Chapter 6

Summary and conclusions
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6.1. Summary

Wave characteristics along the Indian coast have been studied by several researchers. Probably, this may be the first attempt to study seasonal response of coastal waves and wave transformation along the Indian coast using measurement, modelling and remote sensing. The broad objectives of the present study are:

- understanding the wave generation and propagation processes in the select nearshore regions along the Indian coast through measured data
- validation of wave modelling results of deep and shallow waters using measurements and remote sensing data
- to study the interaction between pre-existing swells and wind seas generated by coastal winds
- prediction of wave transformation along the select Indian coasts using high resolution winds such as MM5

Wave data collected using directional wave rider buoys, moored data buoys and non-directional wave recorder have been analysed. Wind data were measured using Autonomous Weather Station (AWS) at various coastal stations. Apart from measurements, significant wave heights ($H_s$) derived from Jason-1 altimeter were used for deep water wave analysis as well as model validation/comparison. Wind data from QuikScat scatterometer and re-analysed winds such as NCEP, CERSAT/IFREMER blended and NCMRWF were considered for the analysis, and applied as input to numerical wave simulations. Fine resolution coastal winds off Goa have been simulated using Mesoscale Model (MM5) to study the wind sea generated by sea breeze – land breeze system during pre-monsoon season.

The specific investigations carried out in the present study are as follows:

i) analysis of spectral wave characteristics along the Indian coast during monsoons and extreme events

ii) dominance of swells over wind seas along the west coast of India
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iii) setting up of a numerical model for the Indian Ocean, and validation of model results with measurements and remote sensing data

iv) identification of potential swell generation areas, and propagation of these swells in the Arabian Sea and their impact on the west coast of India

v) characteristics of “Shamal” swells – generation and propagation, and their influence along the west coast of India

vi) superimposition of pre-existing swells over wind seas off Goa coast during pre-monsoon season

vii) wave transformation along select open coasts and semi-enclosed regions

Spectral characteristics during monsoons and extreme events have been studied using wave spectra measured off Paradip and Goa, along the east coast and west coast of India, respectively. Multi-peaked spectra with spectral peaks in the low and high frequency regions have been observed, indicating the presence of different wave systems in the region. The spectral peak in the low frequency region indicates the dominance of distant swells and that in the high frequency region indicates the dominance of wind seas. During extreme events, the spectra are single-peaked and the energy is centred on a narrow band in the low-frequency region with an average directional spreading of 20°. It is evident from the spectra that wave energy during the southwest monsoon season is higher than the northeast monsoon season along the east coast as well as west coast of India.

Wind sea and swell energies have been separated, and the respective parameters have been calculated from the wave energy spectra using the methodology proposed by Gilhousen and Hervey (2001). It has been found that swells are dominated along the west coast of India during SW monsoon (93%) and NE monsoon (67%) seasons; however, wind seas are dominated during pre-monsoon season (51%). Annually, the dominance of swells is around 70%. The mean wave periods ($T_m$) during SW monsoon season are generally above 5 s, whereas, $T_m$ are below 5 s during other seasons, indicating the superimposition of local wind seas over pre-existing swells during the pre-monsoon and NE monsoon seasons. The predominant swells observed along the west coast of India during pre-monsoon and NE monsoon seasons are in the SW/SSW directions, which are mostly propagated from the south Indian Ocean. However, the predominant swells during SW monsoon season are generated from the north Indian Ocean. NE monsoon winds could have negligible impact along the west coast of India, as waves generated due to these winds propagate away from the coast. Wind seas are predominantly in the NW direction during pre-monsoon and NE...
monsoon seasons, and those during pre-monsoon season are generated by sea breeze. It has been found that the nearshore waves during extreme events are dominated by swells.

Numerical models were set up for large domain (the Indian Ocean region) and small domains (off Goa, Ratnagiri, Dwarka, Paradip and Dhamra) to simulate waves during various seasons. Model results have been validated with measurements at deep water locations as well as nearshore depths, and the match is very good. Correlation coefficients of model and measured $H_s$ and $T_m$ at a deep water location off Goa are 0.96 and 0.85, respectively, and at a nearshore location off Goa are 0.96 and 0.83, respectively. The bias and r.m.s. error between measured and model wave parameters are as follows: $H_s$: 0.00 and 0.37 m, respectively in deep water; 0.06 m and 0.29 m, respectively in a nearshore depth; $T_m$: -0.32 s and 0.80 s, respectively in deep water, and 0.10 s and 0.80 s, respectively in a nearshore depth.

Coastal wind seas off Goa simulated using MM5 winds are validated with measured wind sea parameters off Goa and the match is very good. The correlation coefficient, bias and r.m.s. error between measured and modelled wind sea $H_s$ are 0.73, 0.03 m and 0.12 m, respectively. Diurnal variations associated with winds are evident in the simulated wind sea parameters also.

Analysis of winds and simulated waves in the Indian Ocean revealed the areas of potential swell generation; these swells propagate in the Arabian Sea and effect the west coast of India. Predominant swells are in the SW direction during SW monsoon season and in the SW/SSW and NW directions during both pre-monsoon and NE monsoon seasons. The potential swells are generated primarily in the following areas: (i) area covered by 52.5° E to 62.5° E and 5° S to 15° S for SW swells during SW monsoon season, (ii) area covered by 40° E to 70° E and 30° S to 50° S for SW/SSW swells during pre-monsoon and NE monsoon seasons and (iii) area covered by 60° E to 67.5° E and 17.5° N to 25° N for NW swells during pre-monsoon and NE monsoon seasons.

Shamal winds are meteorological events associated with winds, which normally occurs in the Arabian Peninsula, especially during the winter season. They generate large swells in the Persian Gulf and in the Arabian Sea. Characteristics of the “Shamal” swells were studied by analyzing measured wave parameters along the west coast of India during winter season. Increase in wave heights associated with decrease in swell periods and a common propagation direction (NW) for wind sea and swell are the distinct features of the Shamal swells. The associated significant wave heights and mean swell periods are between 1.0
and 2.0 m and between 6.0 and 8.0 s, respectively. Numerical simulations reproduced the Shamal swells in the Arabian Sea. It has been found that the Shamal swells are generated in the Gulf of Oman and off the east coast of Oman, which propagate to the west coast of India in the NW direction. The analysis of swell parameters extracted at 6 locations (Dwarka, Mumbai, Ratnagiri, Goa, Mangalore and Kochi) along the west coast of India indicates that the swell heights are larger off Dwarka and relatively smaller off Kochi, i.e., in the decreasing order of magnitude from north to south. The swells reach first along the Gujarat coast and then on the Kerala coast with time lags according to their arrivals.

Superimposition of coastal wind seas with pre-existing swells during pre-monsoon season was investigated. A distinct and systematic diurnal variation in wind speed, wave height and wave period, especially increase in wave height and decrease in wave period following the increase in the intensity of coastal winds due to sea breeze system has been observed. During the onset of sea breeze, a wind wave system grows in time, following the progressive extension of the sea breeze area towards offshore. After cessation of the sea breeze, wave energy level gradually decreased and the associated wave period increases. During a typical daily cycle, the wave height reaches its peak early in the afternoon, then it decays progressively back to the swell conditions within 5 or 6 hours. It is evident from the wind sea that the wind sea $H_s$ gradually increases towards the coast from offshore, and the maximum wind sea $H_s$ has been observed close to the Goa coast. The wind sea growth towards the coast is proportional to the wind speed gradient, available fetch and sea breeze duration.

Wave transformation along the open coasts and semi-enclosed regions has been studied using measurements and simulations. Reduction in significant wave heights among two nearshore water depths measured off Goa, Ratnagiri and Dwarka were estimated. Least reduction is observed off Goa and maximum off Dwarka. In fact, a wind sea growth in the NE direction (away from the coast) off Dwarka has been observed, which sufficiently contributes to the prevailing waves at 30 m depth location. Simulated wave parameters at water depths of 100 m, 50 m, 30 m, 20 m, 10 m and 5 m off Mumbai, Goa and Kochi (along the west coast of India), and off Nagappattinam, Visakapatnam and Paradip (along the east coast of India) were analysed. Wave patterns along the west coast of India are nearly the same, but in increasing order of wave heights from south to north. It is found that wave dissipation is high off Mumbai and low off Kochi along the west coast of India. Wave heights along the east coast of India are in the increasing order during pre-monsoon and SW monsoon seasons, and in the decreasing order during NE monsoon season, from
south to north (Nagappattinam to Paradip), and the reduction among various depths are relatively less as compared to those along the west coast of India. Bottom dissipation causes higher reduction in wave heights over wide continental shelf, and the continental shelf of west coast is wider compared to east coast of India.

Wave transformation at naturally protected (Dhamra Port) and artificially protected (Mormugao Port) semi-enclosed regions has been studied. The Dhamra port is protected from direct waves by Kanika sands, Gahirmatha beach and surrounding mangroves, and is only partially open to the waves from NNE to NE and from ESE to SE. Diffraction and bottom dissipation play major role in controlling the wave energy while propagating towards the Port. The Mormugao Port is protected from waves by breakwaters, and during any season, wave height inside the port is very low, and only diffracted waves propagate towards the port. During an extreme event prevailed in the Arabian Sea, the significant wave height observed inside the port was only 0.33 m.

A case study was carried out to demarcate inland vessels’ limit (IVL) limit off Mormugao Port region for demonstrating the operational use of wave model results. It has been found that during September – May, significant wave heights do not exceed 2.0 m off Mormugao port and coastal regions. Based on the significant wave height distribution around the coastal region, the IVL has been demarcated.

6.2. Conclusions

- Time series wave data measured off Goa (west coast of India) and off Paradip (east coast of India) distinctly show the response of coastal waves to the seasons and extreme events.
- Monthly, seasonal and annual characteristics of wind seas and swells off Goa have been separated from the measured wave spectra using the separation frequency method. The wave pattern primarily follows swell pattern during most part of the year, especially during SW monsoon and NE monsoon seasons. Wind seas are dominated during pre-monsoon season.
- Numerical model results have been validated with measurements in deep water as well as nearshore locations, and the match is very good.
- MM5 winds have been simulated for Goa region during pre-monsoon season, and applied to simulate coastal waves off Goa. Significant improvement in simulated wave
parameters was observed, urging the need of using high resolution winds for coastal wave predictions.

- Superimposition of locally generated waves from NW with the pre-existing swells from SW along the west coast of India results in diurnal variations in waves. Increase in wave height and decrease in wave period with increase in wind speed, especially during fair weather season, are the important effects of dominance of sea breeze.

- Though waves during southwest monsoon season have high impact on the west coast of India, the wind seas super-imposed on pre-existing swells do cause geomorphological changes during non-monsoon months. The role of distant swells in modulating the wave generation along the west coast of India, where the impact of sea breeze is dominant during pre-monsoon season, is yet to be understood.

- The “Shamal” swells were identified along the west coast of India during winter season. Increase in wave heights associated with decrease in swell periods and common propagation direction (NW) for wind sea and swell are the distinct characteristics of Shamal swells. Shamal swells are generated in the northwestern Arabian Sea, especially in the Gulf of Oman and off the east coast of Oman, and propagate towards the west coast of India in the NW direction. Influence of Shamal swells is the maximum along the Gujarat coast and the minimum along the Kerala coast.

- Shamal winds can influence the wind-induced circulation in the Arabian Sea. Study on Shamal wind extension and their distribution along the west coast of India require fine resolution winds (e.g. MM5 winds). Even though swells from the south Indian Ocean are always present along the west coast of India, the presence of Shamal swells cannot be ignored.

- Transformation of wave parameters in the nearshore depths at various locations along the Indian coast has been assessed. Wave height reduction is higher along the west coast compared to the east coast, since bottom dissipation causes higher reduction over wide continental shelf. Along the west coast of India, the wave dissipation increases from south to north (Kochi to Mumbai). Attenuation due to bottom friction varies along the west coast of India according to the size of the bottom sediments, and it is in the increasing order from the south to the north.

- Wave patterns along the west coast of India are nearly the same, with wave heights increasing from south to north (Kochi to Mumbai). Wave heights along the east coast
of India increase from south to north (Nagappattinam to Paradip) during pre-monsoon and SW monsoon seasons and decrease during NE monsoon season. Diurnal variations are evident at nearshore depths along the west coast of India during pre-monsoon season, but in the decreasing order of magnitude from north to south (Mumbai to Kochi).

- Wave modelling results have been applied to an operational use: based on the distribution of significant wave heights, inland vessel’s limit (IVL) of the Mormugao port has been demarcated.

### 6.3. Future perspective

The present work can be extended further to study the following aspects:

- Role of distant swells in modulating wave generation along the west coast of India, where the impact of sea breeze is dominant during pre-monsoon season, is yet to be understood – a detailed investigation is required.

- Shamal winds can influence the wind-induced circulation in the Arabian Sea. Shamal wind extension along the west coast of India has to be analysed in detail utilising fine resolution atmosphere models.

- Since, swells (SW/SSW) from south Indian Ocean are always present along the west coast of India, they interact with Shamal swells (NW) during Shamal events. The interaction of these multi-directional swells deserves special attention in future research.

- A detailed field study should be carried out to understand the nature of attenuation of short period wind seas observed at the nearshore depths off Goa during pre-monsoon season.
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