

A SYSTEMATIC STUDY OF WAVE CONDITIONS AND SEDIMENT TRANSPORT NEAR MORMUGAO HARBOUR

By

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Abstract

Wave conditions and the nature of sediment transport in the Mormugao Harbour area have been evaluated in view of the proposed development project of this harbour. It has been found from this study that generally high waves will be experienced in this area from S. W. to west, particularly from W.S.W. during the south-west monsoon season. Minimum wave heights have been found just north of the present breakwater and maximum wave heights have been found near Dona Paula and Cabo regions. The off-shore sediment movement appears to be directed towards north or north-west due to the combined influence of currents and waves. Littoral drift has been found to be directed into the Mormugao Bay both from its northern and southern sides.

Introduction

The Port of Mormugao is one of the major ports on the west coast of India and it has assumed great importance in international trade due to the existence of rich deposits of iron ore near the port area. As the present available facilities by way of permissible drafts, berthing length etc. are not adequate, it has been decided by the Government of India to develop this port in stages so that it can handle iron ore of the order of 8 million tons per year in the first stage and 12 million tons per year in the second stage. For this development it was considered essential to deepen the entrance channel to 45 feet in the first stage and to 57.5 feet in the second stage so that ships of 1,00,000 DWT could visit the port. It was also considered essential to construct an additional breakwater in the second stage to provide better shelter during the south-west monsoon season.

Since this development project of deepening the harbour and the approach channel will be governed to a large extent, with respect to maintenance cost, by the rate and mode of sediment transport in that area, a systematic study to understand the sediment transport in the Mormugao Port area has been carried out. This study will be quite helpful while constructing the breakwater also because any structure which extends into the sea will both affect and be affected by the sediment transport. An idea of wave characteristics in the region under consideration will be very useful in selecting the proper location of the proposed breakwater and its design.

Sedimentation phenomenon : Erosion and deposition of sediments at and close to the shore are due to the complex interactions of waves and currents and the changes which occur are determined by the shape and material of the coast and adjacent sea bed. There is a marked difference in the phenomenon occurring seaward and shoreward of the breaker zone, which are referred to as Off-shore and shore zones respectively. In the offshore zone the currents will be predominantly due to distribution of mass, tidal action and wind action, although in relatively shallow water the mass transport current caused by the waves can also move fine material. The transport of sediments in the inshore zone, *i.e.*, the zone shoreward of the breakers is mainly due to the effects of secondary currents called longshore or littoral currents generated by wave action. However, a feature distinctly common in both the regions is that the forces involved are those produced by wave action. Another common feature is the importance of the character of bed material upon the manner of transport.

Description of the Area Under Study

General location and bottom topography : The general location of Mormugao harbour and its surroundings along with bed contours adjacent to the harbour as in the Survey Chart published by the Naval Hydrographic Office, Dehra Dun, in 1966 (Chart No. 2022) is shown in Fig. 1. The harbour which is situated at the foot of a promontory has the natural advantage of deep water very near to the shore. At present a breakwater 1,714 feet long extending north-northeastward from the shore protects the harbour from the southwest monsoon. About 180 feet within the outer end of this breakwater, a mole extends in an easterly direction which offers protection to the berths from the NE monsoon.

The river ZUARI discharges into the eastern part of the Mormugao bay. There are scattered rocky shoals and small islands outside the harbour west of Mormugao Port. The southern side of Mormugao bay is mostly bold and rocky, rising inland to tableland (West coast of India Pilot, 1961). The bottom in the south western part of the harbour is reported to be of very soft mud.

TABLE I
Wind Climate on a Monthly Basis Near Mormugao Harbour

Percentage Frequency :

Direction of wind	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Average in an year
N	5	11	10	13	10	4	4	3	5	3	2	3	7
NE	10	9	8	6	4	3	1	3	3	7	14	13	7
E	26	15	9	5	2	2	2	1	4	11	21	27	10
SE	6	6	5	2	2	3	2	1	3	6	6	5	4
S	2	3	5	6	4	8	2	2	5	11	5	3	4
SW	15	8	9	9	4	22	18	14	14	12	15	13	12
W	18	20	18	25	29	40	54	49	26	23	24	20	29
NW	15	24	31	28	41	15	15	21	28	13	9	14	21
Calm	3	4	5	6	4	3	2	7	12	14	4	2	6

Winds : In any place, knowledge of statistical wind data will be helpful to understand the probable directions from which wind waves are approaching that place. In order to study the mean wind pattern near Mormugao Port, data were taken from the records of I.M.D. (India Meteorological Department). Mean monthly winds are presented in Table I. This table was prepared from the climatic table compiled for Mormugao for the period 1891 to 1955 (West Coast of India Pilot, 1961). From this statistical information it can be observed that the predominant winds over the year are from S.W. (12%), West (29%) and N.W. (21%).

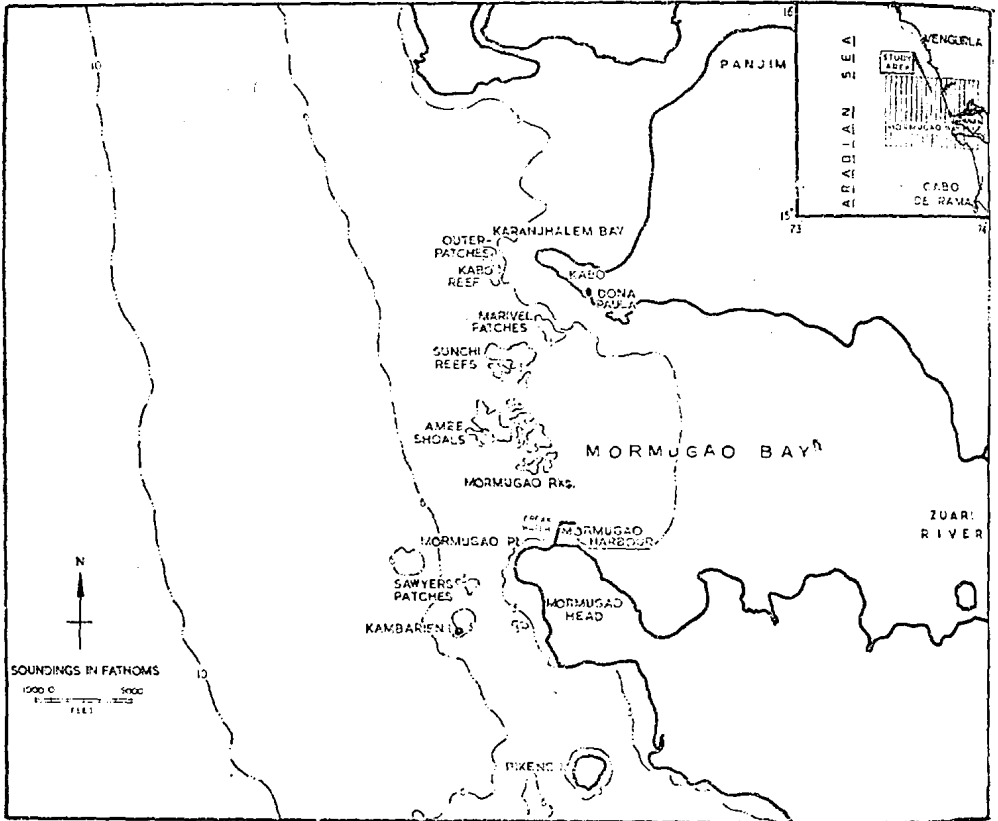


Fig. 1. Mormugao harbour and its surroundings with the adjacent bed contours.

Wave Conditions

Estimation of wave climate : Following the general concept of littoral processes, the currents induced by waves are considered to be the dominating force. Hence the initial step in this problem is a statistical determination of wave characteristics. The data required are direction, height and period of all waves reaching the seaward limit of the littoral berm for a sufficient length of time to encompass a reasonable meteorological cycle for the tributary wave generating force.

Waves may be generated either by local winds or by storms at a relatively great distance from the shoreline (Bigelow and Edmondson, 1947). Locally generated waves generally are referred to as "Sea" and waves generated by a distant storm are referred to as "Swell". The swell generally contains much more energy than the local wind waves; consequently, it is the important sediment-moving factor when the energy is released by breaking at a shoreline (Johnson, 1956). Hence swell wave statistics have been evaluated from the data on visual observations from ships taken from I.D.W.R. (Indian Daily Weather Reports) in the vicinity of Mormugao for the area between longitudes 70° to 74° E and latitudes 13 to 18° N for the years 1968 and 1969. Wave statistics determined by this procedure establish the wave characteristics in deep water.

The wave height estimates for all the relevant directions are shown in Fig. 2 in the form of a linear wave rose. It can be seen from the figure that the predominant directions from which severe waves are experienced are between west and south-west. In general wave height reached 18 feet three times a year for 11 sec., 12 sec. and 13 sec. periods and these waves have been found to occur during the S.W. monsoon period. In the remaining' period of the year, waves generally approach from west-northwest with a maximum height of 10 ft. for high period waves. It can be seen from Fig. 1 that only waves coming from directions

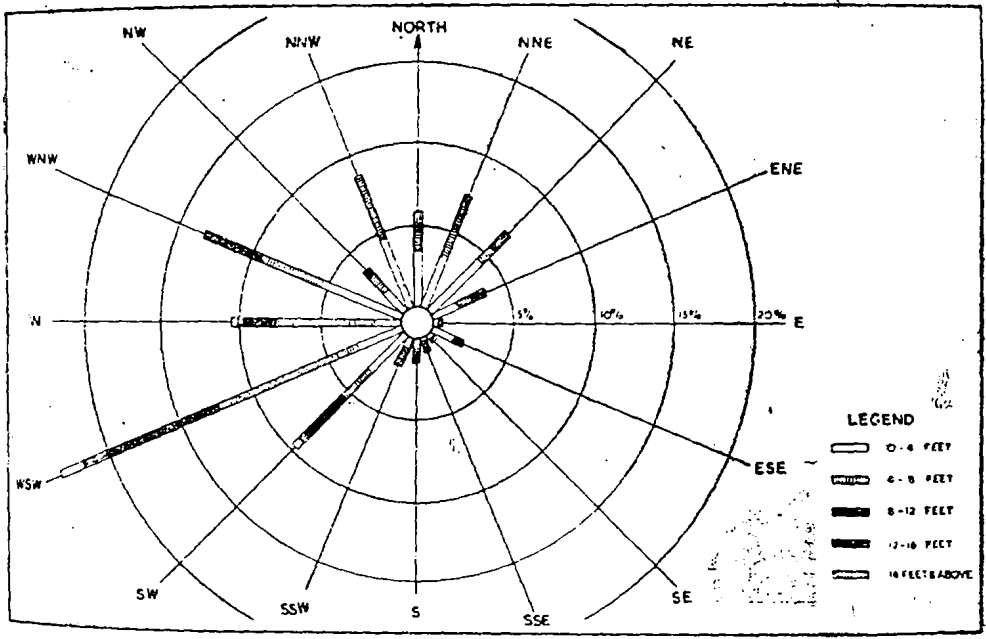


Fig. 2. Annual wave height Rose by directions and height groups. Vector Magnitudes indicate percent of time at each height and from each direction.

between W.N.W. and S.W. will affect this harbour. The predominant wave periods during the south-west monsoon season *i.e.* for waves from S.W. and W.S.W. are 5 sec., 6 sec. and 8 sec., and for waves from west are 5 secs., 7 secs. and 10 secs., and during the remaining time of the year the predominant wave periods to be considered are 5 secs., 6 secs., and 7 secs., for W.N.W. waves as is evident from the Table II.

Wave refraction: To determine changes in wave height and direction over any point on a littoral berm, wave refraction diagrams have to be constructed. For a given wave period and deep water wave direction the pattern of wave rays can be constructed on a paper containing the bathymetry of the area under consideration using the method of Arthur, Munk and Isaacs (1952).

TABLE II
Annual Wave Period Percentage Frequencies for the Region Around Mormugao Harbour

Period in sec.	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total in the year
5	27.27	5.0	52.0	42.85	5.0	37.5	5.0	5.0	—	14.3	15.8	22.6	22.5	23.5	28.5	42.4	29.4
6	13.63	25.0	—	7.14	—	12.5	—	5.0	20.0	28.5	15.8	15.47	10.0	19.6	21.4	9.0	14.2
7	22.54	7.14	8.0	14.28	—	12.5	5.0	—	20.0	—	—	8.33	15.0	19.6	14.3	18.1	11.3
8	9.09	—	4.0	14.28	—	—	—	—	—	14.3	23.7	23.8	10.0	9.8	—	12.1	12.7
9	4.54	—	—	—	5.0	—	—	—	—	14.3	10.5	13.1	12.5	5.9	—	—	6.8
10	9.09	—	4.0	7.14	—	—	—	—	4.0	—	7.9	2.38	15.0	2.0	7.15	—	5.4
11	4.54	10.7	12.0	—	—	12.5	—	—	—	14.3	2.63	4.76	2.5	2.0	—	3.0	4.5
12	—	—	4.0	—	—	—	—	—	—	—	13.15	2.38	5.0	2.0	14.3	—	3.4
13	—	3.57	12.0	—	—	—	—	—	—	14.3	5.26	4.76	5.0	7.8	7.15	6.0	5.3
14	9.09	3.57	4.0	14.28	—	25.0	—	—	20.0	—	5.26	2.38	2.5	7.8	7.15	9.1	5.8

The wave height at any point can be determined from the water depth and spacing of the orthogonals if the deep water wave height is known using the equation (Beach Erosion Board, 1954).

$$\frac{H}{H_0} = \sqrt{\frac{1}{2} \left(\frac{1}{n} \right) \left(\frac{L_0}{L} \right)} \quad \left(\sqrt{\frac{b_0}{b}} \right) \quad \dots (1)$$

where
$$n = \frac{1}{2} \left[1 + \frac{4\pi d/L}{\sinh 4\pi d/L} \right]$$

In this equation

- b_0 is the separation between the wave rays in deep water,
- b is the separation between the wave rays in shallow water at the point of investigation,
- H_0 is the wave height in deep water,
- H is the wave height in shallow water (i.e., at the point of investigation),
- L_0 is the wave length in deep water,
- L is the wave length in shallow water,
- d is the depth of water at the point of investigation.

In the above equation the reduction in wave height due to friction is disregarded.

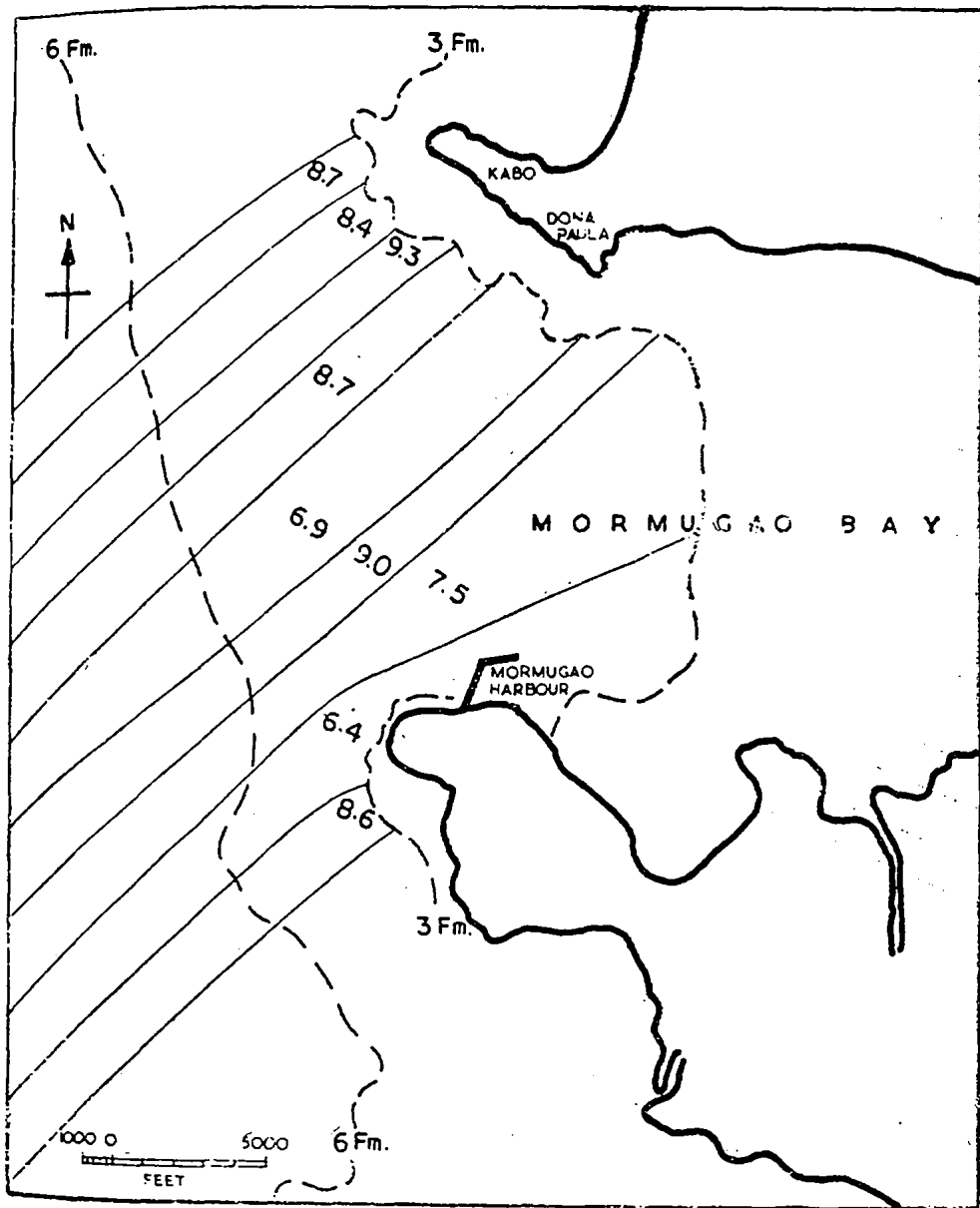


Fig. 3. Wave Refraction diagram for waves from S.W., Period=6 seconds, deep water wave height (highest for 6 secs.) = 9 ft. solid lines represent wave orthogonals and broken lines represent bottom contours. The numbers depict the wave heights in feet at the corresponding depth.

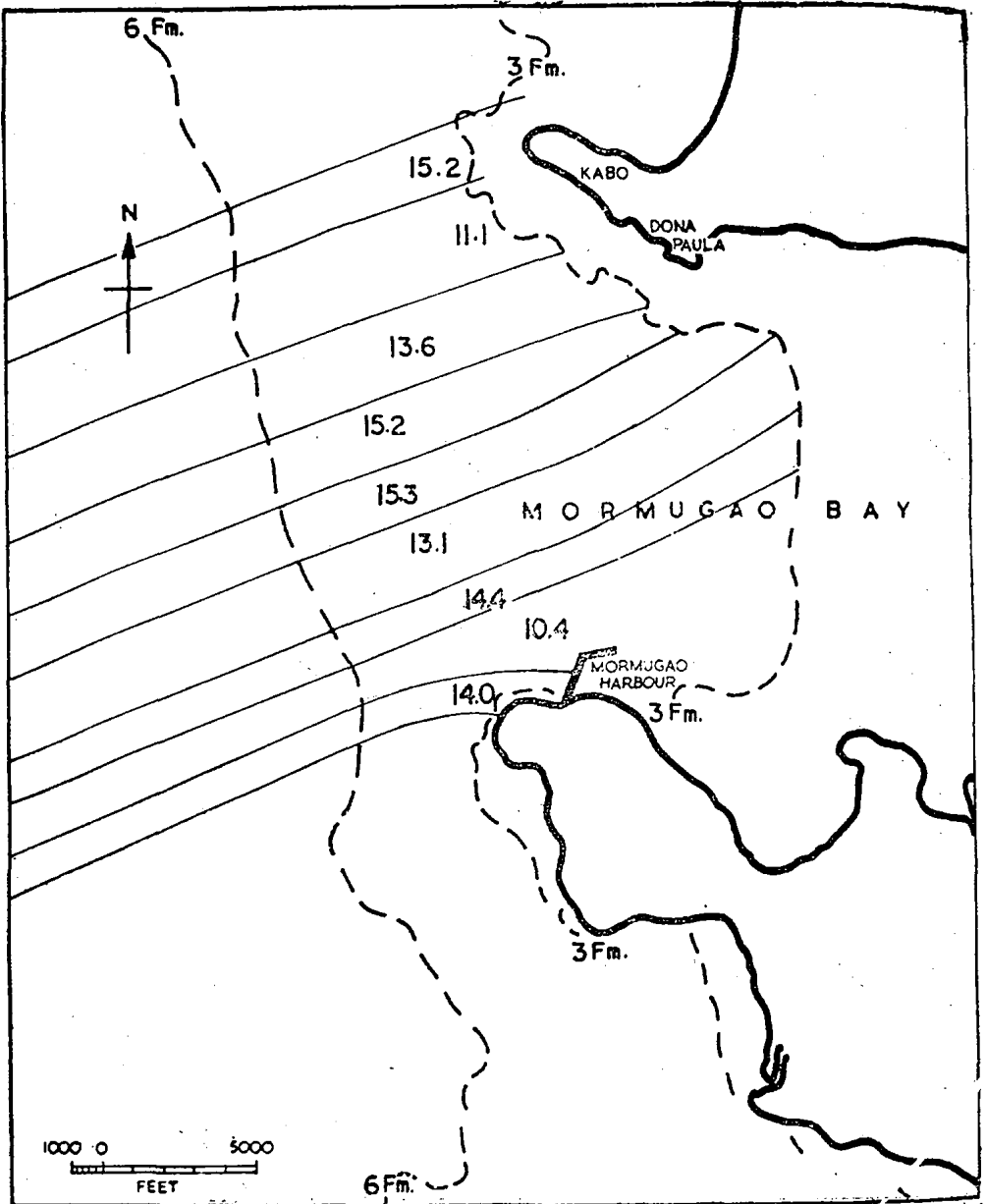


Fig. 4. Wave Refraction diagram for waves from W.S.W., period=8 seconds, deep water wave height (highest for 8 seconds)=13.5 ft. solid lines represent wave orthogonals and broken lines represent bottom contours. The numbers depict the wave heights in feet at the corresponding depth.

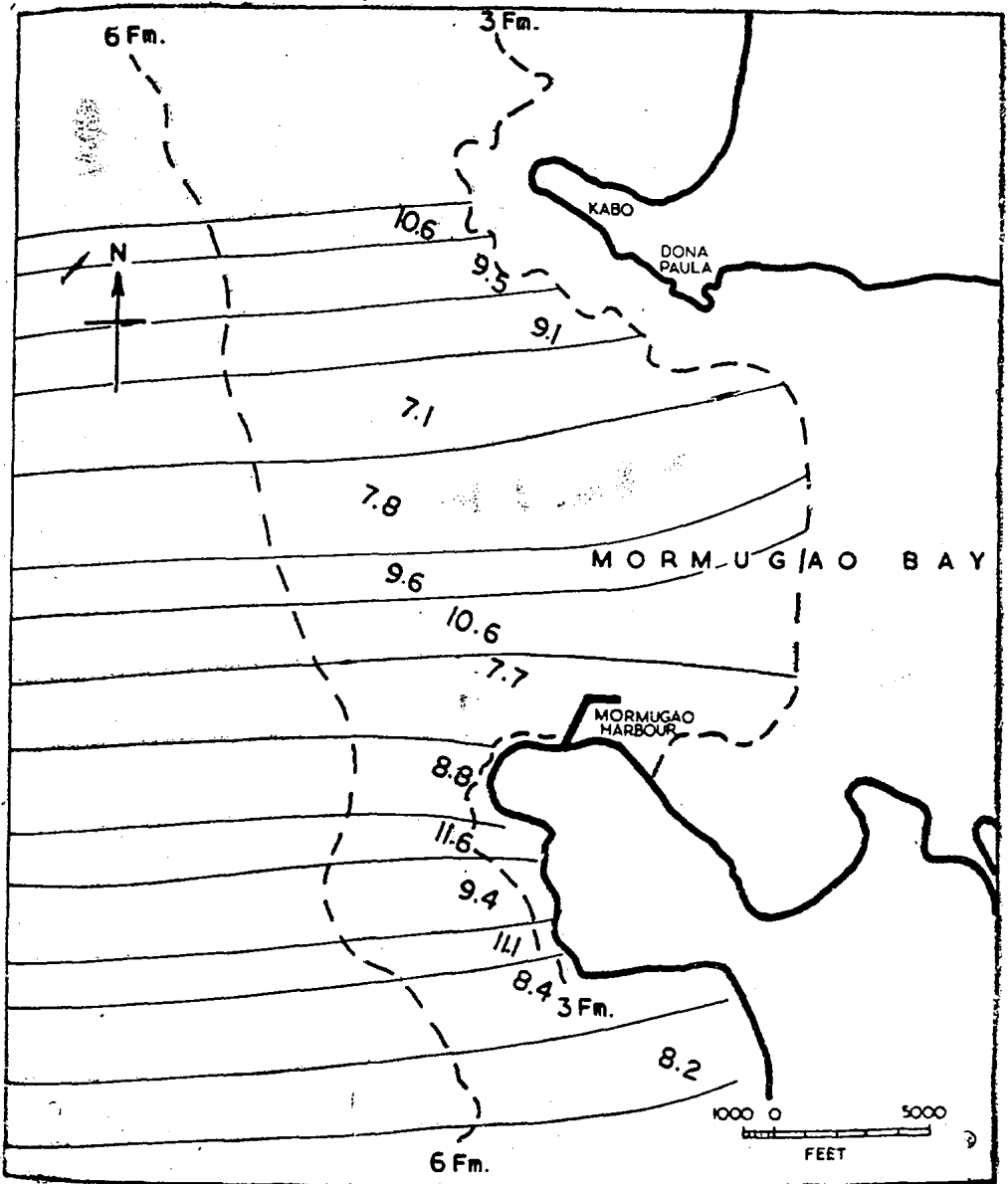


Fig. 5. Wave Refraction diagram for waves from west, period=8 seconds, deep water wave height (highest for 8 secs.)=9 ft. Solid lines represent wave orthogonals and broken lines represent bottom contours. The numbers depict the wave heights in feet at the corresponding depth.

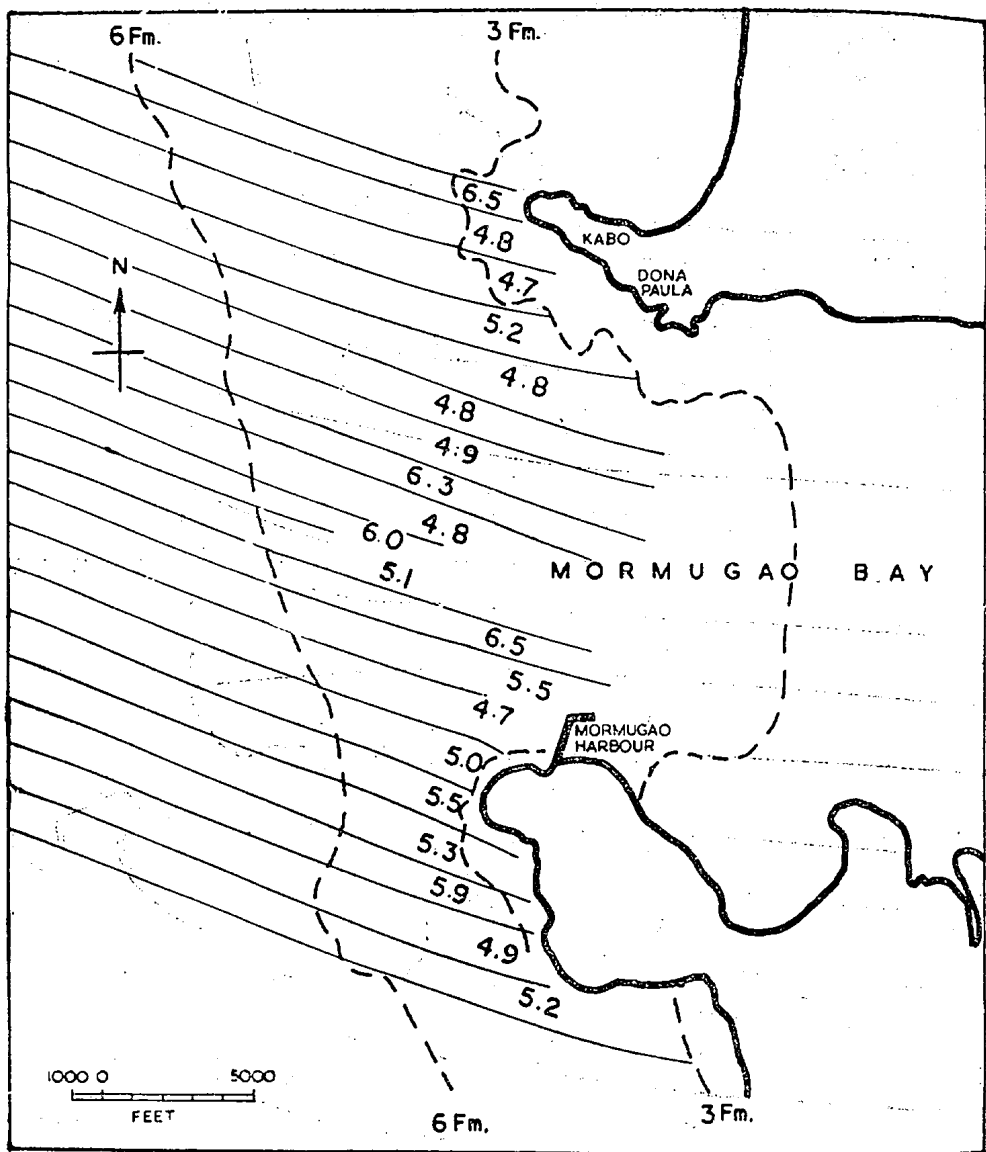


Fig. 6. Wave refraction diagram for the waves from W.N.W., period=5 seconds, deep water wave height (Highest for 5 seconds)=6 ft. Solid lines represent wave orthogonals and broken lines represent bottom contours. The numbers depict the wave heights in feet at the corresponding depth.

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For the Mormugao harbour area, wave refraction diagrams have been prepared using Survey Chart No. 2022 of Naval Hydrographic Office, Dehra Dun for the directions and periods listed below since these are found to be the possible wave directions and predominant wave periods for which the refraction diagrams could be conveniently prepared with the help of this map.

Wave direction	Period in sec.
S.W.	5 and 6
W.S.W.	5 and 8
West	5 and 8
W.N.W.	5.

Wave heights in shallow water (at 20 ft. depth) for these directions and periods have been calculated using the equation (1). It can be seen from the refraction diagrams (Figs. 3 to 6) that generally high waves are experienced from S.W., west-southwest and west which are predominant during the south-west monsoon. For 8 sec. period waves from W.S.W. (Fig. 4) maximum waves height in shallow water is found just opposite Kabo (15.2 ft.) and south-west of Dona Paula (15.2 ft. & 15.3 ft.) and minimum value is found just north of the present breakwater (10.4 ft.). For 8 sec. period waves from west (Fig. 5), maximum height is found opposite Kabo (10.6 ft.) and a minimum is found south-west of Dona Paula (7.1 ft.) while a low wave height has been found near the present breakwater (7.7 ft.). The same trend follows for 6 sec. period waves from S.W. (Fig. 3) with maximum height (9.3 ft.) south-west of the strip between Kabo and Dona Paula and a minimum height (6.4 ft.) near the present breakwater.

For waves approaching the area from W.N.W. which is the predominant direction during the N.E. monsoon season, the refraction diagram (Fig. 6) shows that wave heights are generally low and the heights are less than or equal to 6.5 ft. in the entire Mormugao Bay.

Tides and Currents

The tide affects nearshore processes in two ways. Firstly because of the rise and fall of the water level and, secondly, because it gives rise to currents. So, tidal observations have particular importance in any development project near the shore such as maintenance and improvement of a harbour and its channel. The rise and fall of the tide is a continuing phenomenon and varies from day to day and from place to place. The tide at Mormugao harbour is predominantly semi-diurnal i.e., there are two tides per one lunar day (24.8 hrs.).

Average spring tide range in 1969 :

(i.e., Average High tide H.W.—Average Low tide L.W.)=6.8 ft.

The values corresponding to the recorded extremes for Mormugao harbour from 7 years records from 1894 to 1910 are :

Highest tide =7 ft. 6 inches,

Lowest tide =(1 ft. 4 inches).

Currents : Current measurements have been carried out by the Bhabha Atomic Research Centre (Nair *et al.*, 1968) at three stations off Mormugao during the period January 6-14, 1967. Measurements were carried out near the surface, mid-depths and near the bottom at hourly intervals for 25 hours at each of these stations. Mean depths obtained during these observations were 10.8 m, 11.69 m and 16.65 m at the three stations. According to this study the currents near Mormugao harbour are basically towards northwest throughout the tidal cycle except in areas very close to the mouth of the estuary.

These studies also revealed that at Mormugao the currents are weak with the order of the velocities of flow generally around 1.0 ft./sec., both in the vicinity of the port as well as outside in the Bay area. Since these observations refer to conditions in a particular month of the year namely January, they cannot be taken to be representative of the conditions of flow throughout the year.

Sediment Transport

(a) **Off-shore sediment motion :** In the off-shore zone the oscillating shearing stress and turbulence due to the orbital motion of the wave lift particles from the bed which are then carried along by currents. As pointed out earlier, the currents will be predominantly due to distribution of mass, tidal action and wind action, although in relatively shallow water the mass transport current caused by the waves can also move fine material.

Currents acting alone can move sediment if the velocity and shear stress are sufficiently great. Making some reasonable assumptions regarding the hydraulic roughness of the bed it is estimated (McNAMARA, Belledune point report, 1964) that the following particle sizes can be moved by the velocities indicated :

Particle diameter 0.1 mm - - velocities greater than 0.6 ft./sec.

Particle diameter 1.0 mm - - velocities greater than 1.7 ft./sec.

Particle diameter 10.0 mm - - velocities greater than 5.5 ft./sec.

These values which are approximate, were based on the Meyer-Peter and Muller sand transport formula and would apply to water depths in the order of 20 ft. to 40 ft.

For particles larger than sand the size of particles that can be put in motion increases as the velocity of the water becomes greater ; but for smaller particles like silt and clay the minimum velocity that is required in order to bring them into suspension does not decrease as the particle becomes smaller ; instead it increases. Thus it is easier to move sand off the bottom than silt and clay (Hjulstrom, 1939). Once a particle is in motion it continues to be transported until the velocity of the water decreases to a certain speed. This minimum transporting velocity of particles of sand size or larger size, seems to be about 30 percent less than the velocity needed to remove the particles from the bottom ; but for progressively smaller particles, the minimum transporting velocity becomes increasingly less in proportion to the velocity required to make the particles go into suspension.

An analysis of the bed samples collected at different locations of the Mormugao Bay to get an idea about the nature of the bed material, by the Central Water and Power Research Station (C.W. & P.R.S. Sp. Note No. 904) revealed that the material inside the Bay is mostly black sticky clay with a little amount of very fine silt, whereas that outside the Bay is of coarse nature consisting mostly of shells. Near the iron jetty the bed sample showed a median diameter of 0.06 mm. in the

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flocculated state. A visual inspection of the samples recently collected in the harbour area (C.W. & P.R. Station Sp. Note No. 939) indicated the presence of soft grey clay in the proposed approach channel. The inner basin also showed presence of clay. A mixture of shells and clay was observed in the bed samples collected between the present breakwater and 6 fm contour. The southern portion of the proposed channel consisted of brown sand.

So, from the velocities of currents both in the vicinity of the Port as well as outside in the Bay as observed by B.A.R.C. and from the analysis of bed samples, it can be seen that currents alone will move some sediment in this area and it will be towards north-west in January. It remains to be proven that currents in the Bay are directed towards north or north-west always throughout the year since the present available information on currents in this area is limited only for the month of January.

It has been shown experimentally (Bagnold, 1947) and mathematically (Longuet-Higgins, 1953) that a strong mass transport velocity occurs at the bed in the direction of wave propagation. It is strongest for small ratios of depth to wave length (Silvester, 1959). Hence, for a given depth, it is strongest for long period waves, and for a specific wave train, it increases as the depth decreases. Associated closely with the mass-transport effect is that of the differential forward and backward velocities of the water particles especially for waves in shallow water. It has been shown experimentally (Morison & Crooke, 1953) that in such cases the forward velocity under a crest may be twice the backward velocity under a trough. This greater forward velocity gives momentum and rotation to the sediment which causes a net forward movement (Manohar, 1955).

It is also pertinent to examine the minimum wave heights which will disturb sediments in the proposed approach channel and in the harbour. For an effective particle size of 0.1 mm. at a depth of 42 ft. the following conditions are estimated using the equation (Shepard, 1963)

$$U_m = \pi H/T \sinh \frac{2 \pi d}{L} \quad \dots (2)$$

where U_m is the maximum horizontal orbital velocity,

H is the wave height,

T is the wave period,

' d ' is the water depth and

L is deep water wave length.

Wave period (sec.)	4	5	6	7	8	9	10	11	11
Wave height (ft.)	6	5	4	3	3	3	2	2	1.5
Maximum Orbital velocity (ft./sec.)	0.34	0.76	0.92	0.85	0.95	1.0	0.72	0.76	0.57

From this it can be seen that generally waves of any height with periods less than 5 seconds and long waves less than 2.0 ft., height will not be able to lift sediment particles of diameter of 0.1 mm. or more.

From the wave climate and refraction diagrams it can be seen that waves from S.W., W.S.W. and west can lift significant quantity of sediment. Hence, taking into account the combined action of currents and waves it appears that there will be a net transport of sediment towards north or north-west in the off-shore zone in this area.

Radioactive tracer studies conducted by the Isotope Division, BARC in the Mormugao harbour area both in the fair weather season (Epen, 1967) and in the monsoon season (C.W. & P.R. Station Sp. Note No. 901) also revealed the north or north-westerly movement of the sea bed material in this area.

(b) *Inshore sediment motion*: As mentioned earlier, the transport of sediment in the zone shoreward of the breakers is mainly due to the effects of secondary currents generated by wave action. A train of waves moving along the

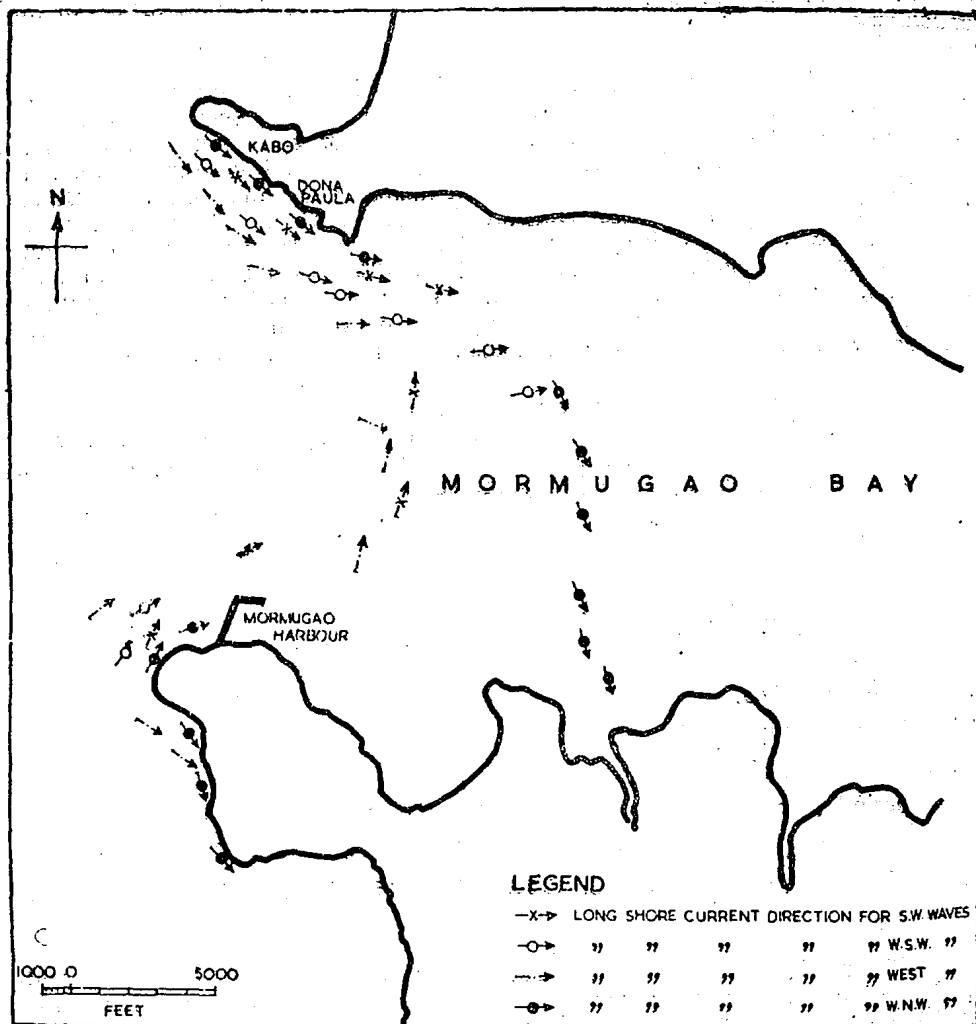


Fig. 7. Direction of Longshore currents for waves from different directions.

surface of the sea carries energy which is dissipated or converted into other forms in the process of breaking onshore. If waves approach a straight beach at right angles, the thrust due to the wave maintains a higher water level close to the beach than exists seaward of the breaker zone. When waves break at an oblique angle to the shore the component of wave thrust parallel to the shore drives a littoral current in the same direction, while the perpendicular component of thrust still causes a rise in the mean water level.

Littoral currents have been extensively investigated and methods of estimating the transport rate for straight coastlines have been devised by Putnam, Munk and Traylor (1949) and later modified by Inman and Quinn (1952). But, on an irregular coastline such as Mormugao Bay attempts to estimate transport rates from wave conditions have not given definitive results. However, using wave refraction diagrams the probable direction of sediment transport shown in Fig. 7 has been estimated from the angle between the wave ray and the normal drawn from the coast.

The refraction diagrams lead to the conclusion that the average littoral drift rate will be somewhat heavy due to the generally large wave heights in the S.W. Monsoon season all around the Bay area. It is evident from Fig. 7 that the sediment will accumulate within the Bay area throughout the year as the littoral currents are directed into the Bay both from its northern and southern sides, for all wave directions.

Conclusions

From this study it has been found that generally high waves will be experienced in this area from S.W. to west, particularly from W.S.W. during the south-west monsoon season. Minimum wave heights are found just north of the present breakwater and maximum wave heights are found near Dona Paula and Cabo regions. During the N.E. monsoon season when waves generally approach from W.N.W., waves are found to be comparatively small in the entire Mormugao Bay.

It has been found from the studies of BARC during certain periods of the year that in the off-shore region, the sediment movement is towards north or north-west. This may be due to the combined influence of currents and mass transport due to waves. It is felt, however, that a detailed current survey in this area throughout the year is essential to have a clear idea of the effect of currents on the sediment movements in this region. It has also been found from the wave refraction studies that the littoral drift is directed into the Mormugao Bay both from its northern and southern sides. Due to the irregular shape of this coast, it has not been possible to make a quantitative estimate of this littoral drift.

As the probable maximum wave height is to be taken into consideration while designing any breakwater, it appears that the area just north of the present breakwater is the suitable place for the location of the proposed breakwater in this Bay since wave heights are comparatively low at this place.

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