Ice in Numerical Modelling of Sea Waves for Development of Sea Ports and Berthing Facilities – A Case Study

Dr Zaman Sarker, Principal Engineer at Royal HaskoningDHV, describes a practical technique to consider sea ice in numerically transferring offshore waves into inshore for a proposed bulk terminal in a partially frozen sea environment in the Russian Far East...

In recent years, there is a growing trend for development of marine berthing terminals including Liquefied Natural Gas (LNG) terminals in the frozen sea regions of the world. Reliable inshore wave conditions are important in the planning and development of such marine facilities and in making various technical and commercial decisions. Appropriate consideration of sea ice is essential in deriving such reliable inshore wave conditions. This article describes a practical technique for deriving reliable inshore wave conditions at a proposed bulk terminal considering sea ice. As part of the overall study, numerical modelling of wave transformation was carried out using the MIKE21 Spectral Wave (SW) Model of DHI (DHI, 2012) to derive inshore wave conditions at the bulk terminal. Both wind waves and swell waves were considered in association with sea ice. The methodology bed contours broadly follow the alignment of the shoreline with the 5m and 10m water depth contour located approximately 100m and 250m respectively from the shoreline. The foreshore slope is of approximately 1 in 30. A dredged depth of approximately 22.0m will be maintained at the berths, in the turning circle and in the navigational approach channel. Three-hourly time-series wind and wave data for 21 years (1992 to 2012) were purchased from BMT ARGOSS (2013). The study site was located in a remote area behind islands where reliable offshore data from Global Model of BMT ARGOSS were not available. Therefore, BMT ARGOSS set up a local refined model to derive reliable offshore data for the study. The offshore wind and wave roses are shown in Figures 1 to 4. Winds blow predominantly from the north, north-westerly and south. However, most of the higher speed winds come from the north and north-westerly directions. The dominant swell wave directions are south-westerly. Dominant resultant wave directions are north, north-westerly, south and south-westerly which reflects the directions of the wind waves and swell waves. As wind waves and swell waves arrive at the site from very different directions, it was considered that has been successfully applied to a project in the Russian Far East and the results presented in this paper are from this project. The methodology and lessons learnt from the study would be useful for the development of any sea port or bulk terminal in ice affected regions.

Meteorological conditions

At the study site the coastline is characterised by a series of headlands and bays. The sea a more accurate description of inshore conditions would be obtained by analysing wind waves and swell waves separately. Resultant waves were, therefore, not used in the analysis. The astronomical tidal level variation at the site is small and does not exceed 0.5m. Global sea level rise for various scenarios was extracted from the Intergovernmental Panel on Climate Change (IPCC, 2007). A sea level rise of 0.5m has been adopted for the study.

| Table 1: Monthly and yearly ice coverage (percentage) |
|----------------------|----------------------|----------------------|----------------------|
| January | 49 | 44 | 40 | 43 | 18 | 24 | 40 | 11 | 12 | 82 | 11 | 29 | 21 | 9 | 9 | 9 | 10 | 28 | 8 | 0 | 2 | 50 | 26 |
| February | 47 | 40 | 43 | 34 | 34 | 41 | 47 | 35 | 40 | 64 | 61 | 47 | 18 | 38 | 43 | 45 | 48 | 2 | 7 | 17 | 62 | 39 |
| March | 34 | 33 | 36 | 33 | 33 | 35 | 39 | 38 | 38 | 42 | 47 | 40 | 19 | 44 | 18 | 46 | 21 | 4 | 36 | 24 | 70 | 34 |
| April | 31 | 29 | 30 | 10 | 4 | 1 | 4 | 11 | 4 | 11 | 5 | 6 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 0 | 7 | 5 | 41 | 10 |
| May | 18 | 8 | 10 | 3 | 1 | 1 | 0 | 1 | 3 | 4 | 3 | 4 | 2 | 1 | 0 | 1 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 |
| June | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| July | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| August | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| September | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| October | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| November | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| December | 21 | 18 | 25 | 4 | 5 | 3 | 1 | 1 | 4 | 9 | 16 | 6 | 2 | 5 | 5 | 9 | 5 | 0 | 12 | 5 | 7 |
| Yearly Average | 17 | 14 | 15 | 11 | 8 | 11 | 8 | 14 | 15 | 11 | 6 | 9 | 8 | 0 | 4 | 5 | 19 |

BMT ARGOSS (2013). A sample time-series plot of ice coverage for 1993 is shown in Figure 5. Ice data were analysed to derive monthly and yearly averaged ice coverage (percentage) as shown in Table 1. Table 1 shows the following:

- Average ice conditions for each month of each year (see the body of Table 1)
- Monthly averaged ice condition for the entire data duration (see the right column of

Ice conditions

Important ice terminologies have been defined as below:

- Sea ice coverage (also known as ice concentration) – is defined as the percentage of ice surface area over sea surface area. A 0% means no ice and 100% means total coverage by ice.
- Sea ice thickness - is defined as the thickness of the ice from the surface.
- Sea ice extent - if the ice concentration is higher than a threshold concentration e.g. 33% then the sea surface is defined as covered.
- Sea ice volume - is found from multiplying the concentration by the area and thickness. Sea ice shape and age - sea ice is divided into different shapes (such as frazil ice, grease ice, slush ice, shuga ice, nillas and floes) and ages (such as new ice, young ice and first year ice).
- Sea ice charts are used to display information about the ice in an area. The data is displayed in egg shaped blocks. This code is known as the ‘egg code’. An ice egg code consists of information on ice such as concentration, stage of development, forms and thickness. Three-hourly time-series ice data for 21 years (1992 to 2012) were purchased from

has been successfully applied to a project in the Russian Far East and the results presented in this paper are from this project. The methodology and lessons learnt from the study would be useful for the development of any sea port or bulk terminal in ice affected regions.
The analysed ice data for various years suggest the following:

- Last occurrence of the ice season is in June [1999, 2003]
- Higher coverage of ice is generally found during December to April
- Ice coverage > 33% generally during January to March

The MIKE21 Spectral Wave (SW) Model developed by DHI was used to transfer offshore waves into the study site (DHI, 2012). The model covers the study site and the surrounding area so that the impact of the headlands and nearshore bathymetry is included in the simulations. Overall the area covered by the model was approximately 90km x 80km. A flexible (triangular) mesh was used in the study which allowed a high resolution to be used within the shallow water areas as well as at the study site where changes in wave conditions take place quickly within short distances. Bathymetry of the wider area was obtained from C-Map (2013). Local survey bathymetry provided by the client was used to improve the model at and around the study site. The combined model bathymetry is shown in Figure 6. In addition to offshore waves (from BMT ARGOSS), the model requires input water levels. A water level of +1.05m Chart Datum was adopted for all model runs. This is the mean high water level plus an allowance of 0.5m for future sea level rise. Ice in sea water obstructs wave growth and propagation. The

Table 2  Limiting wave height, $H_{10}$ (m)

| Angle of waves front impact relative to diametral plane of a moored vessel (degrees) | Limiting wave heights (5% probability) in m, for the vessels with displacement DT, x1000 ton |
|---|---|---|---|---|---|---|
| Up to 45 ( means beam) | 0.7 | 0.9 | 1.1 | 1.2 | 1.5 | 1.8 |
| 90 ( means head on or stern on) | 1.2 | 1.5 | 1.8 | 2.0 | 2.5 | 3.2 |

Source: SNiP 2.06.04-82

Figure 5: Time-series plot of ice coverage for 1993
introduction of partially obstructed grid points in the wave model provides a more natural way to continuously model ice coverage. As reported in Tolman (2003), detailed analyses of the effects of ice floes on wave propagation have been published (e.g. Wadhams et al., 1986; Masson and LeBlond, 1989; Lawrenov, 1998). It has been shown that wave attenuation in ice fields shows an exponential decay in space with a given length scale. Wave energy does not dissipate instantaneously when the wave field encounters ice, rather waves are assumed to progressively lose energy while travelling through an ice field, consistent with exponential decay. The decay rates are expected to be a distinct function of the size of individual ice floes (e.g. Masson and LeBlond, 1989), with larger ice floes scattering waves more efficiently and hence resulting in larger decay rates. As the floe size increases with ice concentration, decay rates increase strongly with ice concentration. Detailed ice data are required to estimate such decay rates for any sophisticated approach. Due to lack of necessary ice data to estimate decay rates required for the sophisticated approach, a simplified approach was used in the study. This simplified approach based on cut-off ice concentrations was used to assess the influence of ice on wave propagation. Within the MIKE21 SW model the influence of ice is treated in the following way:

- If the ice coverage (i.e. ice concentration) is greater than or equal to a threshold value (of 33%) then the model considers the ice area as land (i.e. there are no waves in the ice area).
- If the ice coverage is less than the threshold value of 33% then the model considers the ice area as ice-free water (i.e. there is no effect of ice on waves).

The threshold ice coverage value recommended in the MIKE21 Manual (DHI, 2012) is also supported by various other studies such as Tolman (2003) and Tuomi et al. (2011). This method ensures that the wave model uses a fetch starting from the ice edge. Furthermore, waves are not predicted in areas that have ice coverage greater than 33%. A 2-dimensional ice map was prepared for the study covering the entire model area with constant ice coverage value for a particular time step. The ice map covers the entire run duration. Months where ice coverage was ≥ 33% were considered as ice months in the model. These ice months have been showed by green boxes in Table 1. The remainder of the months of various years were considered as ice free months in the model. Model simulations were carried out to transform the two types of waves inshore as below:

- Wind generated waves [generated locally by winds]
- Swell waves [generated by remote meteorological conditions]

Model results (wave heights and directions) were extracted for the entire modelling area (see Figure 7) as well as at selected locations within the navigational areas and along the jetty of the proposed dry bulk terminal (see Figures 8-9).

**Application of the model**

The model results have been used to calculate the operational downtime of the proposed bulk terminal. Operational (wave) downtime may be defined as the number of days per year when conditions at the loading and unloading berths exceed a given height and therefore the berths will not be operational. Downtime due to adverse wave conditions for vessels at berth is an important commercial aspect in the planning and development of a sea port or a berthing terminal. The wave model results from the study were used to assess operational downtime at the berths. Waves affecting the head and beam of a vessel (see Figure 10) were considered separately for a wide range of vessel sizes. The downtime assessment was carried out according to the Russian standards as shown in Table 2. The bulk carriers DW-40, DW-70, DW-115 and DW-168 were considered. Here, DW-40 means a bulk carrier of 40,000 tonnes deadweight. Hₜₙ was used as the limiting wave height. Operational downtime was also calculated using the significant wave height, Hₚ as a criterion with limits of Hₚ = 1.0m for beam seas and Hₚ = 1.5m for head seas where Hₚ = 1.2 Hₚ. Here, Hₚ is the wave height exceeded by 5% of the waves in a sea-state. The main waves affecting the ships downtime are wind waves; Swells do not gain sufficient height to influence the downtime; and Downtime caused by wind waves is not significant and does not exceed 1% per year.

**Findings from the study**

The findings from the downtime assessment may be summarized as following:
- Wind generated waves
downtime; and
- Swell waves
downtime are wind waves;
- Swells do not gain sufficient height to influence the downtime; and
- Downtime caused by wind waves is not significant and does not exceed 1% per year.

**Concluding remarks**

The approach set out in the paper has provided a good initial assessment of the influence of ice coverage on operational wave conditions at the proposed project site. For this remote site it was found that a global wave model could not provide reliable offshore data and that it was necessary to undertake some refinement of the model to provide acceptable data. Also for the site it was considered that separate analyses of wind waves and swell waves would provide a more accurate description of the inshore wave climate given differing directions of the two sea conditions.

“The approach of analysing ice data, dealing with ice in the model and the wave transformation modelling described in this paper can be used in the planning and development of sea ports and berthing facilities in the ice affected regions.”

Experience from the study has indicated that for a more detailed wave downtime analysis the sensitivity of inshore wave conditions to the spatial ice coverage, particularly differences between nearshore and offshore conditions should be considered. The approach described in this paper provides a practical and cost-effective method for the evaluation of likely operational downtime at a berth based on waves in the initial stages of a project. The approach of analysing ice data, dealing with ice in the model and the wave transformation modelling described in this paper can be used in the planning and development of sea ports and berthing facilities in the ice affected regions. In the later stages of a project numerical (or physical) modelling techniques to look at operational downtime based on ship motion...
at the berth are likely to be required. The wave data from the study will provide inputs to these ship motion studies.

**Application of modelling results**

In addition to wave downtime assessment, the wave transformation modelling results from the study can also be used as “building block” for a wide range of further calculations and modelling studies required in the planning and development of sea ports and berthing facilities. These calculations and studies include:
- input to wave disturbance models for deriving safe operational conditions at berths;
- input to sediment transport models for assessing siltation in dredged basins;
- input to ship manoeuvring studies for safe navigation;
- deriving optimised conditions for designing marine facilities and
- input to physical model tests in a laboratory.

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