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Sea Ice Scour Depth and Width Parameters for Design of Pipelines in the Caspian Sea

Mark Fuglem[1], Grant Parr[1], Ian Jordaan[2], Paul Verlaan[3], Ralf Peek[4]
[1]C-Core, St John's, Canada
[2]Ian Jordaan and Associates, St. John's, Canada
[3] North Caspian Production and Operation Company, Atyrau, Kazakhstan
[4] Shell Global Solutions, Rijswijk, The Netherlands

ABSTRACT

Wind stresses on sea ice in the north-eastern Caspian Sea during winter result in the formation and movement of ice ridges and grounded ice structures called stamukhi, with resulting scouring and pitting of the seabed. In designing subsea pipelines, consideration needs to be given to associated loads on the pipe. This paper describes methods that were developed to estimate the expected maximum width and depth of scours at specified annual probabilities of exceedance per kilometre of pipe. These parameters were subsequently used with ice-soil-pipe interaction models to ensure pipeline designs and burial depths met required reliability levels.

Available data consisted of multi-beam echo sounder imagery of scour crossings along planned survey lines. Additional images of scour crossings as well as complete scours were obtained from targeted surveys in which operators followed scours or surveyed areas believed to have relatively high probabilities of deep scours. While the general distribution of soil types for the survey region was known; insufficient soil properties were measured at each scour for direct correlation to scour depth and width. The paper describes the methods used to determine appropriate scour width and depth parameters for design given the sources of uncertainty in the data and uncertainties regarding processes and ice features resulting in scour formation. This includes selection and fitting of distributions, accounting for differences between unbiased and biased survey data, and calibration and application of models.

OBJECTIVES

Development of the Kashagan oil field in the North Caspian Sea requires design and implementation of interfield pipelines and export pipelines to shore. The area of consideration (Figure 1) has shallow water depths with a maximum around 6 m to the west of the field and the export pipeline landfall north of the field. The area is subject to sea ice thicknesses up to 0.8 m that forms ridges and stamukhi with heights up to 15 m. A general description of the Kashagan project and requirements for pipeline design with respect to associated ice scouring and pitting is provided in Been et al. (2013), and outlines the basis for the reliability levels used. This paper describes methods used to determine extreme-level (EL; 10^{-3} per km-year) and abnormal-level (AL; 10^{-5} per km-year) scour dimensions required as input for determining design pipeline burial depths given specific soil conditions and pipeline configurations. Maximum depths were needed for consideration of direct interaction of ice keels with the pipeline and average depths and corresponding widths were needed for calculation of subscour soil displacements.

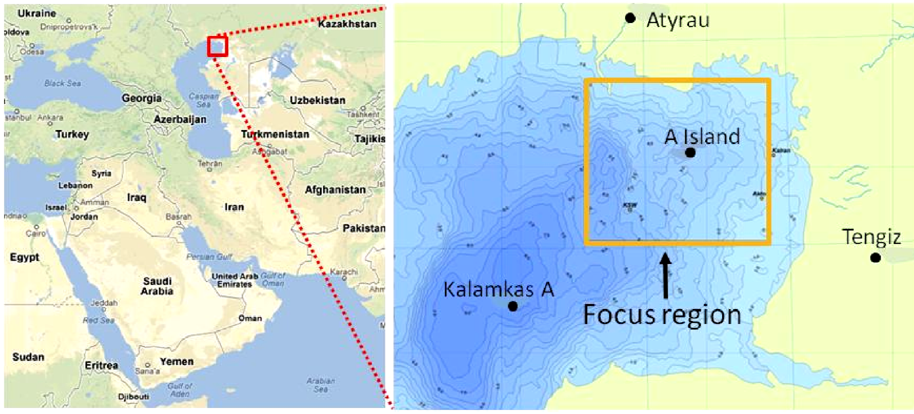

Figure 1 Region of focus for analyses

The measured depth and width parameters are taken from cross-sections perpendicular to the scour. Figure 2 illustrates idealized scour cross sections; the reported dimensions (width, maximum depth and average depth) are measured relative to the undisturbed sea bed. A more complex profile is shown on the right. In ice-soil-pipeline interactions, the influence of a scour on a pipeline is largely determined by contiguous deep areas and using the average depth over the whole width could underestimate the influence of the scour on a pipeline. Scours with significant sections less than half the maximum depth were assigned a reduced width, and scours with troughs a significant distance apart were treated as more than one scour.

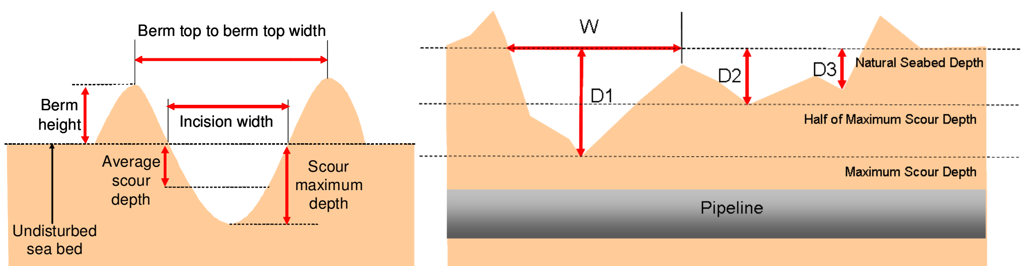

Figure 2 Definitions of key scour parameters

EL and AL maximum and average scour depths were required as a function of scour width, pipeline orientation and vicinity to structures. Scour width is important as strains for specific different pipeline systems and soils depend on the width of soil displaced. Pipeline orientation is important as the scours are observed to have a predominant north-east and south-west orientation. Higher scour rates have been observed in the vicinity of structures; as the structures result in formation of grounded ice features.

PHYSICAL PROCESSES

There is a broad spectrum of ridge and stamukhi shapes and sizes, with stamukhi having diameters in the order of 100 m with freeboards up to 15 m. Figure 3 shows examples of ridges and stamukhi plus a grounded stamukha with a wake due to movement of the surrounding ice.

Figure 3 Examples of ridges and stamukhi, and a grounded stamukha with wake of open water showing ice movement (KRCA, 2011b)

Scours are relatively linear features formed when stamukhi and grounded ridges move relative to the sea bed, given movement of surrounding sea ice. Figure 4 shows example multi-beam echo sounder (MBES) images of two deep scours, with berms around the scours shown in pink and the deepest sections of the scours shown in light blue. Scours may start and end with pits, and abrupt changes in direction associated with changes in sea ice driving forces often occur. Separate deep sections are associated with scouring by more than one ice keel and can change spacing depending on the direction of travel and orientation of the ice feature.

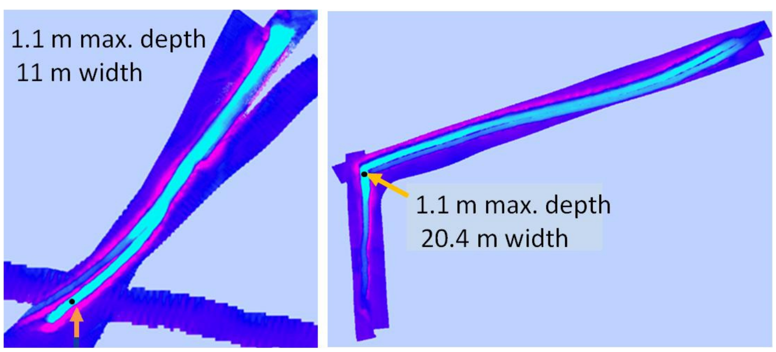

Figure 4 ARCGIS images for two deep scours

Winds from the north-east drive ice features into deeper water while reducing the water depth, thereby increasing the bearing force on grounded features. Winds from the south-west push ice into shore, resulting in additional ridging while causing surges in water depth than can lift grounded features.

Ridges form due to ice pressures in the ice and reach the sea bed if the ice is thick enough to support sufficient downward force, and the ice movement provides the required volume of crushed ice. Stamukhi form when ice starts to ride up on top of grounded features, and result in surplus bearing pressure. Stamukhi can be compact or fairly disperse with varied freeboard. Stamukhi with very large freeboards are unlikely to move and scour.

The deepest scours will occur when there is weak soil, large driving forces from the surrounding ice, a strong relatively narrow keel and sufficient vertical bearing pressure to cause a deep scour while not prohibiting movement. Deep scours could occur from stamukhi with moderate freeboards or grounded ridges either driven into shallower water or moved following significant reductions in water level. For ridges, sufficient resistance to lifting at the point of scour is required (bending resistance and shear strength). The strength of stamukhi and ridge keels may result through previous sintering of ice blocks under pressure, or dynamic effects due to loading during the scouring process.

AVAILABLE DATA

Data on environmental and ice conditions and scours has been acquired for the Kashagan region since 2002 with the methods used evolving over time. Winter field programs were conducted by helicopter to observe general ice conditions and identify positions and sizes of stamuki. LMS (Laser Mirror Scanner) surveys were conducted to measurement above water portions of stamukhi. Thermal drill programs were conducted on stamukhi to obtain direct sail height and draft profile measurements. Ice movements were measured and correlated to wind events and ice thickness (KRCA, 2011a). In 2002, scours were detected and measured from a vessel in open leads in winter using a single beam echo sounder. From 2003 to 2009, MBES data was obtained each spring after the ice had disappeared. The MBES data provides 3D profiles of the seabed surface over swath widths that depend on the MBES system and the water depth. Side scan sonar images were obtained; while not providing quantitative information they have larger swath widths than MBES so enable identification of features further to the sides of the survey vessel.

Two types of MBES surveys were carried out. First, ‘unbiased’ surveys along preselected tracks were carried out, where the tracks were selected in grids or along potential pipeline routes with no intention to focus on known or likely areas having scours and pits. Figure 5 shows the survey routes for 2008 as well as the locations of scour crossings for all years. The location of observed scour crossings depends on the locations of where surveys were conducted in addition to the local scour density. The scours observed in the unbiased surveys were used to estimate scour rates and average and maximum depth distributions from which EL and AL scour depths were calculated.

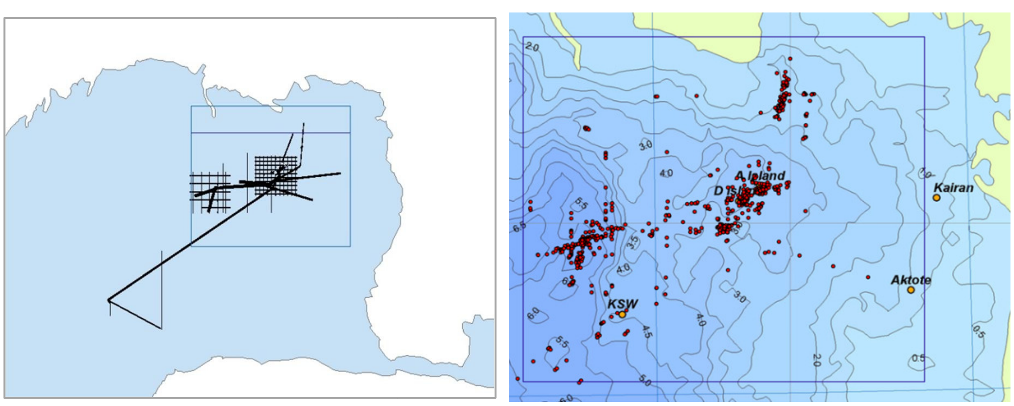

Figure 5 Survey routes for 2008 and locations of scour crossings for all years

Second, ‘targeted’ surveys were conducted whenever a scour in the unbiased survey had measured crossing depth greater than 0.3 m. The operators attempted to survey these scours along their whole length. Surveys were also targeted in areas where stamukhi had been observed. Data from the targeted surveys was subsequently used as a check on the validity of the results from unbiased survey data.

Soil data collected at scour locations was not sufficient for direct correlation with scour depths and widths. A stochastic scour model developed relating scour depths to soil type, calibrated so that distributions for observed and modeled scour dimensions approximately matched given the general distribution of soil properties in the focus region.

PROBABILISTIC APPROACH

Significant variations occur in the ice conditions at Kashagan from year to year and there is randomness in where scours occur and the scour dimensions. Estimates of scour crossing rates and distributions of scour depths are required. The annual rate of scouring over a pipeline is analogous to the rate of scour crossings during unbiased MBES surveys. It was necessary to extrapolate based on the scour data from the seven years of survey data to the low EL and AL probabilities of exceedance. This required fitting distributions to scour average and maximum depths, with emphasis on the behaviour of tails of the distributions at larger values. Procedures were developed to account for the uncertainties involved using a reasonable degree of conservatism.

In fitting scour maximum and average depth distributions to the data, a shifted exponential distribution was assumed. The distribution was fit by plotting the depths on exponential plotting paper (ranked depth versus –log10 of Cunnane plotting position), and using linear regression to determine the intercept and slope. Because of natural variations and corrections for infill, there were variations in the intercepts; for consistency corrections to crossing rates were applied to obtain the same intercept values (the original applied cut-off). For scours associated with an annual crossing rate ρ per km and shifted exponential depth distribution defined by intercept a and slope β, AL and EL depths are determined using the equation:

$$x = a + \beta\left[2.303\log_{10}\left(\frac{\rho}{p_{ep}}\right)\right]. \qquad (1)$$

where p_{ep} is the specified annual probability of exceedance per kilometer.

Separate values of β were determined for maximum and average scour depth for scours having widths in the ranges 0-5, 5-10, 10-15, 15-20 and greater than 20 m. To account for annual variations in conditions, given the limited number of years of available data, a separate analysis was conducted to determine scour rates and values of β for each of the seven available years. All widths were included as there was not enough data to conduct individual fits by both year and width bin. The values of the maximum and average depth β values for each width bin were then increased by 2 standard deviations on the mean value, i.e.

$$\beta' = \beta \cdot \left(1 + 2 \cdot CV / \sqrt{n}\right) \qquad (2)$$

where CV is the estimated coefficient of variation on β based on annual variations over the n = 7 years.

ANALYSIS AND MODELING

Analysis of Unbiased Survey Data

Cross-sections perpendicular to the scours were examined to determine the width, average depth and maximum depth of each scour relative to the undisturbed seabed. Only scours with maximum uncorrected depth greater than 0.1 m were used in further analyses. This cut-off was applied to limit the number of scours to a value that was reasonable to analyze; to limit the analysis to scours that would have a measurable effect on the pipeline; to eliminate problems with detection of very shallow scours; and to exclude relict or severely infilled scours. The cut-off is accounted for in the probabilistic methodology. As the MBES surveys were conducted after the ice had melted and wave-action could disturb the seabed sediments, corrections were made to the average and maximum scour depths to account for the estimated amount of infill between the time of ice breakup and the survey. The amount of infill was estimated based on number of storm hours (defined based on winds in excess of 10 m/s) using a model calibrated based on a limited amount of data where specific scours were measured both in the spring and fall.

Scour rates were determined as the total number of crossings divided by the total unbiased survey length. They are shown as a function of scour width in Figure 6. In determining EL and AL scour depths, the total scour rate was conservatively applied independent of the width range to which the distribution being used applied, the conservatism will be greater for larger widths. The influence of pipeline orientation and proximity to structures was evaluated and appropriate rate correction factors determined (the influence on depths was found to be small). There was an approximate 50% change in scour rates depending on the pipe orientation. The scour crossing rate within a half km of existing structures was found to be seven times higher than average rate away from structures.

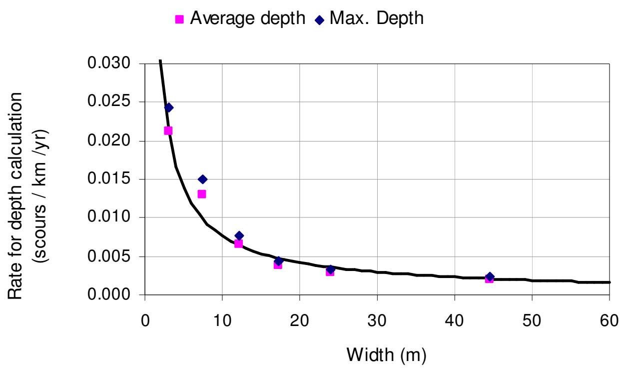

Figure 6 Scour rates as a function of scour width.

Survey widths varied from approximately 7 to 37 m. Within a crossing, there were varying lengths of scours sections depending on survey track orientation relative to the scour. Because the numbers of scour cross-sections for fitting depth distributions was limited; a decision was made to utilize more than one cross section per crossing when sufficient spacing between cross sections could be achieved (Figure 7). A statistical analysis was conducted to determine the correlation between scour depths for cross-sections at different spacings, a lower bound of 6 m was selected to limit correlation between cross-sections from the same scour.

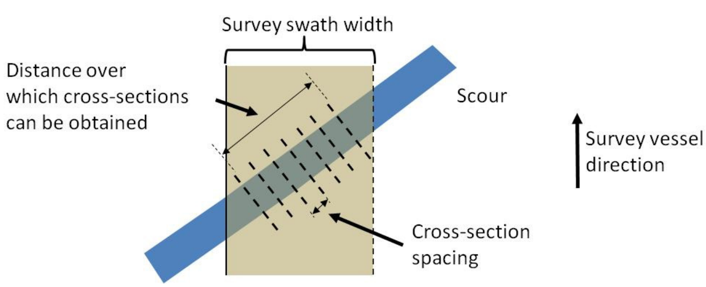

Figure 7 Multiple cross sections per encounter

Figure 8 shows the resulting distributions of average depth and width for single and multi-keel scours. Figure 9 shows example probability plots of scour depth with fits. For larger width ranges the deepest scours tended to be smaller than the best fit line (to roll off on the right side). This could result from limiting physical processes (relating to ice or soil strength), in which case use of a shifted exponential distribution would be conservative. Care is needed that the roll off is not due to correlations between data points. The resulting average scour depth beta values for different scour width bins are shown in Figure 10. A conservative envelope was fit to this curve and applied for determining EL and AL scour depths. Additional conservatism was applied for the smallest width bins to account for possible slumping during and immediately after scours.

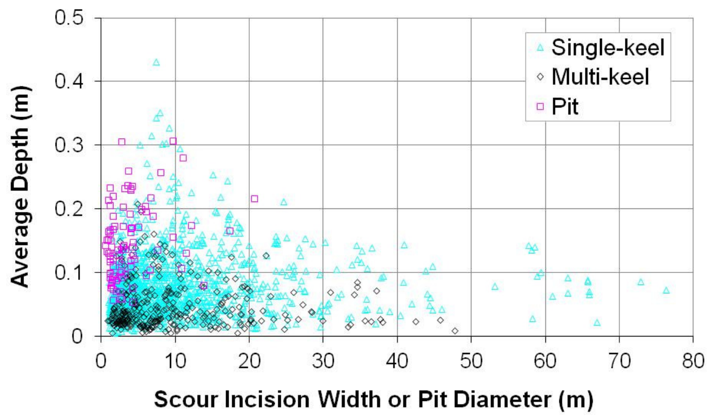

Figure 8 Average depths and widths for single and multi-keel scours and average depths and equivalent diameters for pits

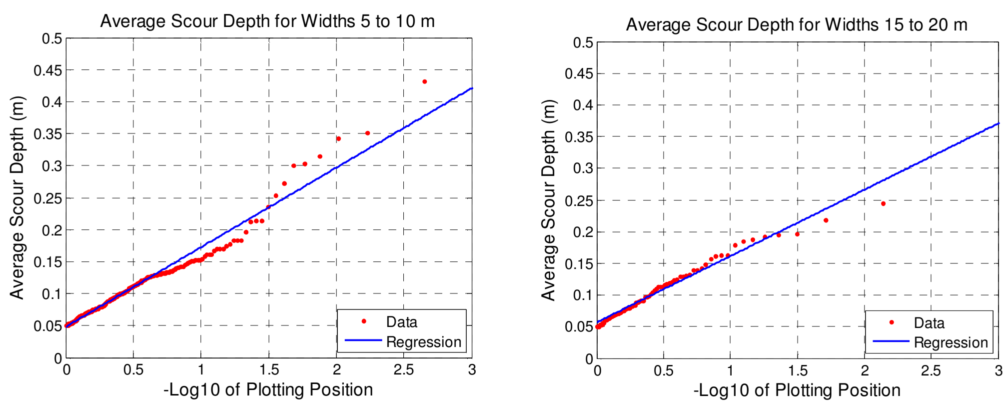

Figure 9 Example probability plots of scour depth with linear fits to provide parameters for shifted exponential distribution

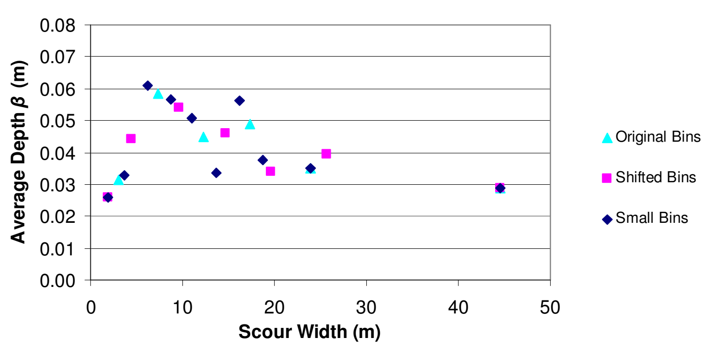

Figure 10 Average depth beta as a function of scour width: effect of bin size indicated

Analysis of Targeted Survey Data

Scour depths found during targeted surveys (with a maximum depth corrected for infill of 1.15 m) were deeper than the deepest scour depths from the unbiased surveys (0.66 m). As a check, a detailed review of the deepest nine scours was carried out. Five of these occurred within the focus region and four occurred outside. Figure 11 illustrates the variation in depth along two deep scours; the scour on the left has deep sections that are quite short, whereas the scour on the right has deep sections that are much longer and would pose more risk to a pipeline.

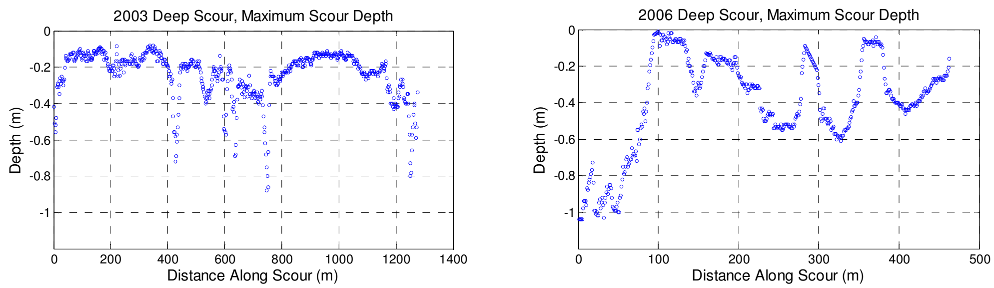

Figure 11 Variation in scour depth along the length of two deep scours

The equivalent unbiased survey effort to find the maximum targeted scour depth was estimated as the probability of an unbiased survey crossing of one of the deep scours at a location with depth greater than 0.3 m (resulting in a targeted survey) times the expected number of deep sections that would be analyzed, divided by the chance of crossing a deep section in an unbiased survey. The estimated probability of exceedance was slightly higher than expected given the depth distribution and crossing rate based on unbiased surveys, but lower and therefore conservative with respect to the distribution based on the recommended beta value accounting for uncertainties as calculated using Equation 2.

Check on assumed distribution type

As a check on the assumption of an exponential distribution, alternative EL and AL scour depths were determined using a non-parametric distribution for the maximum scour depth following the approach suggested in Peek (2009). Best, low and high estimates for scour depth distribution were selected using available information while ensuring the observed data generally remained with upper 95% and lower 5% confidence bounds on the probability of exceedance. Assume that N measured data points are the specific outcome of independent trials from a process that generates random values X from cumulate distribution $F(x)$ and that the data have been sorted, i.e. $x_i = x_1 \le x_2 \le \ldots \le x_N$. Based on the binomial distribution, the probability that at least n of N new samples would be less than or equal to a value x_i is:

$$P(X_n \le x_i) = 1 - B(n-1, N, F(x_i)) = B(N-n, N, 1-F(x_i)) \qquad (3)$$

where $P(.)$ denotes the probability of the event indicated within the parenthesis and $B(n, N, p)$ is the cumulative distribution function for the binomial distribution, giving the probability of n or fewer successes of N trials with probability of success p for each trial. The number of samples n (and hence the associated cumulative probability $F' = n / N$) associated with given values of P (for example, 0.05 and 0.95 representing 5 and 95% confidence levels respectively) can then be determined. Figure 12 illustrates the 5 and 95% confidence bounds on the 'high' estimate distribution for maximum scour depth from the Kashagan study. Note that the spread increases significantly at lower probability levels, reflecting the observed variance typically seen in the tail of distributions. The main advantage of the approach is that it gives a graphical picture whether the data provides evidence for rejection of proposed distributions. It should be noted that checks for different values x_i. are not independent so the method is approximate.

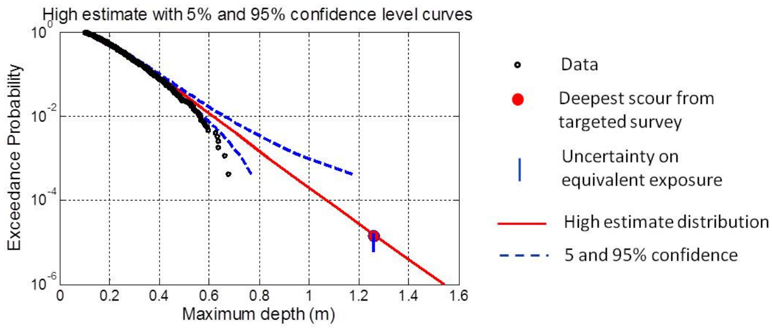

Figure 12 High estimate of distribution for maximum scour depth, with confidence bounds

The 'best estimate' distribution used was the shifted exponential distribution from the unbiased surveys. A 'low estimate' distribution was selected such that the available data generally fell within the 95% confidence limit. A 'high estimate' distribution was selected such that the available data generally fell within the 5% confidence limit and the cumulative probability for the deepest observed targeted scour depth matched the estimated equivalent unbiased exposure probability. The low and high estimate distributions were user defined. The low, best and high estimate distributions were combined with corresponding weights of 25%, 50% and 25% based on judgment. A factor of $\left(1+2\cdot CV/\sqrt{7}\right)$ was applied to account for annual variations. The different maximum depth distributions are shown in Figure 13; the final distributions for both maximum and average scour depth result in EL and AL values slightly less conservative than the approach actually used.

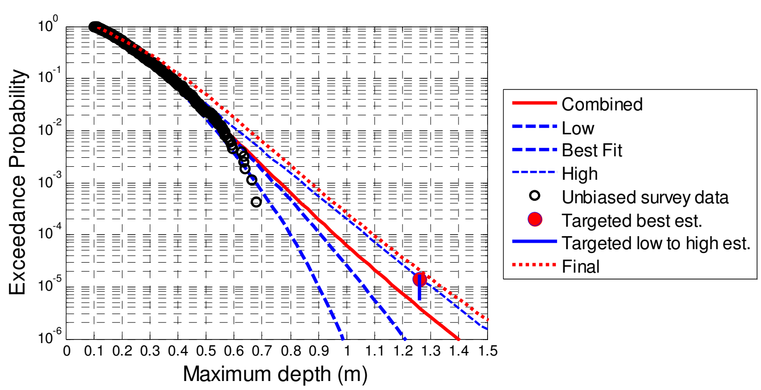

Figure 13 Final distribution of normalized maximum scour depth using alternative probabilistic method

Stochastic Scour Model

A stochastic scour model was implemented that considers soil type and was calibrated to approximately match observed distributions of scour widths and depths given the general distribution of soil properties, ice feature sizes and shapes, and water depths in the focus region. The model could then be applied to estimate scour depth distributions for particular soil types such as proposed backfill materials. An initial model was developed that simulated movement and scouring of both stamukhi and ridges. A population of ridges and stamukhi were generated and their behaviour in the environment modeled. The model accounted for changes in ice thickness during the year, the occurrence wind-induced ice movements, and changes in water depth plus seabed slope. The shape of ice keels (as scour) were treated as random; calibrated so that observed and modeled distributions of scour dimensions match. Soil resistance was modeled as a function of soil type and ice pressure was treated as a function of nominal contact area. One conclusion from the model runs was that deeper scours result from larger features because they can provide sufficient bearing pressure. A simpler model was then developed that was more effective for probabilistic analyses; the model was considered appropriate for relative comparisons. The model indicated that deeper scour depths occur in clay soils; with scour depths in sand approximately one third of those over the overall survey region. Table 1 shows the ratio of beta values for different soil conditions. EL and AL scour depths in typical backfill materials were estimated to be two-thirds deeper than the scours in 100% clay soils. The model indicated that the use of a shifted exponential distribution is conservative if soil strength consistently increases with depth. The model also showed that scour depths should be relatively independent of water depth; this agreed with analysis of observed data.

Table 1. Simulation results for effect of soil type on scour depth distribution parameters.

Case	**Ratio of beta to survey route value**
Survey Route: 33.7% Clay 66.3% Sand	1.00
100% Clay	1.15
100% Sand	0.37

CONCLUSIONS

The selection of scour depths as input for pipeline design for the northeast Caspian requires careful consideration, given limits in the amount of scour data available, conditions that vary both annually and with soil conditions and imperfect understanding of the processes involved. A probabilistic approach has been utilized based on unbiased survey data. Shifted exponential distributions have been fit to the scour depth data and used to extrapolate to lower probabilities of exceedance given observed scour crossing rates and specified reliability targets. To account for annual variations given the limited number of years of data available, the annual variation in depth distributions, characterized in terms of the variance in the parameter beta for the exponential distribution has been determined. As a safety factor, in determining EL and AL depths, the parameter beta was increased by an estimated two standard deviations on the mean. Checks were made on the sufficiency of this factor to account for uncertainty regarding the selection of distribution type and distribution parameters.

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