

Wave Refraction Studies off Calangute Beach, Goa with Special Reference to Sediment Transport & Rip Currents

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Wave energy distribution, direction of longshore currents and the volume of littoral transport at 4 m depth contour along Calangute beach (from Aguada to Baga) were worked out from the wave refraction diagrams for predominant waves approaching the shore from directions varying between SW and WNW and periods varying from 6 to 12 sec. Probable areas of rip currents were demarcated along the beach. These areas generally coincided with the areas of low wave energy. It was estimated that about 9 million m^3 of littoral drift takes place along this beach annually. The net annual drift of 1.9 million m^3 was directed towards north.

CALANGUTE beach, on the west coast of India, extends between two promontories, Aguada in the south and Baga in the north (Fig. 1). The almost straight strip (7.5 km) of beach is known by different names at different parts of it. South of Baga is the proper Calangute beach and in between Calangute and Aguada are the Candolim and Sinquerim beaches. The river Mandovi joins the sea in the south and there is a small creek entering into the sea near Baga in the north. The bottom contours off this part of the beach run almost parallel to the coast except at Calangute where the depth contours bulge slightly seaward. Generally, medium to very fine sand is encountered at the bottom up to a depth of about 8 m and beyond that sediments with their mean grain size in the silt and clay ranges are present¹. Except for the field studies on littoral currents and rip currents during certain months by Murty *et al.*², no detailed information is available on the current pattern in this region. The present study attempts to provide some idea about the distribution of wave energy, direction of the longshore currents, areas of rip currents which are dangerous to swimmers, and the volume of littoral transport along the Aguada-Baga beaches, with reference to offshore wave climate.

Materials and Methods

Deep water wave characteristics — Estimation of these characteristics becomes important for a study like this, because, the utility of the results depends mainly on the reliability of the offshore wave data. The offshore wave parameters may be obtained from (i) wave records, (ii) hindcasting, and (iii) visual observations. For the wave refraction studies off Mormugao Harbour, Reddy³ has collected the necessary wave data from the visual observations (Indian daily weather reports). As the methods of wave hindcasting are time consuming and the data obtained from wave records are more reliable than the data based on the visual estimates, for the present study, the data from the wave records obtained for this area are utilized.

Using an OSPOS wave recorder, the wave parameters off Calangute are measured during December to March and these data (heights only) are considered for the fair weather season (Oct.-May)⁴. For the monsoon season, however, the data obtained from a wave recorder installed at Mangalore (about 200 km south) has been used. The offshore wave data for Mangalore region will reasonably hold good for Goa coast as the offshore wave characteristics of these parts are almost identical throughout the year⁵.

Wave characteristics as obtained from these recorders are presented in Table 1. During monsoon (June-Sept.) significant wave heights of 3, 2 and 1.5 m occur 5, 10 and 25% of the time respectively. The remaining 60% of the time, a wave height of about 0.75 m has been assumed to occur. The analysis of wave records of Mangalore⁵ does not cover waves of 6 sec period. Taking into consideration the locally generated wind waves, waves with 6 sec period are assumed to occur 25% of the time. The general directions of wave approach during the monsoon season are SW, WSW and W.

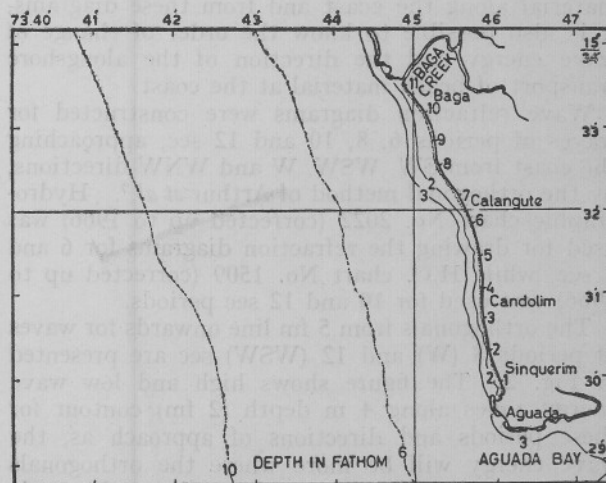


Fig. 1 — Station location

TABLE 1 — DEEP WATER WAVE CHARACTERISTICS, EXPRESSED AS FREQUENCY OF OCCURRENCE FOR WAVES APPROACHING THE GOA COAST

Monsoon season* (June-Sept.)		Fair weather season† (Oct.-May)	
Wave height (m)	Frequency (%)	Wave height (m)	Frequency (%)
3.0	5	0.48	10
2.0	10	0.23	90
1.5	25	—	—
0.75	60	—	—
Period (sec)		Period (sec)	
6	25	6	35
8	15	8	10
10	55	10	25
12	5	12	30

Direction of wave approach: *SW, WSW and W; †W and WNW.

During the fair weather season (Oct.-May) waves of heights 0.23 and 0.48 m occur 90 and 10% of the time respectively. For this season, the wave periods and their percentages of occurrence have been obtained from the analysis done by Dattatri⁵. The directions of the predominant waves in this season are W and WNW.

As the percentages of occurrence of these waves from different directions are not available, it is assumed that the waves approach the coast in equal percentage of time in both the seasons, i.e. 33-1/3% each for SW, WSW and W in the monsoon and 50% each for W and WNW in the fair weather seasons.

Wave refraction — When waves approach the coast from deep water, all wave characteristics except the wave period change depending on the depth contours. From the deep water wave characteristics, it is possible to evaluate the wave conditions near the coast by constructing wave refraction diagrams. According to Krumbein⁶, wave refraction is partly responsible for the transport of beach material along the coast and from these diagrams, it is also possible to know the order of change of wave energy and the direction of the alongshore transport of beach material at the coast.

Wave refraction diagrams were constructed for waves of periods 6, 8, 10 and 12 sec, approaching the coast from SW, WSW, W and WNW directions, by the orthogonal method of Arthur *et al.*⁷. Hydrographic chart No. 2022 (corrected up to 1966) was used for drawing the refraction diagrams for 6 and 8 sec, while H.O. chart No. 1509 (corrected up to 1966) was used for 10 and 12 sec periods.

The orthogonals from 5 fm line onwards for waves of periods 8 (W) and 12 (WSW) sec are presented in Fig. 2. The figure shows high and low wave energy zones along 4 m depth (2 fm) contour for these periods and directions of approach as, the wave energy will be more where the orthogonals converge and will be less where the orthogonals diverge.

The refraction functions were calculated using the formula⁸:

$$K(f, \theta)^2 = \frac{b_a/b}{C/C_a + \frac{4\pi d}{L} \left(\sinh \frac{4\pi d}{L} C_a/C \right)^{-1}} \quad \dots(1)$$

where K is refraction function; θ , angle between wave ray and normal to the depth contour; b_a , width between wave rays in deep water; b , width between wave rays at the point of interest; C_a , wave velocity in deep water; c , wave velocity in the point of interest; L , wave length; and d , depth at the point of interest.

Using K values, the wave heights at 4 m depth were evaluated for selected deep water wave heights. Wave height at any point in shallow water will be K times the deep water wave height, where K is the refraction function at that point.

Arbitrary* stations were fixed covering the entire beach and distributions of K at these stations are presented in Fig. 3. Whenever a marked increase or decrease in the value of K was noticed in between the stations, they were also represented in the graphs. The angle θ , taken from the refraction diagrams has been superimposed on these graphs. The angle measured towards north and south of the normal to the depth contour is indicated as north and south in the figures.

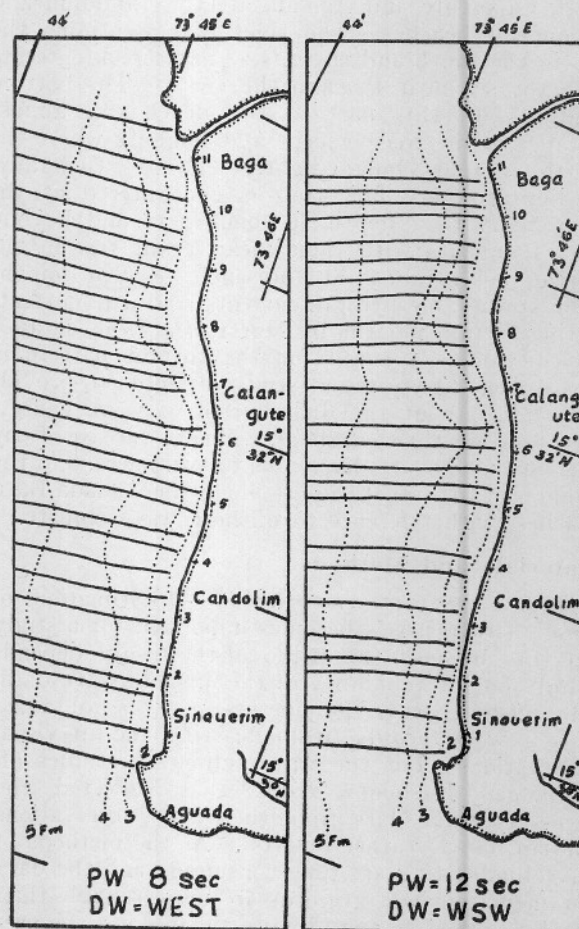


Fig. 2 — Orthogonals for waves of periods 8 and 12 sec and for deep water directions of W and WSW respectively

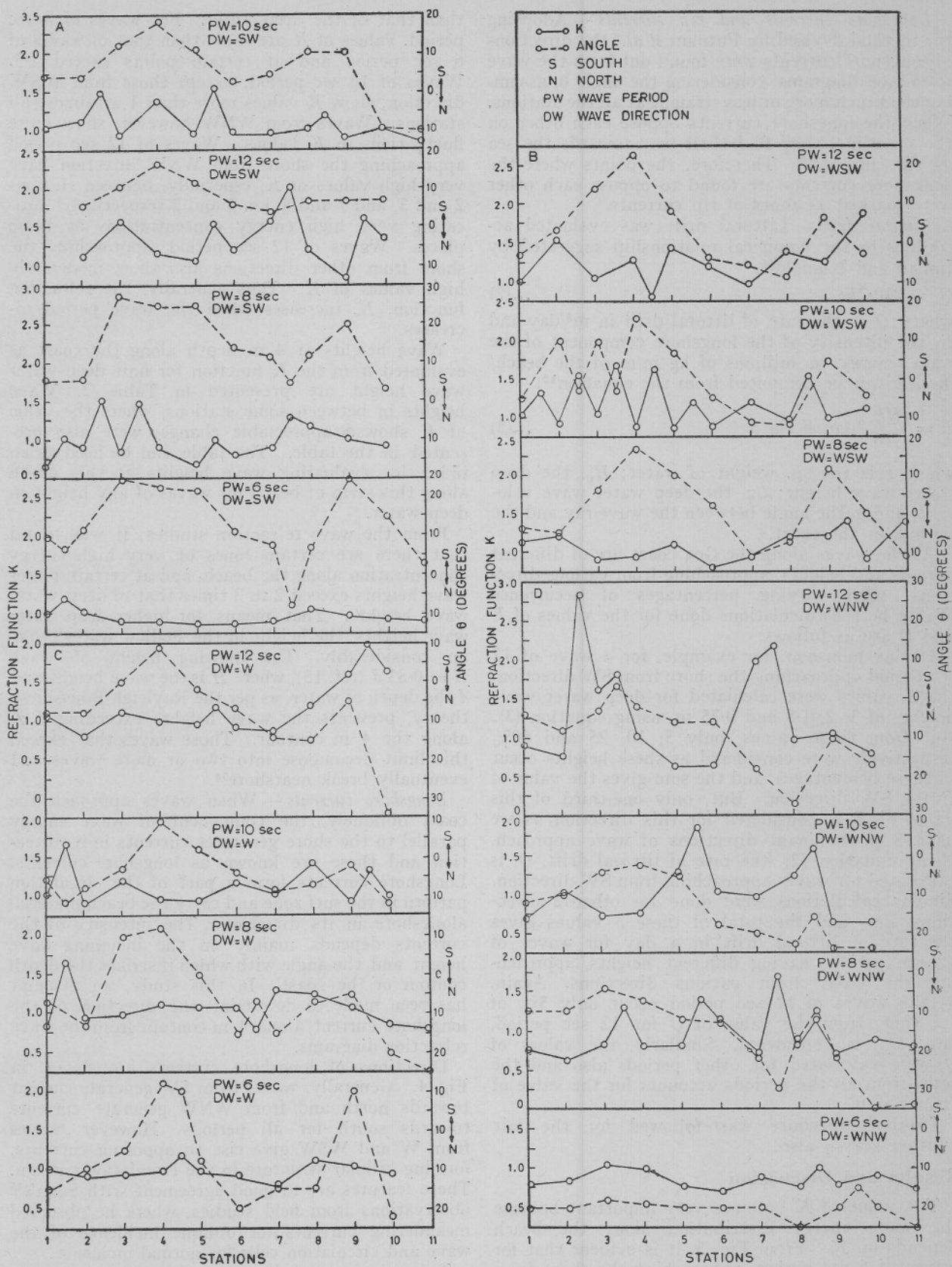


Fig. 3 — Refraction function K and angle θ , at the station for waves of different periods, approaching from SW (A), WSW (B), W (C) and WNW (D)

Longshore currents and rip currents—Adopting the method devised by Putnam *et al.*⁹ the directions of longshore currents were found out from the wave refraction diagrams, considering the angle θ , assuming the beach more or less straight at all the stations. When the longshore currents oppose each other on the coastline, they find their way towards the sea as rip currents¹⁰. Therefore, the points where the longshore currents are found to oppose each other were marked as zones of rip currents.

Littoral drift—Littoral drift was evaluated according to the empirical relationship suggested by Inman and Bagnold¹¹,

$$Q = 210.7E \quad \dots(2)$$

where Q is the rate of littoral drift in m^3/day and E , the intensity of the longshore component of the wave energy in millions of $kg\ m/m$ of the beach/ day. E can be computed from the equation¹²:

$$E = \frac{rH_0^2C_0}{16} \cos \theta \sin \theta \quad \dots(3)$$

where r is the sp. weight of water; H_0 , the deep water wave height; C_0 , the deep water wave velocity; and θ , the angle between the wave ray and the normal at the coast.

As the waves along the Goa coast are of different periods and heights, approaching from various directions, with varying percentages of occurrence (Table 1), the calculations done for the values of E and Q are as follows:

During monsoon, for example, for a wave of 12 sec period approaching the shore from SW direction, the E values were calculated for deep water wave heights of 3, 2, 1.5 and 0.75 m, using equation (3). But from these values, only 5, 10, 25 and 60% respectively were considered as these heights occur in these percentages, and the sum gives the value of E for SW direction. But, only one-third of this value of E is considered for this direction as we have 3 predominant directions of wave approach. Using equation (2), the rate of littoral drift, Q , is calculated for waves approaching from SW direction. Similar calculations were done for other 2 directions also, and the total of these 3 values gives the rate of littoral drift in a day for waves of 12 sec period, having different heights, approaching the coast from various directions. Again, as the waves of 12 sec period occur only 5% of the time, from the value of Q for 12 sec period, only 5% is considered. Similarly, the values of Q were calculated for other periods also and the total from all the periods accounts for the value of Q in a day.

Similar procedure was followed for the fair weather season also.

Results and Discussion

The value of K becomes very important because the wave energy distribution along the beach depends on K . From Fig. 3, it is evident that for waves of 6 sec period, approaching the shore from various directions, the K function is generally less than 1 for all stations except for a few. Therefore, heights of these waves at shallow water will be less

than that of the deep water. For waves of 8 sec period, values of K are more than that of waves of 6 sec period and at certain points exceed 1.5. Waves of 10 sec period, except those from WNW direction, show K values more than 1 at almost all stations. Waves from WNW however, show more fluctuations in K values. Waves of 12 sec period approaching the shore from WNW direction have very high values of K , especially, between stations 2 and 3, and 7 and 8, i.e. 3 and 2 respectively, indicating very high energy concentrations at these places. Waves of 12 sec period, approaching the shore from other directions also show moderately high values of K . Thus generally, the refraction function, K , increases when the wave period increases.

Wave heights at 4 m depth along the coast as evaluated from the K function for unit deep water wave height are presented in Table 2. Wave heights in between some stations, where the value of K showed appreciable change, were also presented in the table. The table can be used as an index for evaluating wave heights at this depth along this strip of beach for waves of any height in deep water.

From the wave refraction studies, it was found that there are certain zones of very high energy concentration along the beach, and at certain places wave heights exceed 2 to 3 times that of deep water wave heights. That means, for higher deep water wave heights, the height in the shallow water peaks up considerably. The limiting height of wave $H = 0.83 d$ (ref. 13), where H is the wave height and d the depth of water, as per the Rayleigh-Boussinesq theory, prevents the wave heights exceeding 3 m along the 4 m contour. Those waves that exceed this limit decompose into two or more waves and eventually break nearshore¹⁴.

Longshore currents—When waves approach the coast obliquely, the component of wave energy parallel to the shore generates currents in its direction and these are known as longshore currents. Longshore currents form a part of the circulation pattern in the surf zone and carry the beach material alongshore in its direction. The intensity of the currents depends mainly on the incoming wave height and the angle with which it strikes the depth contour or the coast. In this study, an attempt has been made to determine the direction of the longshore current along 4 m contour from the wave refraction diagrams.

Directions of longshore currents are shown in Fig. 4. Generally, waves from SW generate current towards north and from WNW generate currents towards south for all periods. However, waves from W and WSW give rise to opposing currents, forming cellular structure in the circulation pattern. These features are in good agreement with Sonu's¹⁵ observations from field studies, where he observed meandering currents for oblique incidence of the wave and circulation cells for normal incidence.

Thus, the general direction of longshore currents during a particular season depends mainly on the direction of predominant waves. During SW monsoon, when the direction of predominant waves are

WAVE HEIGHTS (m) AT STATIONS (4 m) FOR UNIT DEEP WATER WAVE HEIGHT FOR VARIOUS WAVE PERIODS AND DIRECTIONS OF APPROACH

	Stations													
	1	2	3	4	5	6	7	8	9	10	11			
	PERIOD 6 SEC													
	1.0	1.0	0.9	0.9	0.9	0.9	0.9	1.1	1.0	0.9	0.9			
	1.0	0.9	0.9	1.0	1.0	0.9	0.8	1.1	1.0	0.9	—			
	0.8	0.9	1.1	1.0	0.8	0.7	0.9	0.8	1.0	0.8	0.9	0.7		
	PERIOD 8 SEC													
	0.7	1.0	0.9	1.5	0.9	1.5	0.9	0.7	1.0	0.8	0.9	1.3	1.2	1.0
W	1.1	1.2	0.9	0.9	0.9	1.1	0.8	0.9	1.2	1.2	1.4	0.9	1.4	—
W	0.9	1.7	1.0	1.0	1.1	1.1	1.1	1.3	1.2	1.1	—	0.9	0.8	—
WNW	0.8	0.6	0.8	1.3	0.8	0.8	1.4	1.1	0.7	1.7	0.8	1.1	0.7	0.9
	PERIOD 10 SEC													
SW	1.0	1.1	1.5	0.9	1.4	1.0	1.5	0.9	0.9	1.0	1.2	0.9	1.0	0.9
WSW	1.0	1.3	0.9	1.6	1.0	1.7	0.9	1.6	0.9	1.2	1.0	1.0	1.1	—
W	1.0	1.7	0.9	1.2	1.0	—	0.9	—	1.2	1.0	1.4	0.9	1.3	1.0
WNW	0.7	1.0	0.7	0.8	1.3	1.9	1.0	1.0	1.2	1.6	0.6	—	0.6	—
	PERIOD 12 SEC													
SW	—	1.2	1.6	1.2	1.1	1.6	1.2	1.6	2.0	1.2	0.9	1.6	1.4	—
WSW	1.0	1.5	1.0	1.3	0.8	1.4	1.2	1.0	1.4	1.4	1.3	1.9	1.9	—
W	1.1	0.8	1.1	1.0	1.0	—	0.9	0.9	—	1.2	1.6	2.0	1.6	—
WNW	0.9	0.8	2.9	1.6	1.8	1.0	0.6	0.6	2.0	2.2	1.0	1.1	0.8	—

from S to WSW, longshore currents are expected to be towards north. Similarly, during fair weather season, longshore currents would be southerly as the directions of the predominant waves are from W to WNW.

Rip currents—These narrow but strong currents in the nearshore region are directed away from the coast and their intensity and the extension towards the sea are related to the incoming waves¹⁶. Identification of the areas of rip currents is very important as they carry the beach material offshore and are dangerous to swimmers.

Probable areas of rip currents have been identified (Fig. 4). During monsoon season, areas around stations 9 and 10 (near Baga) and stations 4 to 7 (Candolim) were identified as zones of rip currents. During fair weather season, however, rips are active mostly around areas from stations 4 to 6, i.e. along the Candolim part of the beach.

The area from stations 7 to 9 and 1 to 4 (Calangute and Sinquerim parts, respectively), of the beach may be relatively safer for swimmers as no rips could be located at these places in any of the seasons.

Murty *et al.*² made field observations on the currents in the surf zone along the Calangute beach using dyes and located rips at different parts along the beach. Out of 7 field observations made in different months, on 6 occasions rips were recorded around stations 8-10. In the present study, almost the same region has been identified as a zone of rip currents. The field observations also revealed that the area between stations 4 and 7 is also a zone of rip currents.

Sediment transport—Sediment transport in the surf zone is very complicated and depends on various factors like wave characteristics, surf zone circu-

lation, grain size, slope of the beach, tidal currents, etc. No perfect method has been evolved so far, to determine the rate of sediment transport directly or compute by relating with the factors responsible for it. But the work so far conducted in the field and in the laboratory could yield some empirical relationship between the sediment transport and the incident wave characteristics. Various workers^{11,16,18} have suggested similar empirical relationships and these relationships were found to be useful in design studies, etc. In this study, an attempt has been made to estimate the littoral drift along Aguada-Baga beaches for different seasons using the formula suggested by Inmann and Bagnold¹¹. Similar evaluations of littoral drift have been made by Sastry and DeSouza¹⁹ in the neighbourhood of Tarapur Atomic Power Station, north of Bombay.

Using Eq. (3), the value of E /meter of the beach was calculated at the stations for various wave, periods and directions of approach, for a deep water wave height of 1 m. The results are presented in Table 3. This can further be used as an index evaluating the values of E for any desired water wave height. The negative sign in E indicates the drift towards south and the positive sign, towards north. E values at certain stations are not given in the table as the angle θ , at those places is either zero or could not be measured.

From the average value of E at each station, total E for the entire beach (7.5 km) was computed.

Table 4 presents value of E and Q for various periods and directions of approach according to their percentages of occurrence, for monsoon and fair weather seasons.

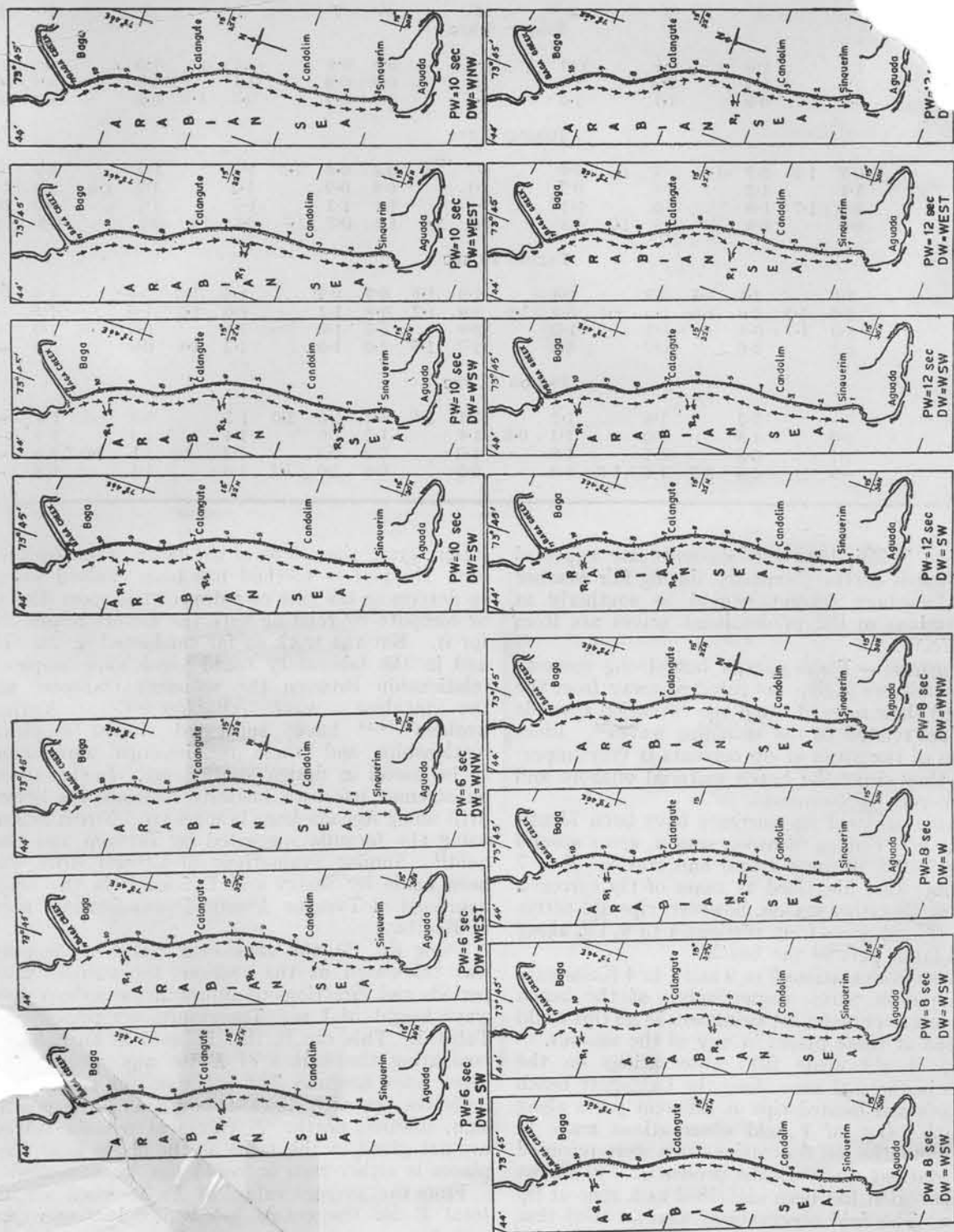


Fig. 4 — Direction of longshore current and the areas of rip currents for waves of different periods and directions

TABLE 3 — ALONGSHORE ENERGY FLUX E (kg m) PER METER PER SECOND FOR UNIT DEEP WATER WAVE HEIGHT AT STATIONS FOR DIFFERENT PERIODS AND DIRECTIONS OF APPROACH

Direction	STATIONS										
	1	2	3	4	5	6	7	8	9	10	11
PERIOD 6 SEC											
SW	0.981	1.167	2.197	2.063	1.992	1.074	0.791	0.694	2.197	1.434	0.3
W	-1.434	-0.981	-0.498	1.167	-0.791	-1.844	-1.434	-1.434	0.981	-1.992	—
WNW	-1.844	-1.844	-1.686	-1.762	-1.844	-1.844	-1.844	-2.197	-1.434	-1.844	-2.197
PERIOD 8 SEC											
SW	0.795	0.795	3.170	2.928	2.928	1.795	1.555	1.555	2.457	0.4	—
WSW	-0.532	-0.664	0.795	2.137	1.307	0.267	-1.432	-0.927	1.555	—	—
W	-0.927	-1.676	1.307	1.555	—	-1.911	-1.911	-0.927	-0.664	-2.457	-2.928
WNW	-1.307	-1.307	-0.531	-0.927	-1.555	-1.676	-2.655	-2.137	-2.655	-3.59	-3.545
PERIOD 10 SEC											
SW	0.665	0.665	1.944	2.67	1.635	0.333	0.665	1.635	1.635	-1.635	1.635
WSW	-0.83	-1.635	1.635	2.533	1.156	-0.83	-1.79	-1.944	0.83	-0.665	—
W	-0.994	-1.318	-0.500	1.156	0.333	-0.665	-1.477	-1.156	-0.333	-1.944	—
WNW	-1.944	-1.635	-0.665	-0.333	-0.83	-2.810	-3.07	-3.438	-3.55	-3.55	—
PERIOD 12 SEC											
SW	—	1.192	2.148	3.205	2.333	1.192	0.798	1.388	1.388	-1.388	—
WSW	-0.599	0.599	2.69	4.125	1.581	-0.798	-1.192	-1.772	1.192	-0.599	—
W	-1.581	-1.581	—	1.772	-0.4	-1.388	-2.69	-2.868	-0.996	-5.313	—
WNW	-0.798	-1.581	-0.599	-0.400	-1.192	-1.192	-3.37	-4.64	-1.962	-3.205	—

TABLE 4 — LITTORAL DRIFT (m^3/day) FOR THE WHOLE BEACH DURING MONSOON SEASON AND FAIR WEATHER SEASON[E values are expressed in kg m/m/day (millions) and Q values are expressed in m^3/day]

Direction	Period 6 sec		Period 8 sec		Period 10 sec		Period 12 sec	
	E	Q	E	Q	E	Q	E	Q
SW	792.0	166873	651.3	137301	305.7	64389	435.0	915786
WSW	—	—	89.0	18738	61.3	12927	185.3	390624
W	-439.5	-92583	-374.0	-78726	-245.0	-51537	-533.3	-1123917
Net*	(25%)	18573	(15%)	11597	(55%)	14179	(5%)	—
FAIR WEATHER SEASON								
W	19.3	-4051	-24.5	-5167	-16.1	-3383	-35.0	-7369
WNW	47.4	-9968	-50.9	-10733	-50.8	-10704	-44.1	-9290
Net†	(35%)	-4907	(10%)	-1590	(25%)	-3522	(30%)	-4998

*Net drift per day, about 45000 m^3 ; total drift for the period (June-Sept.), about 5.5 million m^3 .†Net drift per day, about 15000 m^3 ; total drift for the period (Oct.-May), about 3.6 million m^3 .

During monsoon season, it has been found that, about 45000 m^3 of beach material is moving towards north per day, which means that during the entire season (June-Sept.) the amount of material transported along the beach near 4 m contour, is about 5.5 million m^3 . Similarly, during the fair weather season, about 15000 m^3 of sediment is expected to move towards south per day and this brings the total figure for the whole season (Oct.-May) to about 3.6 million m^3 . Thus it is estimated that about 9 million m^3 of sediment is in transit along this part of the beach annually, with an annual net drift of material of about 1.9 million m^3 towards north. The evaluation of the net drift towards north in the present study is in agreement with the sedimentological studies of Veerayya²⁰ along Calangute beach, where he observed a decreasing trend in the mean grain size from south to

north, which he attributed to the northward littoral current.

Estimation of the net annual drift of the order of 1.9 million m^3 towards north requires some explanation, because, if this continues, the beach should run short of material and would get eroded completely in due course. But such is not the case. The Calangute beach is more or less in a stable equilibrium. It is possible, therefore, that the material transported along the beach towards north returns to the beach through the cellular structures of circulation pattern as described earlier in this study and the onshore transport of material by the waves.

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