Impact of Wave Dynamics on Shoreline Changes Due to Proposed Reclamation by Numerical Models in Tapi Estuary for M/S EBTL, Hazira

Komal S. Vighe, Rahul Sawant, and L. R. Ranganath

Abstract Tapi estuary near Surat city in Gujarat has vital importance due to its conducive hydrodynamic aspects. This led to development of large number of coastal infrastructures. The river bifurcates into two branches, viz. main Tapi river channel and Dumas creek. Several companies like Essar, L&T, RIL, NTPC, KRIBHCO, ONGC, MAGDALA AND GUJARAT AMBUJA CEMENT LTD have come up along the banks of Tapi channel. All ports have developed their captive jetties and successfully harnessed the power of ports to propel their economic growth. Port development in Tapi estuary requires intermittent dredging in channels and the estuary consists of many channels. Developing a deep channel would involve considerable capital dredging and necessitate maintenance dredging in future. Essar Bulk Terminals Limited (EBTL) has developed all weather Deep-Draft Terminal which is advantageously located on the western shore of Tapi Estuary that has come up with a very ambitious proposal of developing a common navigational channel for all ports by deepening the Tapi channel and Dumas creek. The proposal includes widening and deepening of the channel to 12 m depth, and the dredged material is intended to reclaim area between both the channel which comprises Kadia bet and Mora bet with the intention to develop a port city. To check the impact of proposed reclamation from wave perspective wave transformation, wave tranquility and changes in shoreline studies carried out and described in this paper. MIKE21-SW and BW models are used for wave studies and LITDRIFT and LITLINE modules of LITPACK that are used for shoreline evolution studies. The model studies indicated that the proposal is feasible from the wave tranquility and littoral drift aspects.

Keywords Mathematical model · Wave tranquility · Littoral drift · Wave disturbance

K. S. Vighe (✉) · R. Sawant · L. R. Ranganath
Central Water and Power Research Station, Khadakwasla, Pune 411024, India
e-mail: vighe.ks@cwprs.gov.in

P. V. Timbadiya et al. (eds.), *Coastal, Harbour and Ocean Engineering*, Lecture Notes in Civil Engineering 321, https://doi.org/10.1007/978-981-19-9913-0_9

1 Introduction

Essar Bulk Terminals Limited (EBTL), an-all weather, Deep-Draft Terminal is advantageously located on the western shore of Tapi Estuary along the western side of Hazira Peninsula in Gulf of Khambhat. In May 2014, MoEF gave EC (Environment Clearance) for extending the channel from 6.2 km to 17.6 km, deepening from 12 to 16 m and widening of channel to 300 m with two additional TC (Turning Circle), reclamation of 334 ha south of mangrove. Till date channel is dredged to 12 m below CD (chart datum). Two additional TCs have not been undertaken so far. With respect to reclamation of 350 ha, reclamation is still ongoing. Currently, the terminal is operating 5 Berths with a total Quay length of 1,450 m with operational draft ranging 12 m to14 m. The main navigation channel is 7 km long marked with beacons and buoys having a depth of 12 m below CD with width of 300 m and turning circle radius of 600 m (Fig. 1). EBTL has a proposal for the development of Port City in the Tapi estuary with reclamation of total 5114 ha area. In the original layout, the Dumas channel (800 m wide × −14 m deep) on East side of the proposed reclamation ended in the shallow depth, i.e., at −5 m depth contour, but it has to be extended up to −14 m depth contour which is about 15 km southward in the offshore. It is not advisable for navigation of vessels and sedimentation point of view due to occurrence of cross currents perpendicular to the channel and also the channel passing nearer to Purna River confluence. Hence, the original proposal in consultation with EBTL has been modified by restricting the channel depth to −12 m and extending up to −12 m depth contour in south-west direction into the offshore for hydrodynamic studies, and the same proposal has been considered for wave tranquility, and littoral drift studies are shown in Fig. 2.

Fig. 1 Location plan of Essar port

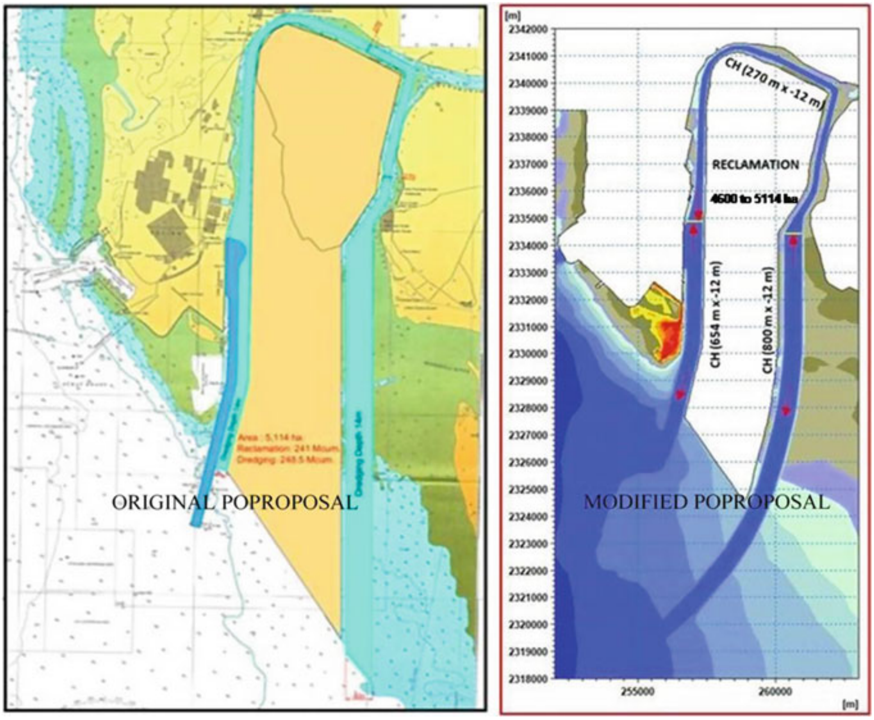


Fig. 2 Layout of the proposed reclamation (original and modified)

To check the impact of proposed reclamation from wave perspective wave transformation, wave tranquility and changes in shoreline studies carried out and described in this paper with different module of MIKE21 software.

2 Site Conditions

2.1 Wave Climate in Deep Sea

To study wave tranquility, nearshore wave data is essential. Instrumentally observed wave data at the site over a period of several years, if available, is best suited for this purpose. However, if such data are not available, the nearshore wave climate can be obtained by mathematically transforming offshore wave data to the nearshore location. For this purpose, the India Meteorological Department (IMD) reported wave data observed by ships plying in the offshore region between latitude 20–25° N and longitude 65–75° E from 1986 to 2000 for 15 years were analyzed. This wave data information was considered at the offshore end of the model limits. The frequency

Table 1 % Occurrence of wave height and direction off Hazira for entire year (Jan–Dec)

Wave ht (m)	0–0.5	0.5–1	1–1.5	1.5–2	2–2.5	2.5–3	3–3.5	3.5–4	4–4.5	Total
Direction (°N)										
22.5	0.00	1.33	0.58	0.58	0.42	0.00	0.00	0.00	0.08	3.00
45	0.00	0.42	1.17	0.83	0.25	0.25	0.08	0.17	0.33	3.50
67.5	0.00	0.33	0.58	0.92	0.33	0.17	0.17	0.17	0.00	2.67
90	0.00	0.25	0.92	0.92	0.50	0.58	0.42	0.00	0.00	3.59
112.5	0.00	0.17	0.25	0.25	0.17	0.00	0.00	0.00	0.00	0.83
135	0.00	0.33	0.25	0.00	0.08	0.00	0.00	0.00	0.00	0.67
157.5	0.00	0.08	0.25	0.42	0.08	0.00	0.00	0.00	0.08	0.92
180	0.00	0.67	1.00	1.17	0.75	0.42	0.42	0.25	0.25	4.92
202.5	0.00	0.33	0.83	0.92	1.42	1.75	0.67	0.58	0.50	7.01
225	0.00	0.75	1.92	2.92	3.17	3.67	2.09	1.00	2.42	17.93
247.5	0.00	0.75	2.00	2.50	2.50	2.25	3.67	1.42	2.42	17.51
270	0.00	1.25	4.09	3.17	2.17	0.75	1.50	0.42	1.83	15.18
292.5	0.00	0.83	2.42	1.33	0.67	0.33	0.25	0.00	0.75	6.59
315	0.00	0.92	1.67	1.17	0.67	0.17	0.08	0.00	0.33	5.00
337.5	0.00	0.83	1.33	0.50	0.67	0.17	0.08	0.00	0.00	3.59
360	0.00	1.67	1.67	0.92	1.00	0.58	0.75	0.08	0.42	7.09
Total	0.0	10.9	20.9	18.5	14.8	11.1	10.2	4.1	9.4	100.0

distribution of wave heights from different directions during the entire year for the above offshore wave data is given in Table 1. A corresponding wave rose diagram is shown in Fig. 3.

The input wave directions and wave height in deep water are obtained from Table 1 and mentioned in Table 2. These deep water wave data were transformed using the mathematical model MIKE21-SW to get near shore wave climate near the harbor entrance.

3 Modeling Techniques

The mathematical models, viz. MIKE21-SW (wave transformation and wave propagation for existing condition) and MIKE21-BW (wave tranquility for proposed condition) were utilized for wave tranquility studies, LITDRIFT module of LITPACK software for littoral drift distribution and LITLINE module used for assessment of shoreline changes. Brief descriptions of these models are given below.

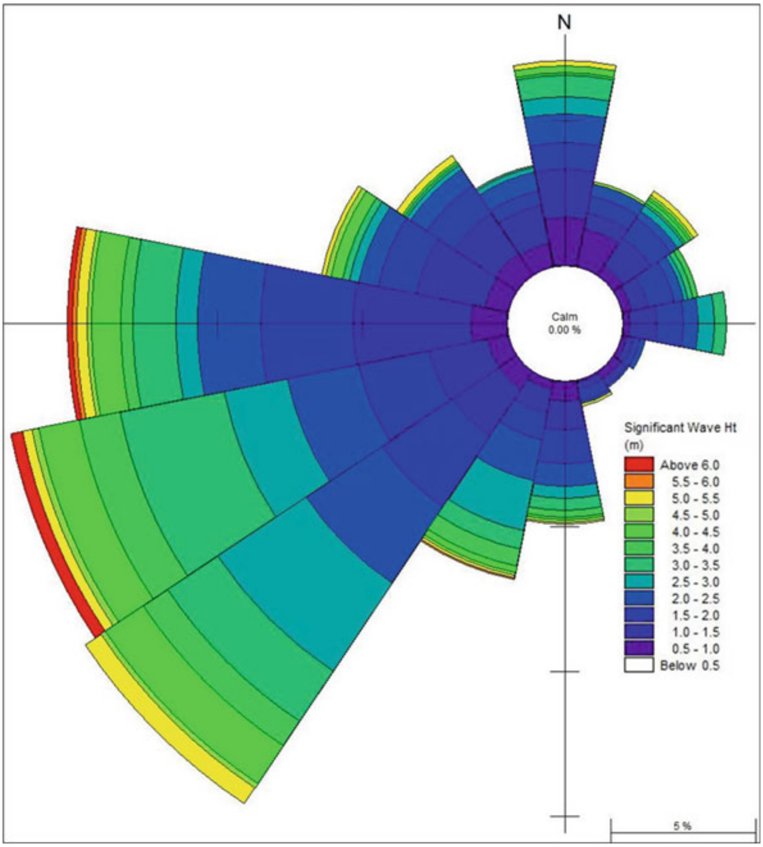


Fig. 3 Offshore rose diagram for entire year

Table 2 Input wave condition

Offshore direction (°N)	Wave height (m)	Offshore direction (°N)	Wave height (m)
22.5	2.5	202.5	4
45	4	225	4.5
67.5	3.5	247.5	4.5
90	3	270	4.5
112.5	2.5	292.5	4.5
135	2.5	315	4
157.5	2.5	337.5	3
180	4	360	4

3.1 MIKE21-SW Model

As waves travel from deep sea to shallow coastal waters, they undergo changes in direction and height due to the processes of refraction and shoaling. The computation of wave transformation from deep to shallow coastal waters was carried out using MIKE21-SW model. MIKE21-SW is a state-of-the-art third generation spectral wind wave model based on unstructured mesh. The model simulates the growth, decay and transformation of wind generated waves and swells in offshore and coastal areas. It takes into account refraction and shoaling of waves. It also includes physical phenomena of wave growth by action of wind, dissipation due to white-capping, dissipation due to bottom friction, and dissipation due to depth induced wave breaking. The effects of wave-current interaction, non-linear wave-wave interaction, time-varying water depth and diffraction are also included within the model. The model is based on flexible mesh which allows for coarse spatial resolution for offshore area and high-resolution mesh in shallow water and at the coastline [3].

3.2 MIKE21-BW Model

Mathematical model MIKE21-BW was used for studying the wave disturbance in the harbor area. The model is based on time dependent Boussinesq equations of conservation of mass and momentum obtained by integrating the three-dimensional flow equations without neglecting vertical acceleration. They operate in the time domain, so that irregular waves can be simulated. The frequency dispersion is included in the flow equations by taking into account the effect of vertical acceleration or the curvature of stream lines on pressure distribution. The model simulates the processes of shoaling, refraction, diffraction from breakwater tips and bed friction. It also takes into account partial reflections from the boundaries, piers and breakwaters [4].

3.3 LITPACK Model

LITPACK software is used for computation of littoral drift and simulation of shoreline changes due to construction of the breakwaters or any development on the shoreline, or due to any break in the sediment movement such as in the case of inlet. LITPACK is a professional engineering software package for the modeling of non-cohesive sediment transport in waves and currents, littoral drift, coastline evolution and profile development along quasi-uniform beach.

The LITDRIFT module simulates the cross-shore distribution of wave height, setup and longshore current for an arbitrary coastal profile. It provides a detailed deterministic description of the cross-shore distribution of the longshore sediment transport for an arbitrary bathymetry for both regular and irregular sea states. The longshore and cross-shore momentum balance equation is solved to give the cross-shore distribution of longshore current and setup. Wave decay due to breaking is modeled, either by an empirical wave decay formula or by a model of Battjes and Janssen.

LITDRIFT calculates the net/gross littoral transport over a specific design period. Important factors, such as linking of the water level and the beach profile to the incident sea state, are included.

LITLINE simulates the coastal response to gradients in the longshore sediment transport capacity resulting from natural features and a wide variety of coastal structures. LITLINE predicts the coastline evolution by solving a continuity equation for the sediment in the littoral zone. The influence of structures, sources and sinks is included. With jetties and breakwaters, the influence of diffraction on the wave climate is also included [5].

4 Wave Transformation from Deep Water to Nearshore Region

In the absence of measured wave data near the proposed site of development, the nearshore wave climate at EBTL Hazira was obtained by transforming the ship observed deep water wave data using MIKE21-SW Model. Model area considered for MIKE21-SW model is shown in Fig. 4. Bathymetry in the model region of about 410 km by 260 km area was discretized using unstructured mesh. The model was run to obtain nearshore wave climate at the Inshore Point in (−) 20 m depth contour (Fig. 4). The wave directions and ratio of wave heights at (−) 20 m depth to deep water wave height, with different directions of wave incidence at the offshore boundary are given in Table 4. This transformation was applied to deep water wave data (Table 4) to obtain frequency distribution in (−) 20 m depth for entire year for the above offshore wave data which is given in Table 5. Corresponding wave rose diagrams are presented in Fig. 5. On the basis of wave transformation studies, it is clear that waves are incident from 180° N direction to 247.5° N at (−) 20 m depth. The following input wave conditions, given in Table 6, were considered for simulation of wave propagation in the proposed harbor using MIKE21-BW model and for existing condition using MIKE21-SW model at (−) 20 m depth.

5 Wave Tranquility Studies for the Existing and Proposed Condition

Wave propagation inside the harbor for existing condition was simulated using MIKE21-SW model for input wave conditions as given in Table 6. The bathymetry

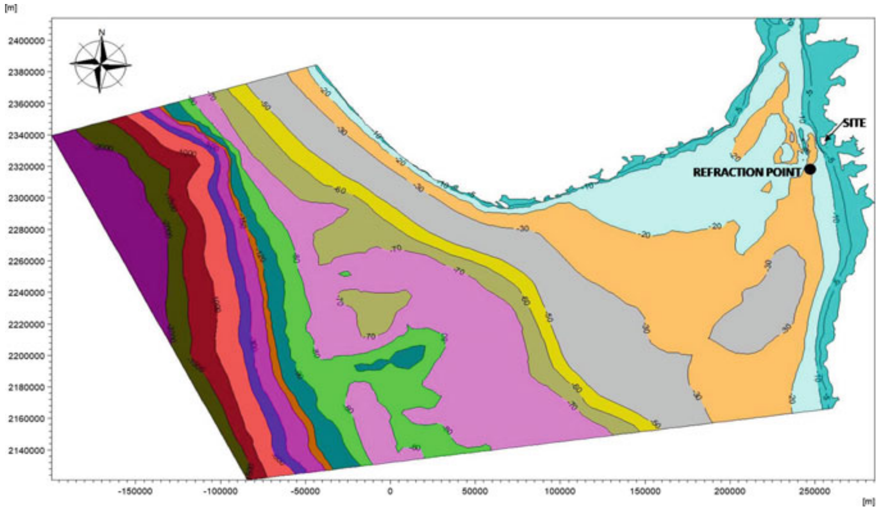


Fig. 4 Bathymetry for the wave transformation studies

Table 4 Wave transformation from deep to shallow coastal water

Sr. No	Offshore direction (Deg. N)	Inshore direction (Deg. N)	Wave height ratio (Hi/Ho)
1	90	181.465	0.0034
2	112.5	182.337	0.0177
3	135	184.626	0.0622
4	157.5	187.094	0.1832
5	180	191.105	0.4196
6	202.5	206.803	0.7099
7	225	224.817	0.5516
8	247.5	242.110	0.4240

Hi = Wave height at Inshore Point Ho = Offshore wave height

Table 5 % Occurrence of wave height and direction in Hazira for entire year (Jan–Dec)

Wave ht (m)	<0.5	<1	<1.5	<2	<2.5	<3.0	<3.5	<4.0	<4.5	Total
Direction (°N)									Calm	32.27
180	1.79	2.39	1.29	0.20	0.10	0.00	0.00	0.00	0.00	5.78
202.5	0.40	1.00	2.79	2.09	1.49	0.30	0.10	0.20	0.00	8.37
225	0.90	5.78	8.17	3.69	2.09	0.80	0.00	0.00	0.00	21.41
247.5	10.0	10.0	9.16	1.99	0.40	0.50	0.00	0.00	0.00	32.17
Total	13.1	19.2	21.41	7.97	4.08	1.59	0.10	0.20	0.00	100.0

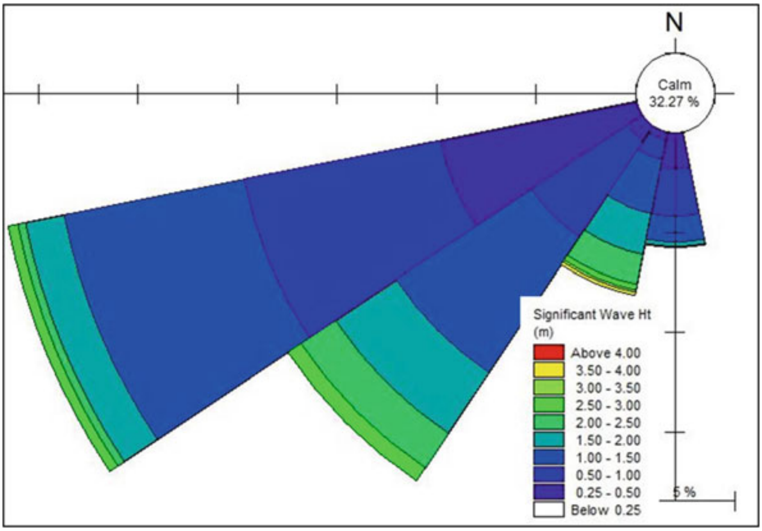


Fig. 5 Inshore rose diagram for entire year

Table 6 Design significant wave heights for wave tranquility studies

Wave direction (°N)	Significant wave height (m)
180	2.5
202.5	4
225	3
247.5	3

of area of 14 km × 24 km for MIKE21-SW model was prepared from C-MAP database and the nearshore bathymetry provided by authority as shown in Fig. 6. The plots for wave height distribution for the existing condition for predominant directions (SW and WSW) are shown in Fig. 7. The bathymetry for MIKE21-BW model for proposed condition was prepared from C-MAP database and the nearshore bathymetry provided by authority. Area of 15 km × 28 km was discretized with a grid of 5 m × 5 m as shown in Fig. 6. Simulation was carried out for tidal level + 4.5 m corresponding to MSL. The plots for wave height distribution and propagation for the proposed condition for predominant directions (SW and WSW) are shown in Fig. 8a, b.

It is seen that the waves are unable to reach the site hence the site of development will be tranquil considering the tranquility limit of 0.5 m. The wave tranquility studies to assess the wave tranquility at the site with proposed reclamation were carried out with the same predominant directions.

It is seen that the waves are unable to reach the site hence the site of development will be tranquil considering the tranquility limit of 0.5 m. The waves do not reach the site through the channel. The results indicate that, at the jetty location, the wave

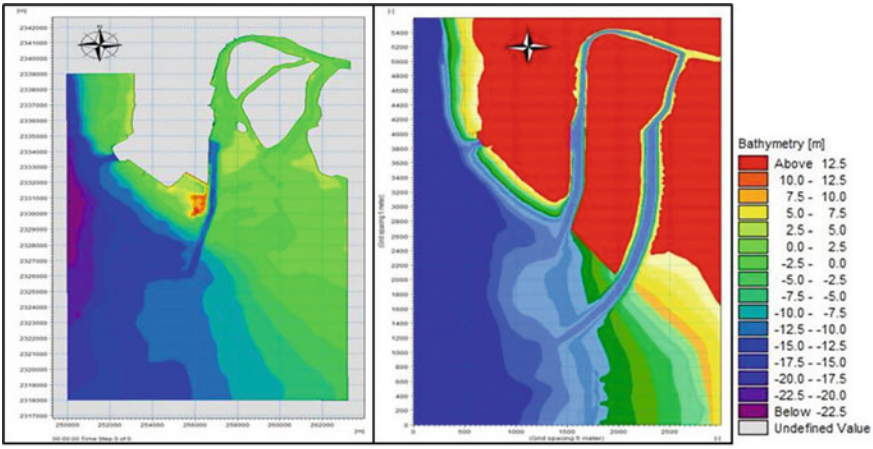


Fig. 6 Bathymetries for the wave tranquility studies for existing and proposed condition

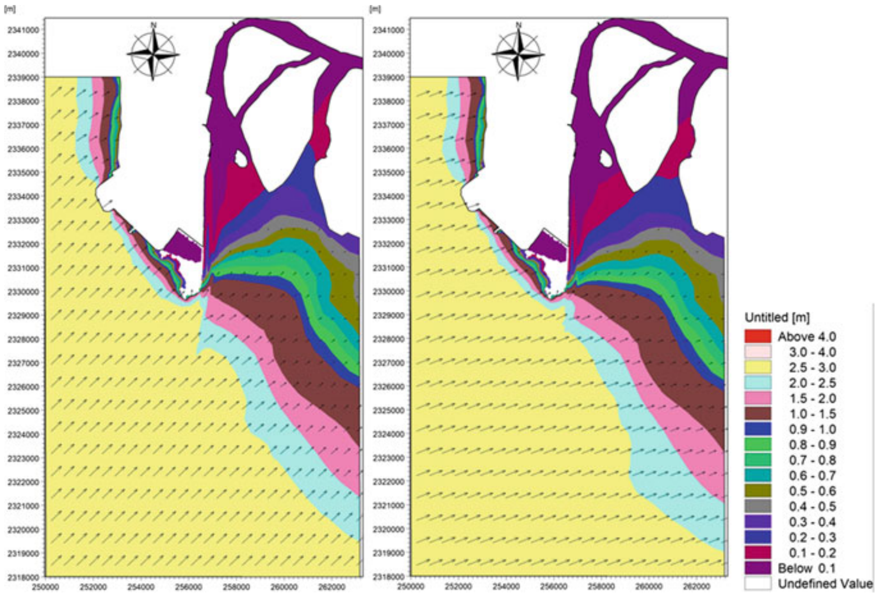
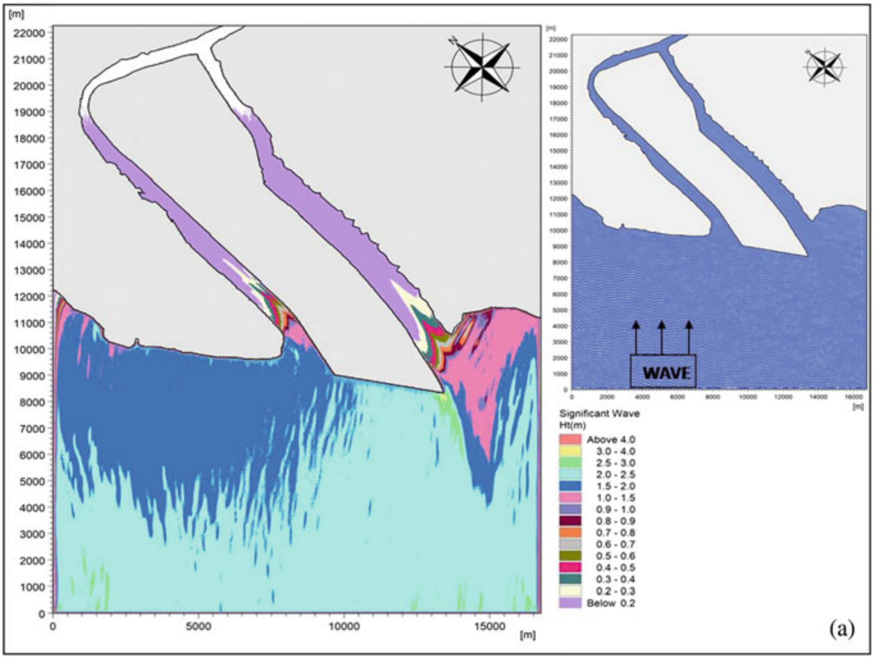


Fig. 7 Wave height and wave vector plot for wave's incident from SW and WSW direction with incident wave height 3.0 m for existing condition

heights are less than 0.5 m which is the permissible wave tranquility limit. The proposed development will be safe from the wave tranquility point of view throughout the year.



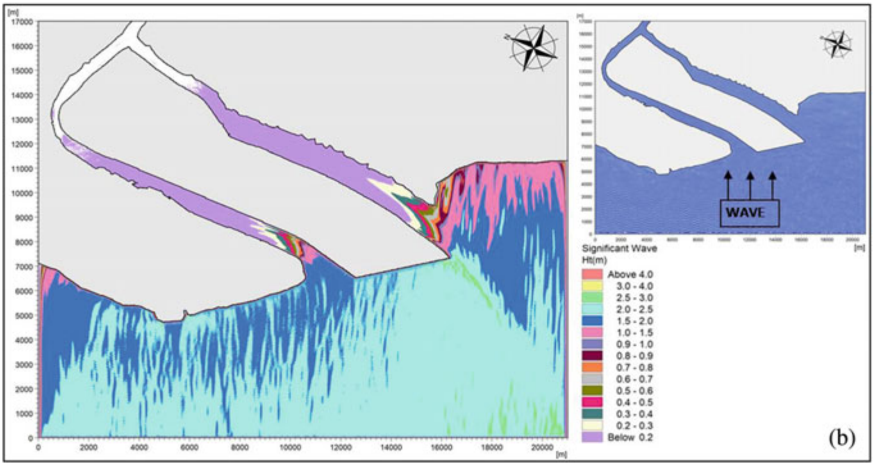


Fig. 8 **a** Wave height distribution and surface elevation plot for wave's incident from SW direction with incident wave height 3.0 m for proposed condition, **b** Wave height distribution and surface elevation plot for wave's incident from WSW direction with incident wave height 3.0 m for proposed condition

6 Littoral Drift Studies

It is understood from the earlier studies that the South Gujarat coast experiences a high sediment transport of the order of 1.52 Mm^3 [1]. Specifically, along the Valsad coast, the estimated southerly and northerly sediment transports are 0.594 and 0.98 Mm^3, respectively. It is seen that the drift is s northward direction. Valsad located near about 90 km from Hazira. The littoral drift study was conducted and a technical report No. 5845 was submitted in August 2020; the net drift 0.58 Mm^3 is reported [2]. The study of sediment movement along the shore is carried out by LITPACK model.

6.1 Estimation of Littoral Drift Rate

The littoral drift along the Hazira coast is estimated using LITDRIFT module of LITPACK software. The location of cross-shore profile is shown in Fig. 10. The profile is taken normal to the shoreline orientation. Littoral drift depends on the shoreline orientation and the near shore depth contours. Thus, the quantity of the drift changes with the orientation, and cross-shore bathymetry. The profile is normal to shoreline is at 225° N. The profile shown in Fig. 9 is prepared, and the littoral drift passing through this profile is calculated. The wave climates are prepared by extracting wave parameters at the (253,031 E, 2,330,975 N, −9.92 m depth). The profile shown in Fig. 9 covers a distance of 1650 m extending up to about −9.92 m depth contour (with respect to Chart Datum). The profile was discretized with grid size of 10 m. The ratio of wave height at the nearshore point (−9.92 m) to the incident wave height and inshore wave directions as given in Table 7 are obtained from the wave transformation studies explained in the paragraph 5.1. The annual wave climate table and the rose diagram are presented in the Table 8 and Fig. 10. When the wave heights are less than 0.2 5 m, the sea state is assumed to be calm, and the percentage of occurrence of waves less than 0.25 m constitutes calm percentage.

The model was simulated for period of one year to arrive at Northward and Southward drift. Littoral drift was computed and is shown in Fig. 11. The northward drift is plotted as positive while southward drift is plotted as negative. The northward, southward, net and gross transport rates are given in Table 9. Net drift is of the order of 0.147 million cum and is toward north, and gross transport is of the order of 0.874 million cum. The maximum transport occurs at −1.8 m depth contour. The surf zone is of the order of 450 m. The net drift may deposit in the channel at the East side of the reclamation. To minimize this problem, yearly maintenance dredging will be required.

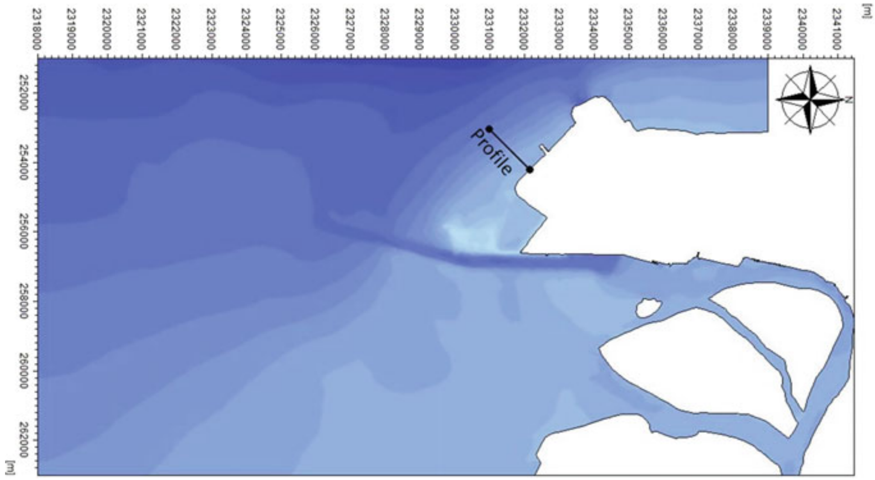


Fig. 9 Bathymetry near shoreline showing the profile

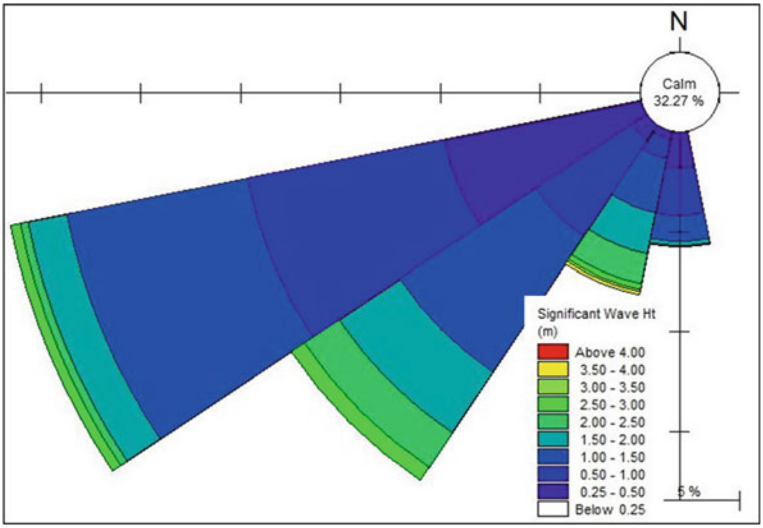


Fig. 10 Inshore wave rose diagram at profile

6.2 Shoreline Evolution

In order to assess the impact of the reclamation on the coastline, LITLINE module of LITPACK software was used for Hazira. The results are given below. The study of shoreline changes at Hazira due to the proposed reclamation shoreline of length 20 km was considered. Shoreline extended about 11 km toward north of the reclamation and

Table 7 Transformation from coastal water for south deep to shallow

Sr No	Offshore direction (Deg. N)	Inshore direction (Deg. N)	Wave height ratio (Hi/Ho)
1	112.5	187.426	0.0153
2	135	191.679	0.0533
3	157.5	195.041	0.1554
4	180	198.592	0.3552
5	202.5	209.236	0.6346
6	225	224.699	0.4702
7	247.5	241.551	0.3675
8	270	244.336	0.1549
9	292.5	244.745	0.0482
10	315	242.122	0.0124

Table 8 % Occurrence of wave height and direction in Hazira for entire year (Jan–Dec)

Wave ht (m)	<0.5	<1	<1.5	<2	<2.5	<3	<3.5	<4	<4.5	Total
Direction (°N)									Calm	32.03%
202.5	1.85	5.45	2.83	3.38	0.76	0.44	0.22	0.00	0.00	14.92
225	2.51	7.95	7.52	3.38	1.09	0.00	0.00	0.00	0.00	22.44
247.5	8.39	12.42	8.50	0.76	0.54	0.00	0.00	0.00	0.00	30.61
Total	12.75	25.82	18.85	7.52	2.40	0.44	0.22	0.00	0.00	100.00

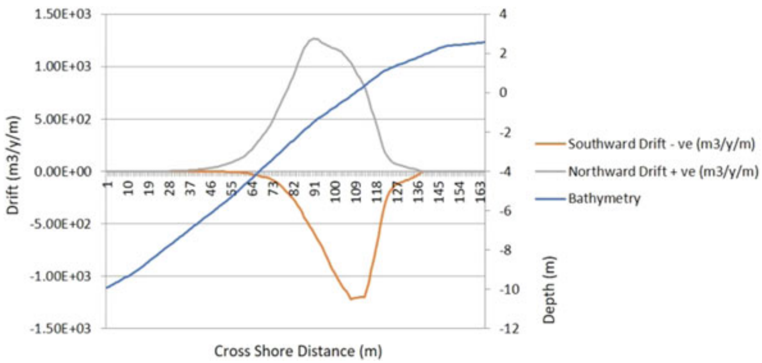


Fig. 11 Annual northern and southern littoral drift for entire year

Table 9 Littoral transport rates (million m^3/year) for South

Season	Northward	Southward	Net *
Annual	0.51	0.36	0.147

Note *For the net drift '+ve' Northward '−ve' Southward

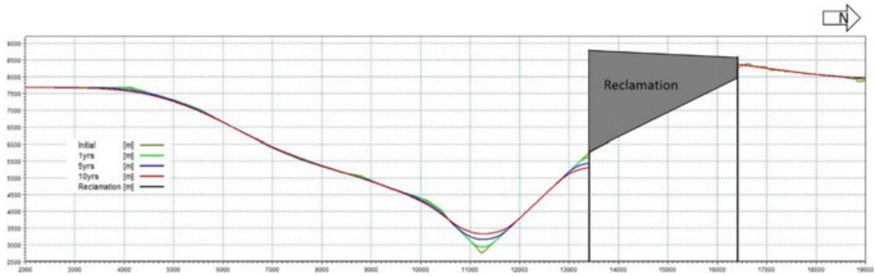


Fig. 12 Shoreline evolution for Hazira

about 9 km toward south of the reclamation. It was divided into 2000 grid points of grid size 10 m. Since LITPACK is a one-dimensional model, hence shore connected breakwaters are assumed as obstructions which are perpendicular to shoreline. The proposed reclamation was represented by two breakwaters with the blocking length of 3000 m and 1000 m with one offshore breakwater joining both the tips of the breakwater which extends clearly beyond surf zone. The model was run for 1, 5 and 10 years with the proposed reclamation as shown in Fig. 12.

7 Conclusions

- The predominant wave directions in deep water are 22.5° N to 360° N with maximum wave heights of 4.5 m were obtained by analyzing 15 years IMD data for Latitude 20–25° N and Longitude 65–75° E for the wave transformation study.
- Wave propagation studies were carried out for transformation of deep to (−) 20 m depth (Table 1D and Fig. 3D) showed that the predominant directions of wave approach at the site of development are South, SSW, SW and WSW with incident wave height 2.5 m, 4.0 m, 3.0 m and 3.0 m, respectively.
- Wave tranquility studies carried with existing and proposed layout of reclamation 4600 ha and Dumas channel with a width of 800 m and depth of 12 m below CD extending up to −12.0 m contour which is about 15 km long. The results show that the jetty and development area are tranquil with respect to wave disturbance considering the permissible limit of 0.5 m. Thus, the area of jetty will be tranquil throughout the year with proposed reclamation and channel.
- The cross-shore profile with the angle normal to the coast 2250N is considered for littoral drift study. The LITPACK model was run for annual period. Annual northward and southward, transport rates were computed for this profile.
- Net transport in a year is of the order of 0.147 million cum and is toward north, and gross transport is of the order of 0.847 million cum. The maximum transport occurs at −1.8 m depth contour. The surf zone is of the order of 450 m. The net drift may deposit in the channel East side of the reclamation. To minimize this problem, yearly maintenance dredging will required.

- For shoreline evolution, LITLINE model was run for 1, 5 and 10 years with the proposed reclamation. It is seen that the sediment will be deposited at north side of proposed reclamation and eroded at south side of proposed reclamation with increasing trend of deposition and erosion periodically.
- Considering all the three aspects of wave tranquility, littoral drift and shoreline evolution, it can be concluded that the reclamation for port city development is feasible with maintenance dredging and monitoring the changes in the shoreline periodically so that suitable remedial measures can be adopted.

Acknowledgements The authors are thankful to the Director, CWPRS, for his kind permission for publication of this paper.

References

1. Nayak BU and Chandramohan P (1992) A longshore sediment transport estimation for the Indian coast. Physical Processes in the Indian Sea. In: Proceedings of first convention of ISPSO
2. CWPRS Technical Report No 5845 (2020) Mathematical model studies for wave tranquility and shoreline changes due to reclamation proposed by M/S EBTL at Hazira, Gujarat
3. DHI, Denmark (2020) MIKE 21 SW model-user reference manuals
4. DHI, Denmark (2020) MIKE 21 BW model-user reference manuals
5. DHI, Denmark (2020) MIKE 21 LITPACK model-user reference manuals