi-enclosed sea. Tidal range is drawn as parallel along the coast in the open sea and the co-tidal line intersects it perpendicularly. But in the closed sea, the tidal range line is drawn around the amphidromic point and the distance between two tidal ranges is much closer. It is found that tidal range is above 2.5 m in bays, enclosed sea, and semi-enclosed sea but in open sea, it is about 30 cm to 1 m. According to the Sindhu and Unnikrishnan (2013), the bay of Bengal is vast enough to call it an open sea. The study area, Kanthi coast is U-shaped in outline (Fig. 1) and may be treated as a bay.

The importance of tidal range to the landforms of the coast has only recently been emphasized (Pethick, 1986). According to Davies (1964), tide range has been classified into three types (Table-1). In 1991, Short modified the classification of beaches on the basis of tidal range (Table- 2). Beaches with macro-tidal ranges (>3 m) may form the transition between wave dominated micro-tidal beaches and tide-dominated tidal flats (Masselink and Short, 1993). Short identified three types of micro-tidal beaches (Table - 3). In Digha coastal beach, tidal range has been measured to be about 3.41 m. Hence, it comes under the 'meso to macro' tidal beach after Short (1991).

Wave Breaking Point

As the wave progresses into shallow water (towards the coast), the various wave parameters, e.g. wave height and wave length become more pronounced until at the critical point the wave breaks or collapses. As waves move toward shallow water, its height increases with decreasing wave length. The ratio between wave height (H) and wave length (L) is quantified as steepness (H / L). When it reaches a critical point, the wave breaks down. Stokes' 'wave theory' predicts that when the angle at the wave crest reaches 120, the wave form becomes unstable and it breaks (Pethick, 1984).

If the value of wave steepness reaches its critical point at (H/L = 1/7 = 0.147), it breaks down. Wave length, wave height, water depth, wind velocity are directly linked with wave steepness. It is an important factor controlling beach erosion. It has been observed that the relation between wave steepness and beach erosion rate is proportional. Wave steepness of Digha coast has been computed as 0.05.

Wave height during breaking is quantified using the following formula:

$$H_b = \text{Mean Cb} - \text{Mean Tb}$$

where, Cb = wave crest height during break and Tb = mean wave trough height during break.

Galvin (1968) identified four types of wave breaking, viz., spilling breaker, plunging breaker, collapsing breaker, and surging breaker. Wave breaking is a dynamic phenomenon. The breaker depends on the 'breaking coefficient' which is influenced by different characteristics of a wave. The on-shore breaking coefficient (B_b) has been measured using following formula and its classification is shown in Table- 4.

$$B_b = H_b / (gST^2) \quad \text{(Galvin, 1968)}$$

where, H_b = wave height during breaking, g = gravitational acceleration, S = beach slope (slope of beach face), and T = wave period

The off-shore breaking coefficient is given by:

$$B_o = H_o / (L_o S^2) \quad \text{(Galvin, 1968)}$$

where, H_o = wave height during breaking, S = beach slope from the field survey.

The on-shore breaking co-efficient has been measured to be about 0.00098 at Digha beach. Therefore, the breaker type is more surging than plunging.

Relative Tide Range (RTR)

Davis and Hayes (1984) introduced the relative tidal range (RTR) as a new parameter to determine the beach morphology and morphodynamics. It is a ratio of tide range to wave breaker height. Large values of RTR indicate tide dominance and small values express wave dominance (Masselink and Short, 1993). There are three types of coasts from the standpoint of their influencing processes:

1) those dominated by waves,
2) those dominated by tides, and
3) those with a balance between waves and tides (Davis and Hayes, 1984).

Wave is a prominent element to develop the coastal geomorphologic features. Energy variation of waves is important to study of the formation of coastal beach profile. It depends on two variables:

i) tidal range (TR) and
Ii) mean wave height (H_b).

The relationship between these two has been measured to find whether the coastal beach is tide-dominated or wave-dominated.

Distribution of wave energy on the coastal beach has been studied in detail by Hayes (1979), Davis and Hayes (1984) and Paul (2002) (Fig. 2). They have identified two dominant sections and three energy sections. Dominant sections are: one dominated by tide, and another by wave, both being further divided into three based on their intensity (Table - 5 and 6). Tide dominated region is characterized by the high range of tide and low range wave height, while the wave-dominated region is characterized by a high range of wave height and low range of tidal height. Table - 7 shows the relationship between them. Their ratio gives the relative tidal range, that focuses mainly on energy variations of the coastal section. The energy variation on the coastal beach has been shown in fig. 2, that identifies three types of energy intensity based on their energy intensity (Table- 8). At Digha beach, the tidal range (TR) has been observed to be about 3.41 m and the wave height during breaking (H_b) is 1.035 m. Hence, relative tidal range (RTR) of Digha beach belongs to mixed zone, characterized by high tidal range and moderate wave height. Thus, the beach of the Digha coast is considered as a highly unstable beach.

The Dimensionless Fall Velocity

Several beach models are available to predict beach state as a function of wave and sediment parameters (Sonu, 1973; Wright and Short, 1984; Sunamura, 1989; Lippmann and Holman, 1990). Variation of sediment transport and deposition due to wave and the tidal range is a direct consequence to beach formation. The beach profiles are related to wave and sediment characteristics via the dimensionless fall velocity, given by:

$$\Omega = Hb / (Ws. T)$$

where, Ω = dimensionless fall velocity, Hb = height of wave breaker (m), Ws = sediment fall velocity (m/sec), T = wave period.

Tides or tidal range plays a passive role in sediment transport and changes in beach morphology (Davis, 1985). The primary role of the tide is to alternately expose and submerge a large portion of the beach and the inner surf zone (Masselink and Short, 1993). Thus, the movement of sea level is to retard the rate of sediment transport and changes in beach morphology. Wright and Short (1984) classified the coastal beaches and there morphology based on the nature of impact of dimensionless fall velocity (Table - 9). The conceptual beach model (Wright and Short, 1984; Wright, Short and Green, 1985); Masselink and Short, 1993) has been illustrated with a set wave period (T = 8 sec), sediment fall velocity (w_s = 0.04 m/sec). According to this model, the dimensionless fall velocity at the Digha beach has been estimated to be about 2.36. Hence, it is considered to be an intermediate beach.

Impact of Spatial Variation in Ω and RTR

In coastal geomorphology, the beach provides the space where waves and tide play. The beach profile is usually influenced by dimensionless fall velocity (Ω) and relative tide range (RTR). Masselink and Short (1993) has developed a relation between these two to analyze the beach profile. Table - 10 shows the impact of spatial variation in Ω and RTR. The relative tide range (RTR = TR/ H_b) of Digha coastal beach has been measured to be about 3.29 and the dimensionless fall velocity ($\Omega = H_b / w_s T$) of about 2.36. Hence, the Digha beach is regarded as a 'Low Tide Bar / Rip' beach under intermediate group according to the Beach Conceptual Model after Wright and Short (1984); Wright, Short, and Green (1985); Masselink and Short (1993).

Impact of Temporal Variation in Ω and RTR

The tidal range of a beach varies temporally through the semi-diurnal inequality and the spring to neap tide cycle. Clarke et al. (1984) and Wright et al. (1986, 1987) found that the impact of spring to neap tide cycle on micro-tidal high wave energy beach morphology is very negligible and also tide-induced morphological change is simply the migration of a swash ridge. The ridge is usually formed during neap tide at high tide level and its move upward with the increase of tide range. It has been observed that beach morphological features as like swash bar, transverse bar and rip morphology is removed during the 2 weeks of the period (Spring to neap tide cycle) because initially, these are wave driven. Maximum impact of spring to neap tide cycle is found on meso-tidal beach to macro-tidal beach. Thus tide range determines the beach profile, features, and their migration; and is more of a spatial than temporal variable regarding its influence on beach morphology (Masselink and short, 1993).

Fig. 4 shows the change of beach morphodynamics with spring to neap tide cycle. Masselink and Short (1993) has drawn it with two constant conditions: T = 8 sec and w_s = 0.04 m/sec. Temporal beach change is primarily wave driven, and the amount and rate of change decreases with increasing tide range, and also with decreasing wave height (Wright et al., 1985). Beaches with large relative tide range (RTR) may be considered as a stable beach system (Table - 7). Thus, based on the values of mean spring tide range and wave breaker height, the Digha beach is considered to be 'low tide bar/ rip beach'.

Conclusion

Tide plays a passive role in the transportation of sediments and in shaping the beach morphology. The initial role of tide or relative tide range is to alternately expose and submerge the large portion of the coastal beach and the inner surf zone. The migration rate of bar decreases with increasing tidal range. The position of swash zone, surf zone, and shoaling wave zone shifts every 12 hours with a tidal prism (i.e., vertical and horizontal change of tide). Geographically, the Digha beach occupies the western part of the Kanthi / Contai coast. Its average width is about 200 m. It is a mesotidal beach as per Davies (1964) and is a macro-tidal beach with higher waves as per Short (1991). Beach slope and gradient is moderate. It is concave and planar in outline and geometry. Wave breaker type is more surging than plunging. As per RTR Model the Digha beach is attributed to 'mixed relative tide range zone'. Impact of the tidal range is high and the wave is moderate. As the energy of both tide and wave is high, the coastal beach is highly unstable. Based on the ratio between RTR and dimensionless fall velocity, the Digha coastal beach is considered as 'low tide bar/rip intermediate type. The upper beach of intertidal zone at Digha is steep and the mid-intertidal zone is characterized by lower gradient. Beach face, berm, runnel etc form successively in the low tidal zone or swash zone or subaerial beach and they remain during the low tide. Beach system becomes more complex during high tide and it reacts as a reflective beach. In addition during low tide of a tide cycle, surf zone may become more dissipative.

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Table 1: Classification of Tidal Beaches on the basis of Tidal Range (TR) (After Davies, 1964)

Beach Name	Tidal Range (TR)	Characteristics
Micro Tidal Beach	<2 m	Presence of oceanic waves
Meso Tidal Beach	2 – 6 m	
Macro Tidal Beach	>6 m	Tide dominance beach

Table 2: Classification of Tidal Beaches on the basis of Tidal Range (TR) (After Short, 1991)

Beach Name	Tidal Range (TR)	Characteristics
Micro Tidal Beach	<2 m	
Meso Tidal Beach	2 – 3 m	Transitional zone between wave dominated micro tidal beaches and tide dominated tidal flats.
Macro Tidal Beach	>3 m	

Table 3: Classification of Macro Tidal Beaches (After Short, 1991)

Types of Macro Tidal Beach	Wave Height (H_b)	Characteristics
Higher Wave Planar	>0.5 m	i. Swell ii. Moderate Beach Gradient (1? - 3?) iii. Concave Beach iv. Planar Beach
Moderate Wave Multi – Bar	0.2 m – 0.5 m	i. Lower Beach Gradient (0.5?) ii. Multi bar (Ridge and Runnel) topography.
Low Wave to Tidal Flats	<0.2 m	i. Tidal Flats ii. Wide Surfing Zone

Table 4: Breaker Type Transition (After Galvin, 1968)

Parameter	Surge – Plunge	Plunge - Spill
B_b	0.003	0.068
B_o	0.09	4.8

Table 5: Tide Dominancy Level Basis on Tidal Range in meter
(After M. O. Hayes, 1979; Davis and Hayes, 1984; Paul, 2002)

Tide Dominancy	Tidal Range in meter
High	>2 m
Moderate	0.5 – 2 m
Low	<0.5 m

Table 6: Wave Dominancy Level Basis on Mean Wave Height in meter
(After M. O. Hayes, 1979; Davis and Hayes, 1984; Paul, 2002)

Tide Dominancy	Tidal Range in meter
High	>1.5 m
Moderate	0.25 – 1.5 m
Low	<0.25 m

Table 7: Relation between Mean Tidal Range (TR) and Mean Wave Height (H_b)
(After M. O. Hayes, 1979; Davis and Hayes, 1984; Paul, 2002)

Relation	Tidal Range (m)	Wave Height (m)	Dominancy	Beach Condition
High – High	>2	>1.5	Mixed	Highly Unstable
High – Moderate	>2	0.25 – 1.5	Mixed	Highly Unstable
High – Low	>2	<0.25	High Tide	High Beach Length
Moderate – High	0.5 - 2	>1.5	Mixed	Highly Unstable
Moderate – Moderate	0.5 - 2	0.25 – 1.5	Mixed	Moderately Unstable
Moderate – Low	0.5 - 2	<0.25	Moderate Tide	Moderately Unstable
Low – High	<0.5	>1.5	High Wave	Highly Unstable
Low – Moderate	<0.5	0.25 – 1.5	Moderate Tide	Moderately Unstable
Low - Low	<0.5	<0.25	Mixed	Stable Coast

Table 8: Intensity of Energy variations
(After M. O. Hayes, 1979; Davis and Hayes, 1984; Paul, 2002)

Energy	Mean Tidal Range (m)	Mean Wave Height (m)	Beach Condition
High	>3.5	1 – 1.5	Unstable Beach
Moderate	2.5 – 3.5	0.5 – 1	Mixed
Low	1 – 2.5	<0.5	Stable Beach

Table - 9 Dimensionless Fall Velocity and Beach Profile
(After Wright and Short, 1984)

Condition	Beach Type	Characteristics
Ω <1	Reflective Beach	i. Beachface is steep. ii. Beach cusped found. iii. The pronounced step is a presence at the base of the Swash Zone. iv. Wave height is small. v. Beach sediment relatively coarse.
1 - 6	Intermediate Beach	i. Bar and Rip morphology consist. ii. Four different intermediate beach states are determined and with increasing Ω. these are – a. Low Tide Terrace (LTT) b. Transverse Bar and Rip (TBR) c. Rhythmic Bar and Beach (RBB) d. Longshore Bar Trough (LBT)
Ω >6	Dissipative Beach	i. Wave energy level is usually high. ii. Sediments are fine. iii. Surf zone is wide. iv. Subdued bar morphology may be present but rips are not found.

Table -10 Conceptual Beach Model
(After Wright and Short, 1984; Wright, Short, and Green, 1985; Masselink and Short, 1993)

Group	Beach Type	Dimensionless Fall Velocity (Ω)	Relative Tidal Range (RTR)	Characteristics
Reflective Group	Reflective Beaches	< 2	< 3	i. Steep Beach face. ii. Cusped iii. A pronounced coarse step generally consists at the base of swash zone fronted by a lower gradient with the finer grained sub-tidal zone (Wright and Short, 1984). iv. Step height increases with wave height and grain size according to the observation of Hughes and Cowell, 1987. v. Waves are generally surging or plunging on the beach and most of the wave energy is at the incident and sub-harmonic (twice the wave period) frequencies (Huntley and Bowen, 1975; Wright and Short, 1984; Masselink and Short, 1993).
	Low Tide Terrace with Rips	< 2	3 - 7	i. Steep and reflective high tidal beach formed. ii. The high tidal beach is consisted of coarser sediments than the low tide terrace. iii. Beach cusps may be formed around the high tide level in a beach. iv. Small rip channel usually formed in the lower terrace or low tidal zone of the beach. Surf zone processes play a role of influencer to form rip channels. v. The textural discontinuity is associated with a distinct break of slope and often the low tide beach groundwater outcrop (effluent line) is located at this position saturating the low tide terrace.
	Low Tide Terrace without Rips	< 2	> 7	i. A very wide and dissipative low tide terrace formed. ii. Low tide terrace is dominated by an unbroken shoaling wave. iii. Low tide terrace of the beach is uniform and featureless without any rip channels. iv. According to Carter, 1988 in high latitude region low tide terrace consists of fine material and high tide beach consists of gravel.

Intermediate Group	Barred Beaches	2 – 5	<3	i. Usually, transverse bars and rips are confined. ii. Bars are spaced along the shoreline and rip current streams between the bars. iii. The shape of the bar is may be crescentic or be linear. iv. Micro-tidal beach width increase during Spring tide is retarded the formation of LBT and RBB with their deeper shore liner troughs in respect of shallower Rip – driven TBR (Wright et al. 1986, 1987) v. The subdued bar is formed with an increase of RTR. vi. Rip circulation is enhanced during low tide.
	Low Tide Bar/ Rip	2 - 5	3 - 7	i. Upper beach of intertidal zone is steep. ii. Mid – intertidal zone is characterized by the lower gradient. iii. In low tidal zone Swash bars and then bars and rip morphology formed alternatively. iv. During high tide, beach becomes more complex and may experience the reflective beach. v. Intermediate and dissipative surf zone conditions developed through a tidal cycle during low tide. vi. Bar and rip morphology exists during low tide.
Dissipative Group	Bared Dissipative Beaches	>5	<3	i. Spilling wave is observed. ii. Infragravity wave is being dominated in the inner surf zone. iii. Onshore mass transport is by spilling waves and bores while a strong offshore directed bottom flow dominates the return current pattern (Wright et al., 1982; Greenwood and Osborne, 1990). iv. Subdued longshore bar – trough morphology formed.
	Non-Barred Dissipative Beaches	>5	>3	i. Beaches become flatter and featureless. ii. The bar does not exist.
	Ultra – Dissipative Beaches	>2	>7	i. It addresses both the extreme dissipativeness of surf zone with multiple breakers and another one is the extreme width of the low gradient dissipative beach profile. ii. Surf zone conditions during high tide may be intermediate to reflective. iii. Surf zone condition is modified into dissipative through the tidal cycle. iv. Beaches are flat, featureless and have very wide intertidal zones.

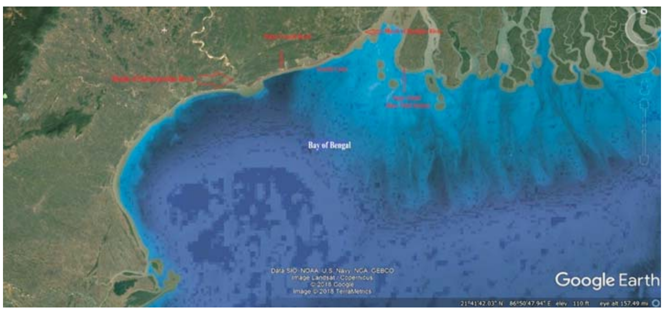

Fig. 1: Kanthi Coastal Beach (Source: Google Map)

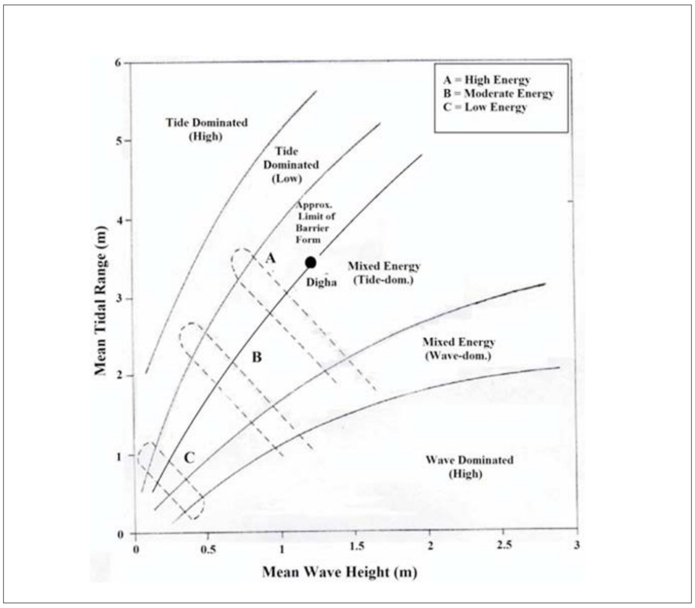

Fig.2: Energy Variations of the Digha Coastal Beach, A Part of Kanthi Coast (After M. O. Hayes, 1979; Davis and Hayes. 1984; Paul, 2002)

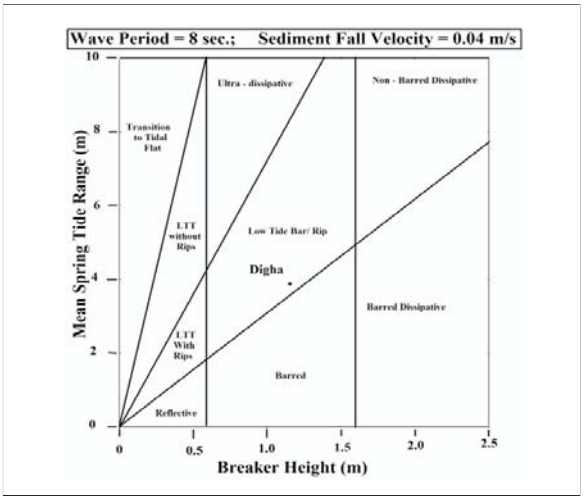

Fig.3: Conceptual Beach Model (After Masselink and Short, 1993)

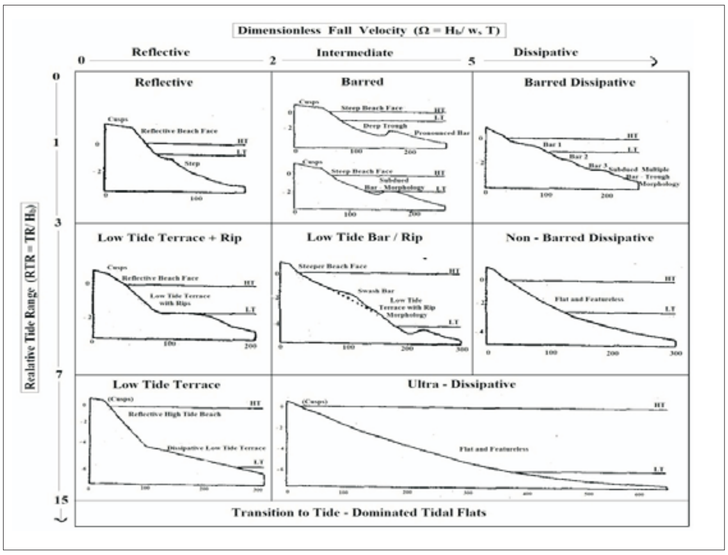

Fig. 4: Temporal Variation in Ω and RTR and Beach Model
(After Wright, Short and Green, 1985; Masselink and Short, 1993)

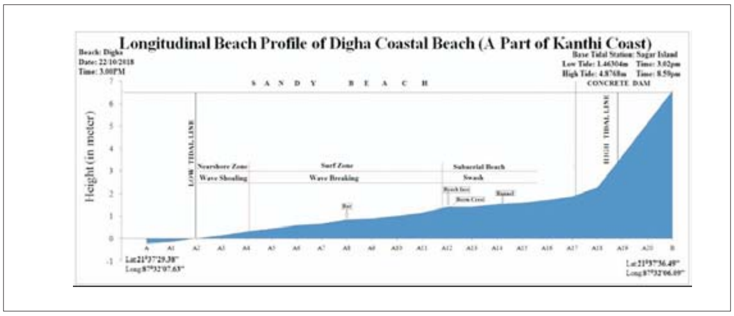

Fig. 5: Longitudinal Beach Profile of Digha Coastal Beach

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