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Wave Conditions & Wave-induced Longshore Currents in the Nearshore Zone Off Krishnapatnam

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Wave conditions along Krishnapatnam coast (lat. 14°15'N and long. 80°07'E) have been evaluated and discussed. Wave refraction diagrams have been constructed for the average wave conditions and the wave energy distribution along the coast has been critically examined. Longshore currents due to oblique wave approach and due to wave breaker height variations have been computed separately and the character of the resultant currents in the nearshore zone has been established. Stability of the coastal inlet near Krishnapatnam in relation to the currents in the region is also discussed.

Krishnapatnam (lat. 14°15'N, long. 80°07'E) is a minor port situated on the east coast of India in Andhra Pradesh, about 20 km east of Nellore and about 200 km north of Madras. A small river Khandaleru joins the sea here, providing a stable coastal inlet which remains open during all seasons of the year. The Khandaleru river has an extensive catchment area in the hilly regions of southern Andhra and flows through a distance of about 110 km before joining the sea. Near the mouth, the river widens and takes a meandering course. The main flow near the mouth is actually through 2 channels coming from north and south respectively with a shallow island-like feature lying in between the channels. The Khandaleru river with an observed tidal excursion of about 30 km from the mouth forms an excellent backwater which is suitable for the development of a commercial port and a fishing harbour. But at present there is no activity in the Krishnapatnam port due to the bar formation near the mouth. At the entrance the depths are about 1 m below low water while a minimum depth of about 2 m is required for the vessels to enter the port. Further, heavy wave breaking near the mouth over the sand bar prevents even the small fishing boats operating through the entrance. Nevertheless it should be possible to dredge the bar near the mouth and maintain the required depths. But prior to this, it is essential that a thorough study of the character of various marine forces that generate coastal currents and the sediment movement near coast must be undertaken. This paper presents the results of a preliminary investigation on wave climate and associated phenomena along Krishnapatnam coast.

Wave-induced Nearshore Currents

Wave action is the primary source of energy available in the nearshore zone for various processes. Waves change considerably when approaching the shores. The character of the wave changes from a short wave to a long wave and the wave velocity very much depends on the water depth. The waves approaching the shore at an angle in shallow water undergo refraction. The part of the wave in deeper water moves more rapidly than the part in shallow water causing the crest to swing round parallel to the bottom contours. However, this process is not complete nearshore and waves break at a small angle to the shore. This gives rise to movement of water parallel to the shore, termed longshore current. This current especially is responsible for the longshore drift of the sediment on the beach and there is considerable interest in the mechanism of its generation and a number of theories have been proposed[1-6].

For a region with an irregular bottom topography, the wave rays (orthogonals) may sometimes converge or diverge at different points alongshore giving rise to variations in the wave breaker heights along the length of the shore[7].

Wave-induced longshore currents can, therefore, be generated within the nearshore zone by an oblique wave approach to the shoreline or by longshore variations in the wave breaker heights or by combinations thereof. The 2 current generating forces may reinforce or oppose each other depending on the wave refraction pattern for any particular stretch of the coast. Komar[8] has presented an analytical equation that combines the 2 generating mechanisms which will be used later in this paper to calculate the wave-induced longshore currents along Krishnapatnam coast.

Materials and Methods

For the Indian coasts there are hardly any wave recorders that are continually working with the result that there is no recorded wave data for the region under investigation. Hence the wave characteristics (height, period and direction) in deep waters reported by the ships plying in the neighbourhood of Krishnapatnam between latitudes 12°N to 17°N and longitudes 80°E to 85°E for the years 1967 to 1976 have been collected from the records of India Meteorological Department. The wave data have been analysed statistically and the frequencies of their occurrence from 16 directions equally divided from north through east to back are obtained. For each direction the wave heights and periods have been classified into 10 ranges. The average annual distribution of wave heights and periods are presented in Fig. 1.

In any region with the knowledge of deep water wave conditions, the wave characteristics before the wave breaks near the coast can be evaluated by constructing wave refraction diagrams. Wave refraction diagrams have been constructed[9] using the topographic survey charts off Krishnapatnam, published by the Naval Hydrographic survey of India (No. 3007). Wave heights in shallow water for different points along 2 fm line have been calculated using the equation[10]

$$\frac{H}{H_o}=\left[\frac{1}{2}\left(\frac{1}{n}\right)\left(\frac{L_o}{L}\right)\right]^{\frac{1}{2}}\left[\frac{b_o}{b}\right]^{\frac{1}{2}}$$

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

in which L_0 is the wavelength in deep water; L wave length in shallow water; h depth at the point of investigation; b_0 separation between wave rays in deep water; b separation in shallow water at the point of investigation; H_0 wave height in deepwater and H required wave height in shallow water.

The term $\left[\frac{1}{2}\left(\frac{1}{n}\right)\left(\frac{L_0}{L}\right)\right]^{\frac{1}{2}}$ has constant value along a fixed depth contour while $\left[\frac{b_0}{b}\right]^{\frac{1}{2}}$ varies along a depth contour and is generally referred to as the refraction factor K.

For the breaking waves, wave heights at the point of breaking have been calculated by a different relation[10]

$$\frac{H_b}{H_o}=\frac{1}{3.3\,(H_o/L_o)^{1/3}}\left(\frac{b_o}{b}\right)^{1/3}$$

where H_b is the wave height at the point of breaking. The term $\left(\frac{b_0}{b}\right)^{1/3}$ is the refraction function (K_b) at the point of wave breaking and varies for different points along the coast.

As a result of wave refraction the direction of wave travel changes as the wave approaches the coast. The change in the direction of wave travel at any point is usually given by the direction function α, representing the angle between the wave ray at the point and the coast normal. The α may vary along a depth contour depending on the wave refraction pattern. The wave breaker heights and the α for different points along the coast have been determined as above from the wave refraction diagrams. The longshore currents are then calculated making use of the following relation due to Komar[8]

$$\bar{V}_1=2.7\,u_m \sin\alpha_b \cos\alpha_b-\frac{\pi(2)^{1/2}}{C_f\,\gamma_b^3}\left[1+\frac{3\,\gamma_b^2}{8}-\frac{\gamma_b^2}{4}\cos^2\alpha_b\right]u_m\frac{\partial H_b}{\partial y}$$

where $\bar{V}_1$ is longshore current velocity; u_m maximum value of breaking wave orbital velocity given by $(2\,E_b/\rho h_b)^{\frac{1}{2}}$ in which E_b is the wave breaker energy; h_b is the water depth at breaking and ρ is the density of sea water; α_b direction function at the point of breaking; C_f drag coefficient taken as 0.017 from Longuet-Higgins[4]; γ_b a constant that depends on the deep water wave steepness and on the beach slope. For Krishnapatnam beach a value of 0.8 has been selected from the curves of Longuet-Higgins[4], $\frac{\partial H_b}{\partial y}$ represents the longshore variation in breaker wave heights along the coast.

The term $2.7\,u_m \sin\alpha_b\cos\alpha_b$ in the above equation for $\bar{V}_1$ represents the longshore current generated by an oblique wave approach while the term $\frac{\pi(2)^{1/2}}{C_f\,\gamma_b^3}\left[1+\frac{3\,\gamma_b^2}{8}-\frac{\gamma_b^2}{4}\cos^2\alpha_b\right]u_m\frac{\partial H_b}{\partial y}$ represents the longshore current due to variations in the wave breaker heights alongshore. If $\frac{\partial H_b}{\partial y}$ is positive, then the driving forces are opposed to one another and the current is reduced. If $\frac{\partial H_b}{\partial y}$ is negative then the driving forces act together in the same direction and the current generated would be larger than produced by the 2 driving forces acting individually.

Results and Discussion

Wave climate off Krishnapatnam—A large percentage of waves in deepwater are from SW and NE directions (Fig. 1). A relatively small percentage of waves are also observed from SE and E while the waves from W and NW are almost negligible. But the swell from SW or S do not reach Krishnapatnam coast due to the particular orientation of the coast line. The

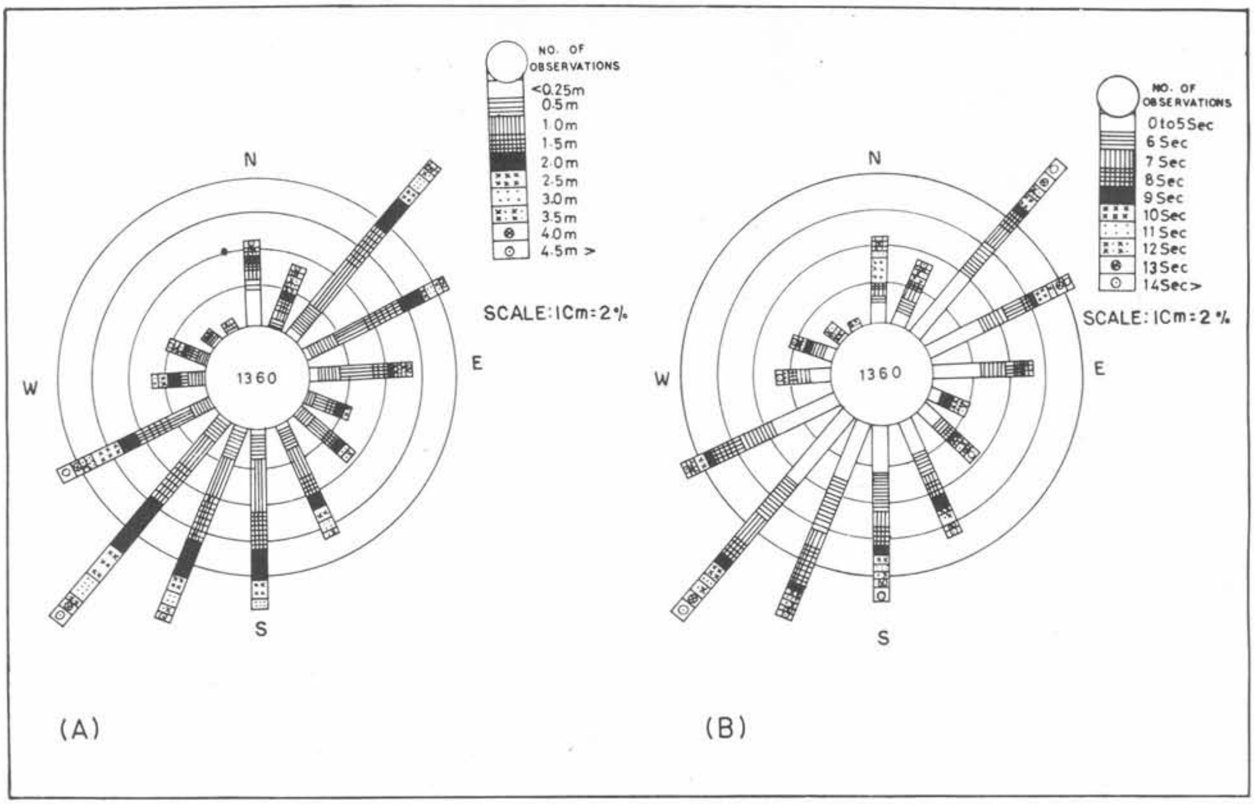

Fig. 1—Average annual wave Rose for (A) wave direction and height and (B) wave direction and period

shores of Krishnapatnam are thus exposed only to the waves coming from NE, E and SE. The wave heights for waves coming from NE, E and SE seem to vary between 0.5 and 2 m on the average, the most frequent wave heights being around 1 m. Exceptionally high waves of the order of 4 m or more also have been recorded but they are very rare and might possibly be related to the cyclones in the Bay of Bengal. The wave periods vary commonly between 5 and 12 sec, the most frequent waves being of 5 sec period. Exceptionally high periods of the order of 14 sec or more are also observed sometimes which again might be related to the cyclones in the Bay of Bengal. The weighted mean of the wave periods is, however, around 7 sec.

Wave refraction and longshore currents—Wave refraction diagrams have been constructed for 7 sec period waves approaching the coast from NE, E and SE. For NE waves [Fig. 2(A)] the wave rays designated as A, B, C, D, ..., start from northeast corner, undergo refraction and terminate near the coast where the waves break. Since the energy between any adjacent wave rays is constant, there is a concentration of energy at points when the wave rays converge, resulting in increased wave heights. The computed wave heights in metres between the successive wave rays are entered in the wave refraction diagrams along 2 fm line. A number of wave convergences and divergences are generally witnessed along the coast. About 2 km south of the entrance channel there is a convergence between the wave rays B and C giving rise to wave heights as large as 2 m at the 2 fm line. Similarly the wave heights are large (2.4 m) just at the northern side of the entrance due to the sharp convergence of the wave rays F and G. The wave heights at all other points along the coast are around 1 m. The values of wave refraction function K [Table 1(i)] at 2 fm line for almost all the wave rays are less than unity except for the zones of convergence where K values exceed unity. The α varies between 8° and 16°, the maximum values being near the entrance. The orientation of the wave rays on the whole indicates a mean longshore component of energy directed towards south.

Distribution of wave-induced longshore currents computed on the basis of wave refraction for NE waves is shown in Fig. 2(B), while the computed current strengths are presented in Table 2(i). The contributions due to the oblique wave approach and the wave height variations alongshore are shown separately in columns 2 and 3 of the Table while the resultant currents are given in 4th column. Distribution of currents is discussed with reference to a number of points alongshore numbered (1), (2), (3), etc. The currents due to NE waves seem to be maintained mainly by the oblique approach since the currents in general are

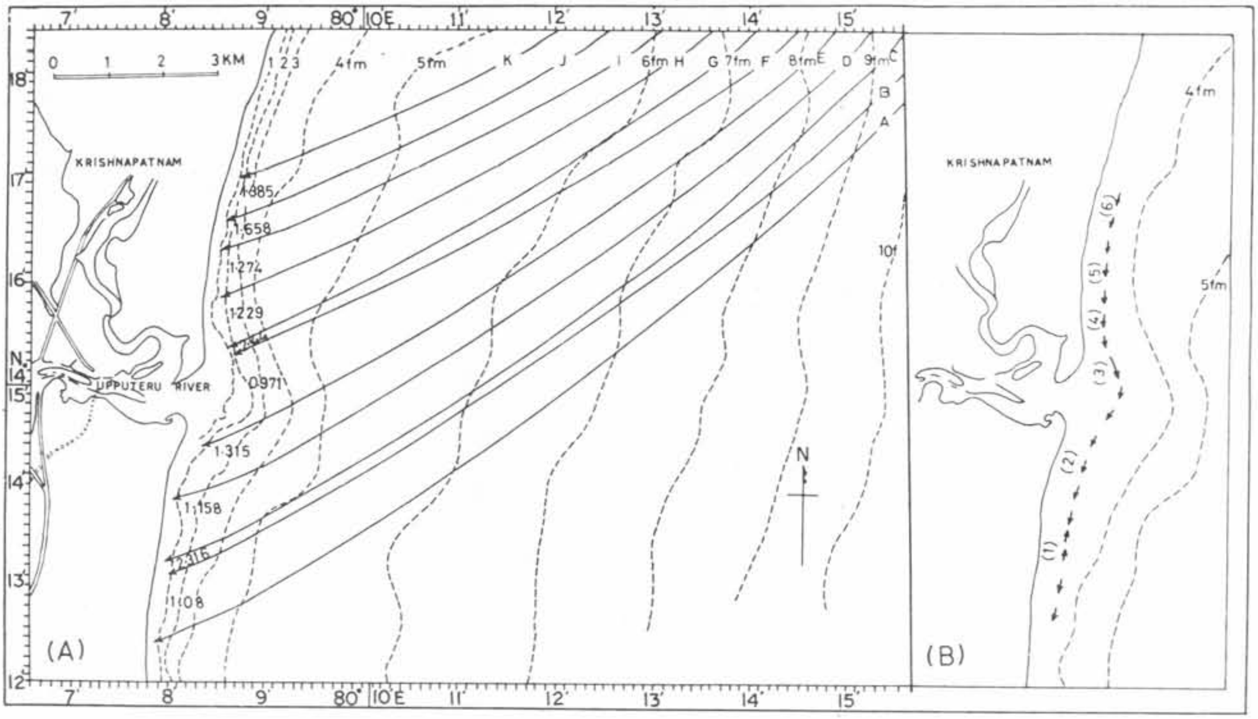

Fig. 2—(A) Wave refraction diagram for NE waves [Period 7 sec, deep water wave height = 1.6375m. Solid lines represent wave orthogonals and broken lines represent bottom contours. Numbers depict the wave heights in meters at the corresponding depth]. (B) Direction of longshore current for NE waves

directed towards south almost along the entire coast. However, between (1) and (2) a weak northerly current due to wave height variations seems to oppose the main southerly current where a small rip current may be generated. Just at the northern side of the entrance (point 3), there are strong currents of the order of 2 m/sec where the contributions due to wave height variations and angle of wave approach seem to add together. These currents can easily move the sediments across the mouth and keep the entrance open during the season of NE waves (November to January). The current strengths at all other points are around 0.8 m/sec. Due to the strong currents in this season, no silting of the mouth is likely to occur.

Fig. 3(A) shows the wave refraction pattern for the E waves. The general bending of wave rays indicate a northerly component of longshore wave energy. Distribution of wave rays along the coast is by no means uniform. Within a distance of about 2 km south of the entrance channel, 3 alternate zones of convergence and divergence are found. Wave heights at the zones of wave convergence are about 1.1 to 1.2 m while at the zones of divergence they are only about 0.6 to 0.7 m. There is a strong zone of convergence again just at the northern side of entrance where the wave heights are as large as 1.5 m. Distribution of wave energy towards north of the entrance channel is almost uniform with wave heights between 0.7 and 0.8 m except for a zone of convergence between wave rays P and Q when the wave heights are about 1.2 m. The wave refraction functions at 2 fm line for E waves are generally between 0.8 and 0.9 except near the entrance channel and the zones of convergence where K values are more than unity. The α seems to vary in general between 0.5° and 3° for E waves [Table 1(ii)].

The current distribution due to E waves are presented in Fig. 3(B), while the current strengths are given in Table 2(ii). South of the entrance channel the wave height variations alongshore seem to control the currents to a large extent. Between (1) and (3), a system of opposing currents related to the alternate zones of convergence and divergence is seen. The southerly current are however very weak (0.05 m/sec) while the northern current dominates (0.8 m/sec). Between (3) and (5), there is a system of opposing currents which may give rise to a rip current around the point (4). Just north of the entrance channel there are strong currents (1.1 m/sec) directed towards north. Further north of this point there are weak northerly currents (0.25 m/sec). The prevailing wave convergence at the entrance may not permit further silting of the entrance channel and the mouth will be open during the season of easterly waves.

Fig. 4(A) shows the wave refraction pattern for the waves coming from SE. The disposition of the wave rays nearshore indicates a northerly component of

Table 1—Values of Wave Refraction Function, Direction Function and Wave Height at 2 fm Line for (i) NE Waves, (ii) E Waves and (iii) SE Waves

Wave ray	Refraction function K	Direction function α in deg.	Wave height m
(i) NE waves			
A		8	
	0.617		1.08
B		12	
	1.323		2.316
C		14	
	0.661		1.158
D		14	
	0.751		1.315
E		15	
	0.555		0.971
F		15	
	1.394		2.44
G		13	
	0.702		1.229
H		10	
	0.728		1.274
I		10	
	0.947		1.658
J		14	
	0.791		1.385
K		16	
(ii) E waves			
A		1	
	1.118		1.082
B		1	
	1.261		1.22
C		0.5	
	0.751		0.73
D		5	
	1.045		1.011
E		2	
	1.118		1.082
F		3	
	0.707		0.684
G		0.5	
	1.208		1.17
H		0.5	
	1.118		1.082
I		6	
	0.986		0.954
J		1	
	1.614		1.59
K		0.5	
	0.959		0.93
L		2	
	0.777		0.752
M		1	
	0.837		0.81
N		2	
	0.805		0.78
O		1	
	0.798		0.772
P		0.5	
	1.323		1.28
Q		0.5	
	0.959		0.94
R		2	
	0.791		0.77
S		1	
(iii) SE waves			
A		12	
	0.986		0.892
B		5	
	0.986		0.892
C		5	
	1.08		0.977
D		5	
	1.046		0.947
E		11	
	1.118		1.011
F		9	
	1.015		0.917
G		9	
	1.015		0.917
H		11	
	1.08		0.978
I		7	
	0.872		0.789
J		7	
	1.261		1.141
K		6	
	0.791		0.715
L		6	
	1.118		1.011
M		2	
	1.08		0.978
N		4	
	1.323		1.196
O		7	
	0.845		0.772
P		8	
	1.096		0.991
Q		4	
	0.739		0.669
R		4	
	1.118		1.011
S		6	
	0.688		0.622
T		5	

alongshore wave energy. Distribution of wave energy is almost uniform along the entire stretch of the coast. However, a small zone of convergence is noticed again at the northern side of the entrance. It is interesting to note that the wave convergence at this point is more or less a permanent feature that occurs for waves from all the directions. The wave heights on the average are about 0.9 m during this season. About 3 km north of the entrance there are 2 zones of large divergence where the wave heights are relatively small. The K values and α values for different zones along 2 fm line are shown in Table 1 (iii).

For SE waves the longshore current [Fig. 4(B)] appears to be predominently towards north and is controlled largely by the direction of wave approach. The average current velocity [Table 2(iii)] is around 0.7

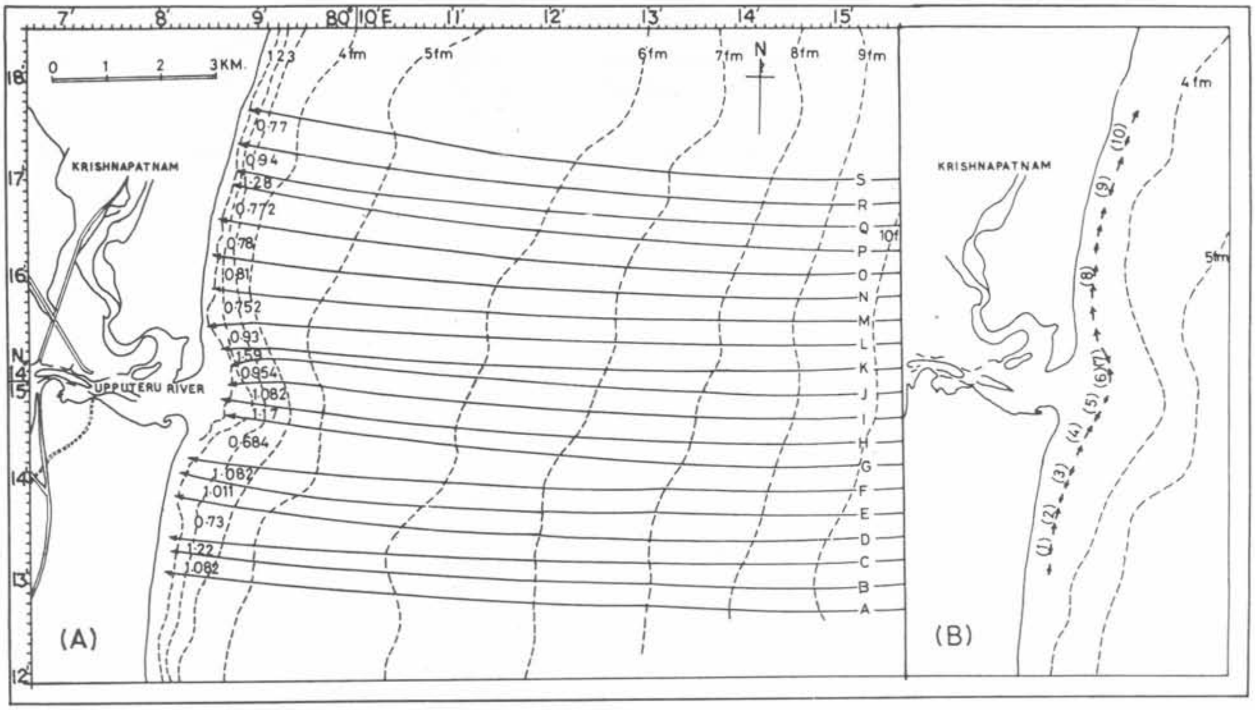

Fig. 3—(A) Wave refraction diagram for E waves [Period 7 sec, deepwater wave height = 0.868m. Other details same as in Fig. 2A]. (B) Direction of longshore current for E waves

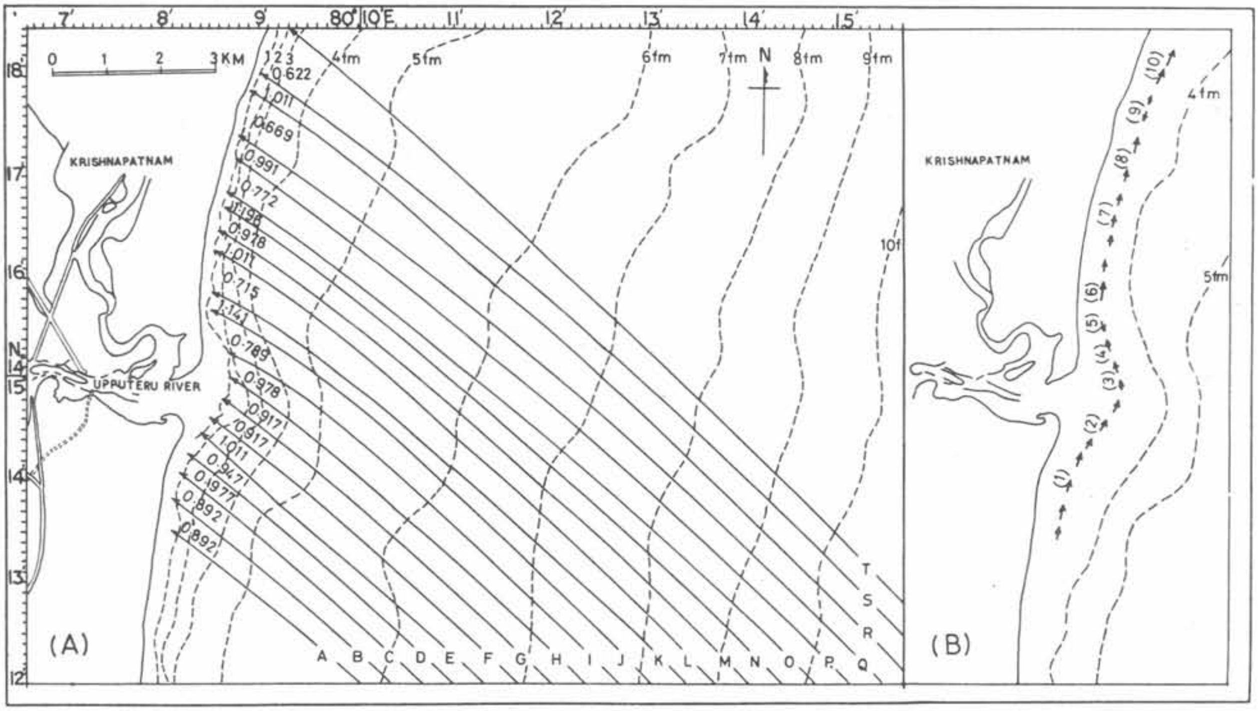

Fig. 4—(A) Wave refraction diagram for SE waves [Period 7 sec, deepwater wave height = 0.9124m. Other details same as in Fig. 2A]. (B) Direction of longshore current for SE waves

Table 2—Values of Wave-induced Currents due to (i) NE Waves (ii) E Waves and (iii) SE Waves for Different Points Alongshore

Point location	Currents due to oblique m/sec	Currents due to height variation m/sec	Resultant current m/sec	Direction towards
		(i) NE waves		
(1)	1.086	1.134	0.048	N
(2)	1.134	0.286	0.848	S
(3)	1.1	1.069	2.169	S
(4)	0.81	0.298	0.512	S
(5)	0.956	0.462	1.418	S
(6)	1.195	0.253	0.512	S
		(ii) E waves		
(1)	0.038	0.427	0.389	S
(2)	0.214	0.661	0.875	N
(3)	0.175	0.226	0.051	S
(4)	0.172	0.359	0.531	N
(5)	0.036	0.51	0.474	S
(6)	0.258	0.607	0.865	N
(7)	0.038	1.22	1.182	S
(8)	0.105	0.157	0.262	N
(9)	0.073	0.974	0.901	S
(10)	0.108	0.365	0.473	N
		(iii) SE waves		
(1)	0.525	0.075	0.45	N
(2)	0.643	0.133	0.776	N
(3)	0.64	0.144	0.496	N
(4)	0.486	0.359	0.845	N
(5)	0.46	0.462	0.002	S
(6)	0.42	0.591	1.011	N
(7)	0.287	0.269	0.018	N
(8)	0.41	0.225	0.635	N
(9)	0.238	0.262	0.024	S
(10)	0.369	0.392	0.761	N

m/sec directed towards north. At points (5) and (9) contributions due to the wave height variations seem to dominate resulting in southerly currents which oppose the north flowing main current. This may give rise to small rip current around (5) and (9). The currents are fairly strong near the entrance and could move the material across the mouth so that no further silting is likely to take place even during the season of SE waves.

Wave-induced currents along Krishnapatnam coast seem to be fairly strong during all seasons of the year. During northeast monsoon season, the currents are especially strong due to the combined effect of oblique wave approach and the wave height variation along the coast. The breakers on the average are of the order of 1 m, but just at the northern side of the entrance there seem to be heavy breakers due to the convergence of wave rays at this point. The northern side of the entrance is likely to be open during all seasons of the year and maintain larger depths as well. Further silting near the mouth is not likely to happen and the existing minimum depth may be maintained throughout the year. This is because of a general convergence of wave rays near the mouth. If the entrance of the mouth is deepend to facilitate navigation then the refraction patterns may change considerably resulting in the siltation at the entrance. If the tidal currents are sufficiently strong then there may not be much silting at the entrance and navigable depths might be maintained with some occasional dredging near the mouth. The present conclusions are based only on the studies of wave conditions and wave-induced currents off Krishnapatnam and should be considered as limited to that extent. Studies on the tidal currents, river currents and wind currents have to be undertaken simultaneously along with the wave studies for a better understanding of the problem.

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