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MODELLING OF ICE RUBBLE ACCUMULATIONS IN THE NORTH CASPIAN SEA

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ABSTRACT

In the shallow waters of the North Caspian Sea, ice rubble can accumulate around island structures, impairing the function of escape, evacuation and rescue (EER) systems and impeding access to quay areas. In this paper, a method is outlined for characterizing ice movement events, defining the geometry of the main structure and protection structures, and characterizing the rubble that can accumulate adjacent to them. The approach is fully probabilistic, relying on the statistical characterization of ice drift, ice thickness, rubble height and rubble extent based on locally acquired data. The plan geometry of the structures and the rubble accumulations are defined on a regular grid. When protection structures or gravel berms are present, the rubble can bridge the gaps, thereby protecting the installation from further rubble accumulations. This effect has also been modelled probabilistically based on local observations.

An important objective of the work is the assessment of downtime for drilling operations. Ice incursions and rubble build-up can prevent the launch and transit of evacuation craft, and also prevent quay access for barges. Explicit consideration is made for EER launch areas, barge footprints, evacuation routes through ice and quay areas that need to be kept free of ice rubble. Based on the probabilistic representation for the ice rubble accumulations, downtime estimates are made for EER and quay access for which examples are shown in the paper. The present approach is used for assessing the effect of different structure geometries and berm layouts.

INTRODUCTION

Background

There is ample evidence of ice rubble build-up against structures in the shallow waters of the Beaufort Sea and the North Caspian Sea, and in many other areas. The movement of the ice sheet is arrested by the structure and, if the structure is wide enough relative to the water depth, ice rubble will remain lodged against it and build down to the seafloor. Once in place, ice rubble can prevent access to and egress from the structure and can consolidate over time, thereby providing protection from further ice impact. The presence of ice rubble has been a significant design issue for escape, evacuation and rescue (EER) system availability, and for supply vessel and barge access to offshore structures in the Kashagan field in the North Caspian Sea.

Some principles for the empirical modelling of ice rubble were outlined in a general paper by the authors (McKenna et al., 2008) using published data from Beaufort Sea structures (Canatec, 1993). Limited data on ice rubble features from the North Caspian Sea are shown in Barker and Croasdale (2004). Although ice rubble features in the Caspian Sea remain relatively undocumented in the general literature, there has been a wealth of data relating to design criteria collected over the last 10 years.

Objectives

In the context of the Kashagan development, the objectives of rubble modelling include the assessment of:

(a) EER downtime for evacuation craft from offshore structures;

(b) downtime for barge access at the quaysides of offshore structures due to ice rubble accumulation;

(c) protection berm and protection structure configurations; and

(d) potential reductions in design loads for structures as a result of ice rubble build-up.

Approach

Probabilistic simulations provide a means of addressing each of the objectives (a) through (d). As the Kashagan project has evolved over the last 10 years, large quantities of ice data have been collected during purpose-specific field initiatives and as part of offshore operations. While the data have not been acquired specifically with the view of conducting probabilistic analyses, there is ample information from airborne ground penetrating radar ice thickness measurements, airborne laser mirror scanner characterization of ice rubble features, ice drift buoy deployments and hindcast wind analyses.

Much of the North Caspian Sea is less than 10 m deep and the offshore structures in the Kashagan field are large footprint rockfill designs. Rubble building processes are complex and relatively poorly understood. While progress has been made with respect to modelling rubble build-up in the Caspian Sea using numerical techniques (e.g. Barker et al., 2001a,b), their direct use for probabilistic simulations is not feasible. The quantity of empirical data has allowed for a statistical characterization, and the large footprint structures in shallow water make the problem well-suited to a spatial grid representation.

Whether for downtime estimation or load transmission, focus is typically on average conditions, the frequency of ice movement events and the proportion of time ice rubble is present rather than on extremes. This means that the characterization of the ice cover and rubble is relatively straightforward even if the datasets are not comprehensive.

STRUCTURE LAYOUTS AND GEOMETRICAL REPRESENTATION

A grid is employed to model the spatial characteristics of ice rubble build-up. The grid serves as a means of characterizing the structures, the encroaching ice cover, rubble build-up and rubble grounding. The grid cell size should be small enough to adequately represent structure shape and to capture the spatial variability in rubble thickness. For the present applications, a grid size of 4 m × 4 m is used.

The grid cells are defined as either structure cells or water (and ice) cells. One can therefore think of a structure mask such that $M_{i,j} \geq 1$ for structure cells and $M_{i,j} = 0$ for ice or water cells. Each portion of the structure can be assigned a unique integer if their distinction is required in the analysis. A depth is assigned to each water grid square, allowing constant or spatially varying depths to be considered. Berms and naturally varying seabed features can also be considered in this way.

ICE MOVEMENT EVENTS

An important aspect of the calculation of ice loads, ice encroachment and downtime due to rubble accumulation is the identification of ice movement events and the key parameters associated with them. An event modelling approach has been developed for the Kashagan field, and applied in a number of studies relating to EER and quay access, ice load calculations, and ice encroachment. More details of the approach are found in Jordaan et al. (2011).

The ice movement events are driven by hindcast winds and are defined for a series of representative years. The frequency of ice events has been verified with observations as part of offshore observations and with the movements of ice drift buoys. Kashagan East (KE) events are used in the present study and event files for other sites in the Caspian Sea have been developed as well. For each event, the following parameters are provided:

- simulation year of ice event;
- number of days from the start of the ice season;
- drift direction;
- average drift speed;
- event duration;
- average ice thickness; and
- maximum or minimum surge elevation.

The drift speed and duration provide the ice length in for the event, which yields the ice volume associated with the event when multiplied by the average thickness and projected structure width.

ICE RUBBLE CHARACTERIZATION

Overview

The approach described in this paper considers the progression of rubble build-up against structures during the course of an ice movement event. It is designed to be run repeatedly and to model a large number of events over many years. All calculations are performed over a series of grid squares representing the structures and the surrounding ice cover. For each event, ice rubble is accumulated to empirically based thickness, extent and plan shape, with consideration of the structure configuration in plan and the direction of ice drift.

This section outlines sampling relationships that capture the essential statistical characteristics of ice rubble in the North Caspian Sea. While physically based models (e.g. Barker et al., 2001a.b) or physical/empirical approaches (McKenna et al., 2008) can be used, experience in the Caspian Sea has shown that a purely empirical approach is sufficient for many probabilistic simulation applications.

Rubble Height

Rubble height distributions were developed based on nine *x*,*y*,*z* profiles of rubble fields around structures for the North Caspian Sea, each resampled to 4 m × 4 m grid cells. The rubble field profiles were derived from airborne laser mirror scanner data with a spatial resolution of approximately 1 m.

Because of the presence of level ice and rafted ice within a rubble field, a single height distribution does not represent all of the rubble heights very well. Areas of apparent level ice and rubble have been identified separately, and the overall height distribution is determined from the two contributing distributions weighted by the proportion of level ice and rubble within the footprint of the rubble field. The combined rubble height distribution $f(H)$ is expressed as a function of the 'level ice' height distribution $f_l(H)$ and the 'rubble' height distribution $f_r(H)$,

$$f(H) = p_l\, f_l(H) + (1-p_l)\, f_r(H) \qquad (1)$$

where p_l is the proportion of grid squares containing level ice. Based on the data, the proportion of the rubble field that is made up of level ice cells, p_l, can be sampled from a triangular distribution with a minimum of 0, a maximum of 0.80 and a peak value of 0.48.

Based on the nine data sets, the mean height of the 'rubble' component of a rubble field can be represented by the Gamma distribution with a mean of $\langle H_{r0} \rangle = 1.91$ m and a standard deviation of $\sigma_{r0} = 1.23$. There was no significant relationship between the surrounding ice thickness, h, and the mean 'rubble' height or mean 'level ice' height within the rubble field based on data from these nine rubble fields. To avoid unrealistically high rubble heights associated with very thin ice thicknesses, h, the values of $\langle H_r \rangle$ and σ_{r0} are reduced in proportion to h for values of h less than 0.1 m.

The mean height $\langle H_r \rangle$ for a particular rubble building event is then sampled from the Gamma distribution with mean $\langle H_{r0} \rangle$ and standard deviation σ_{r0}. The standard deviation for the 4 m × 4 m 'rubble' grid cells is calculated from

$$\sigma_r = \langle H_r \rangle\, c_r \qquad (2)$$

where $c_r = 0.57$ is the coefficient of variation for the 4 m × 4 m 'rubble' grid data.

The mean height of the 4 m × 4 m 'level' grid cells in a rubble field can be sampled from

$$\langle H_l \rangle = 0.20\, \langle H_r \rangle + 0.08 + N(0,0.067) \qquad (3)$$

where $N(0,0.067)$ is a normally distributed random variable with a mean of 0 and a standard deviation of 0.067m (the standard deviation of the residuals). Sampled values less than zero are resampled. The standard deviation for the 4 m × 4 m 'level' grid cells is calculated from

$$\sigma_l = \langle H_l \rangle\, c_l \qquad (4)$$

where $c_l = 0.55$ is the coefficient of variation for the 4 m × 4 m 'level' grid data.

Height values for each 4 m × 4 m grid cell in the level and rubble portions of a rubble field are then sampled from Gamma distributions with parameters $<H_r>$, σ_r and $<H_l>$, σ_l. The combined rubble height distributions are derived numerically from Eq. (1).

For a structure in the Kashagan field, the average of the calculated maximum rubble field heights is 7.0 m to 7.4 m based on the above formulation. This is slightly in excess of the average height of 6m for stamukhi and other observed rubble features in the North Caspian Sea. The estimated annual value for the maximum height in a rubble field around a structure at Kashagan is approximately 16 m.

Spatial characteristics of rubble height

To sample realistic rubble fields, the relationship between adjacent grid squares needs to be considered since a point 4 m away from the highest point in a rubble field will also be high. Similarly, the rubble height in a grid square adjacent to one with a lower height will also tend to be low. From the Caspian data, the lag-1 correlation between adjacent 4 m × 4 m grid squares is calculated to be approximately 0.7.

In many circumstances, there can be preferred orientations of rubble features, created by actions against the structure, linear ridge-like features perpendicular to the direction of ice drift, or features created by the shearing action of the surrounding ice movement (see Figure 1 in which the total width of the rubble is approximately 100 m). Unless there is a practical reason to model rubble anisotropy, isotropic fields can be used as is done in this paper.

Figure 1. Rubble build-up against a steel ice protection structure in North Caspian Sea

Unit normal correlated random values are generated over the spatial grid from the lag-1 correlation matrix and then transformed to the desired rubble height distribution using the cumulative distribution function for rubble height. The rubble height distribution is the combined 'rubble' and 'level ice' distribution, $f(H)$, from Eq. (1).

Rubble thickness

The next step in the process is to convert rubble heights into rubble thicknesses. Although hundreds of kilometres of ground penetrating radar lines have been collected for the North Caspian Sea, these are best for assessing level ice thickness rather than rubble thickness. Over large areas, hydrostatics will provide an exact relationship between sail height and keel depth.

Since the water depth at Kashagan East is around 4 m deep, hydrostatics likely provide an approximate but not exact relationship for 4 m × 4 m grid squares. Hydrostatics are used in the present case and keel depth is truncated at the seabed. Grounded and ungrounded cases are illustrated in Figure 2. In general, rubble porosities in the North Caspian Sea average about 0.3, with a lower bound around 0.1. An average value of 0.3 is used in the paper for the above water and underwater portions. If pressures on the seafloor are to be estimated, more detailed analysis of the data should be considered.

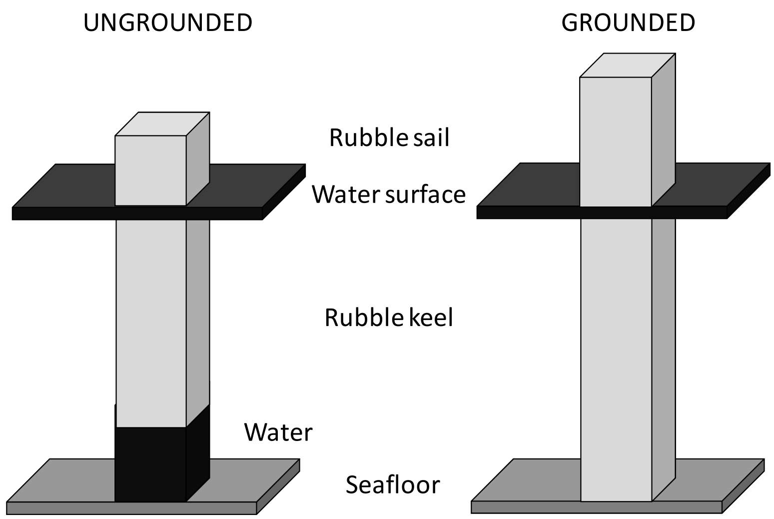

Figure 2. Schematic of ungrounded and grounded rubble grid squares

Rubble Extent and shape

Rubble extent is the perpendicular distance away from the structure or from the previously existing rubble to which the ice builds up during the course of an ice movement event. With reference to Figure 3, consider the ratio

$$r = E / W \tag{5}$$

where E is the maximum rubble extent and W is the projected structure width. Based on data for the North Caspian Sea, the mean value of r is 0.74, the standard deviation is 0.44 and the Gamma distribution can used for random sampling. Although the extent can sometimes be quite large, values have been capped at 2 in the simulations because rubble at this distance from the structure is seldom stable and has very little impact for the present applications. The rubble extent is also capped based on the volume of the encroaching ice during the course of the event, the ice rubble porosity and the average rubble height, $\langle H_r \rangle$, defined above.

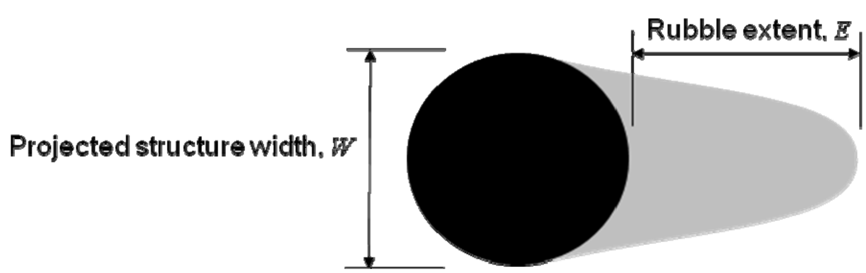

Figure 3. Schematic showing structure and rubble extent

For a given drift direction, the projected width of each structure component is calculated, as is the portion of the ice surface area sheltered by the structure components. A parabolic plan shape for the rubble is assumed and the ice is placed to the prescribed height and thickness within its boundaries. Since actual shapes tend to be more fully developed than a parabola based on observations, a parabola with a power of 3.3 rather than 2 is used.

For some applications such as downtime due to the presence of rubble, the progression of rubble over the course of an event is not that important. In this case, only the full extent of the rubble field is considered. For load transmission to the structure, the progression is important and rubble is fed into the bounding parabola over the course of the event according to the rubble thickness calculated above until the maximum extent is reached.

Bridging

Bridging occurs when ice rubble grounds between protection structures or between protection structures and the main structure during the course of an ice movement event. The rubble forms a bridge, thereby preventing subsequent incoming ice from passing through the gap and promoting further build-up. Of importance in the present situation is the likelihood that rubble bridges depending on the width of the gap.

Based on observations at the Sunkar drilling barge in the Kashagan field, the bridging probability curve in Figure 4 was developed. The data points shown in the figure are ones where there was clear documentation. The data and the experience of ice advisors on Sunkar was factored into the estimation of the 'fit' line. At these water depths (i.e. about 4 m to 7 m), projected widths less than about 75m tend bridge on a regular basis, while bridging is unlikely when the gap exceeds 200m.

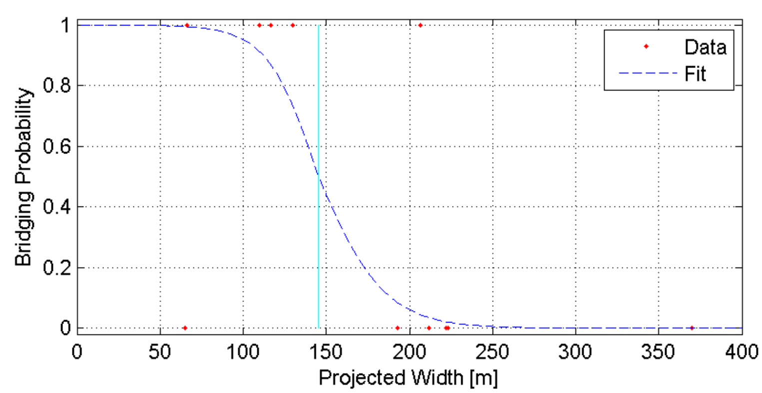

Figure 4. Approximate bridging probability for range of projected widths of gap between structures

Bridging is treated in the rubble simulation model by considering a series of likely bridge locations for each structure layout considered. The width of the bridge (or gap between structures) is then calculated for all possible drift directions. The calculation procedure is as follows:

- for each ice drift event, rubble simulations are performed for the unbridged case and for all of the potential bridged cases;
- the width of the bridge (or gap between structures) is calculated for all possible drift directions;

— the drift direction for each event is used to interpolate the projected width of single (or multiple) gaps;

— the bridging probability is calculated for the projected width of each gap and a random sampling is used determine whether the gap was bridged for the event;

— the bridged (or unbridged) layout is assigned accordingly; and

— a reference table is made up for each layout containing the year, the event number and the bridged configuration for later use in downtime simulations, for example.

The results of typical rubble simulations for bridged and unbridged configurations are shown in Figure 5. A sheetpile retained island (shown by the olive colour) is protected by berms to the south and southeast, and a rock dump area to the left. This particular layout is one of many that were considered for the drilling centres in the Kashagan field.

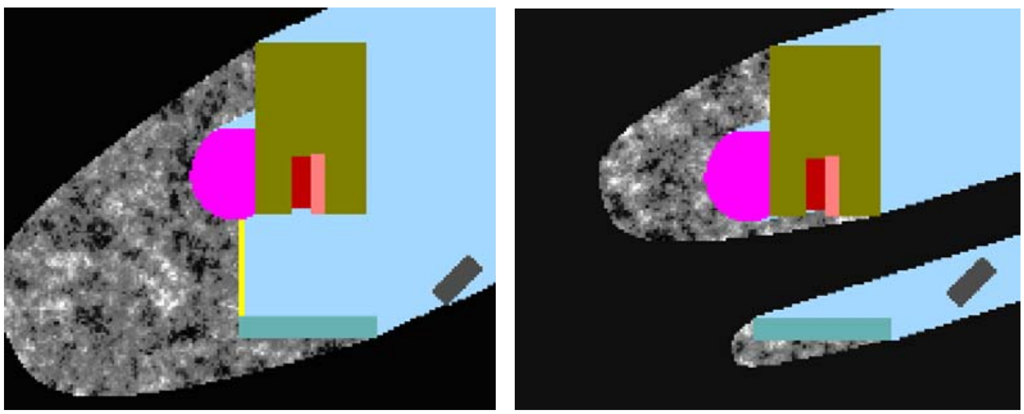

Figure 5. Rubble simulations showing bridged and unbridged configurations; the ice sheet is shown in black, the highest rubble in white, open water in blue, the bridge location in yellow and various colours for the structure components

DOWNTIME CALCULATIONS

Downtime due to ice rubble has been assessed for a variety of situations, including EER and barge (drill pipe and cuttings) access to quay facilities for drilling structures. EER remains an issue for offshore production, transmission and processing facilities, although barge access requirements are reduced. Vessel operations can be improved in the presence of the sea ice cover through the construction of ice protection structures. Rock berms have been built for permanent structures, while refloatable steel protection structures have been built for deployment around movable drilling barges. The above rubble modelling techniques have been quite useful for the comparison of many structural configurations and layouts, and for estimating the frequency and duration of potential downtime events.

For EER, downtime can occur:

— for the duration of events, when rubble builds in the dock or launch area or when ice passing through the launch area or elsewhere exceeds the capability of the evacuation craft; and

— for the time to clear an evacuation route through the ice rubble following an event.

For quay access, downtime can occur:

- for the duration of events, when moving ice encroaches on the barge footprint within the quay area and when rubble builds in the quay area; and
- for the time to clear ice rubble from the quay and surrounding area following an event.

Several potential evacuation routes are considered for each layout and, as specified in the operating procedures, two or more routes should be available. Clearing times using ice management vessels are increased in the presence of grounded rubble, hence the need to characterize grounded features in the rubble modelling approach.

Example EER downtime results are shown in Figures 6 and 7 to illustrate some of the products that can assist with the design process. In this case, the EER installation was at the south end of the structure and a protection structure was in place to prevent direct encroachment.

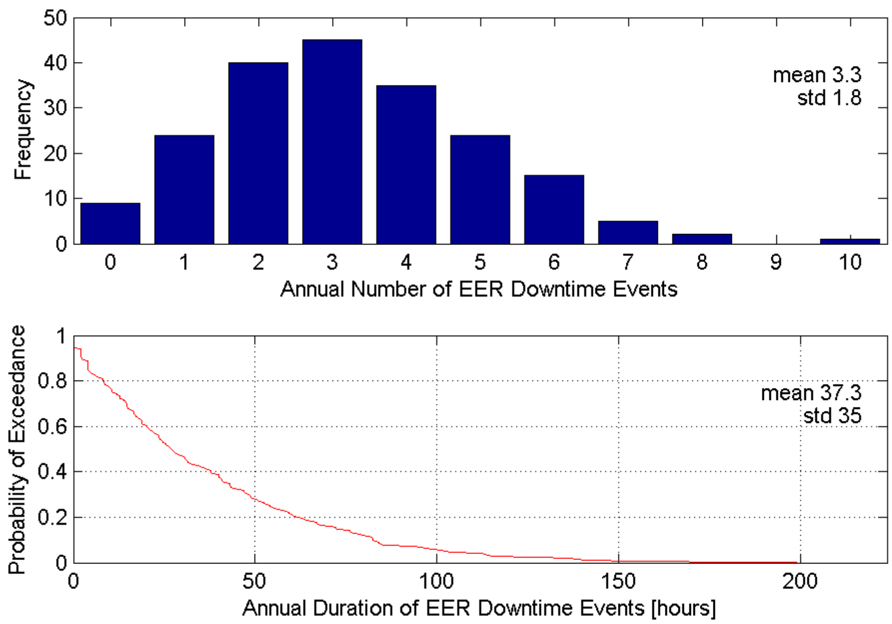

Figure 6. Example EER downtime calculations showing frequency and durations of events

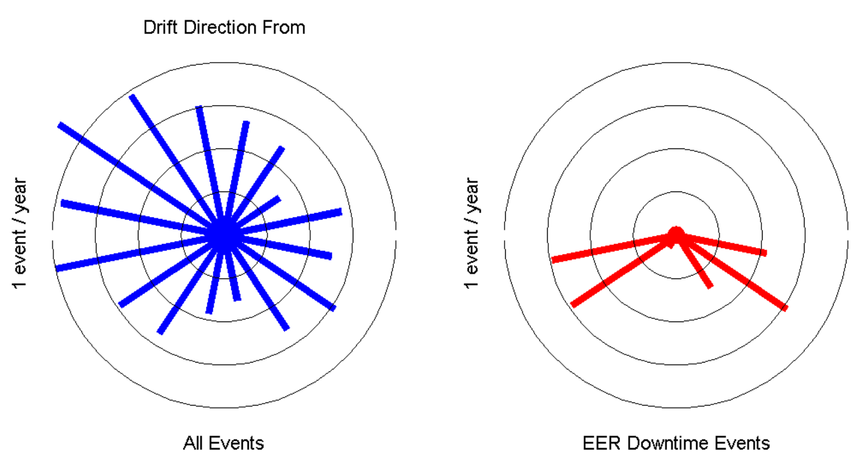

Figure 7. Example showing drift directions causing EER downtime

RUBBLE PROTECTION

For a number of Caspian Sea structures that do not require winter access, ice rubble is left to build up over the course of the winter. In such cases, the frequency of ice interaction events directly against the structure is reduced, which can potentially lead to reduced design loads. The rubble simulation procedures outlined above have also been applied to assist with the calculation of ice loads transmitted to structures through grounded rubble. Pressure on the seafloor can be estimated based on the number of grid squares consisting of grounded rubble and the excess rubble height over and above hydrostatic equilibrium. Regardless of seabed material properties, a lower bound estimate of the seabed resistance can be used to provide a conservative estimate of the ice force transmitted to the structure. Incremental calculations over the course of rubble building events have been used in combination with the probabilistic methodology for ice load calculations in Jordaan et al. (2011).

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