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Stamukha Pits – Input Characteristics for Design of Pipelines in the Caspian Sea

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ABSTRACT

Stamukhi form when moving sea ice piles up on top of grounded ice ridges. Pits in the seabed occur under heavily grounded stamukhi, due to the associated loads. In designing subsea pipelines in the northeast Caspian Sea, where stamukhi up to 15 m freeboard have been observed, potential loads on the pipe associated with development of such pits need consideration. The present paper describes the methods to determine the frequency of pit forming in the vicinity of a pipeline, probability distributions for the pit dimensions and from these, pit dimensions associated with specified annual probabilities of exceedance. These can be used with ice-soil-pipe interaction models to ensure pipeline designs and burial depths will meet required reliability levels.

A key aspect of the work was the statistical treatment of uncertainty in the data and processes. Pitting occurs under different ice conditions, water depths, soil types and distances to existing structures, which influence pitting rates. The influence of these factors was investigated. For example, while an overall distribution of soil types had been established, soil types for specific pits were generally not available. A probabilistic methodology developed to characterize influence of soil type was used to assess the influence of selected backfill materials.

The main analysis was based on data from unbiased surveys along preselected routes without prior knowledge of potential for pits. Additional data obtained from targeted surveys, such as at locations where stamukhi had been observed, was incorporated after assessing the equivalent unbiased survey effort. Methods were also developed to account for uncertainty due to the limited number of years of data available and the selection of appropriate probability distributions for inputs.

INTRODUCTION

Development of the Kashagan oil field in the northeast Caspian Sea requires the installation of pipeline systems. The area of consideration (Figure 1) has shallow water depths ranging from about 1 m near the shoreline to 6 m in Kashagan West. The area has sea ice with thicknesses typically up to 0.5 m. Ridges and stamukhi with heights up to 15 m can form. An example stamukha is shown in Figure 2. These features may grow, move and disperse. Action against the seabed during formation of a stamukha, and under subsequent gravity loads, may result in pitting (in addition to scouring) of the seabed. The largest pits observed in the Kashagan region during geophysical surveys have depths of approximately 1.2 m.

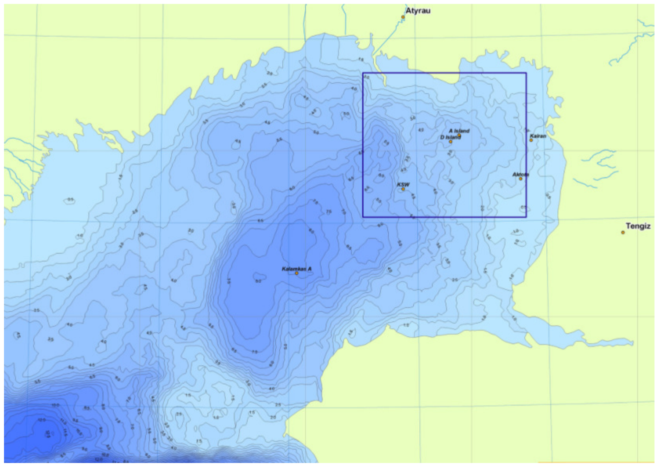

Figure 1. Area of interest in the northeast Caspian Sea.


Figure 2. Grounded stamukhi in the Caspian Sea.

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). This report is a summary of the methods used to determine extreme-level (EL; 10^{-3} per km-year) and abnormal-level (AL; 10^{-5} per km-year) pit 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 were needed for consideration of soil displacements in ice-soil-pipe interactions. Additionally, pit diameter and encounter rate were analyzed.

PHYSICAL PROCESSES

The exact processes involved in the creation of pits underneath ice features in the Caspian are not completely understood and it is likely that a number of processes are involved (Croasdale et al., 2013). Stamukhi generally have a relatively large positive grounding pressure. Stamukhi will remain at the same location unless driving forces (predominantly sea ice loads) are greater than the resistance of the soil to lateral motion, given the indentation into the sea bed and the vertical load. The likelihood of movement will be influenced by the water depth and stamukha size (length, width and height) in so far as these parameters affect both the grounding pressure and driving force. An analysis of stamukhi observations before and after a significant ice movement event showed that stamukhi with large average sail heights (and hence grounding pressure) were much more likely to remain at the same location during an ice movement events (KRCA, 2011a).

A number of mechanisms could result in the formation of pits under a stamukha, including vertical bearing forces due to the weight of the stamukha acting on individual blocks of ice (Figure 3 and Figure 4); increases in vertical forces where ice ramps up the side of a stamukha during formation; vertical and horizontal forces from ice that is subducted during formation of the feature (Figure 5); small translational and rotational motions of consolidated portions of the stamukha; and a floating stamukha or ridge becoming grounded due to moving into an area of shallower water or a reduction in water level. These different mechanisms could result in pits with different characteristics and different loads on an underlying pipeline.

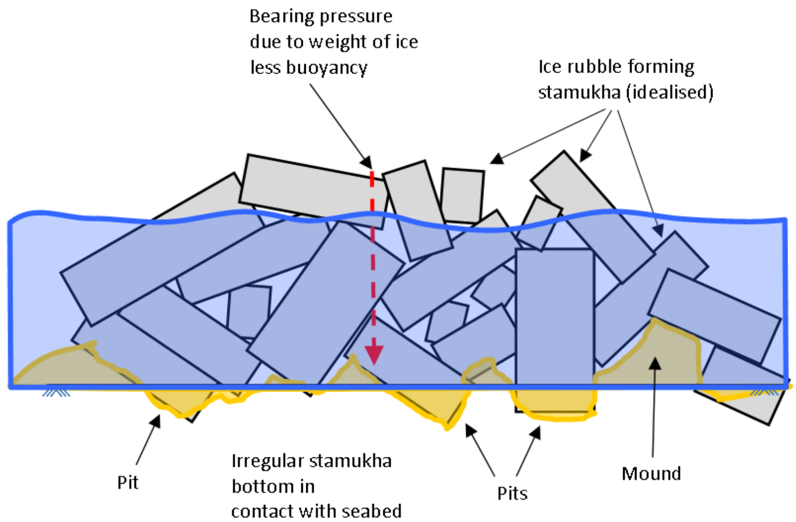

Figure 3. Pit formation due to average bearing pressure.

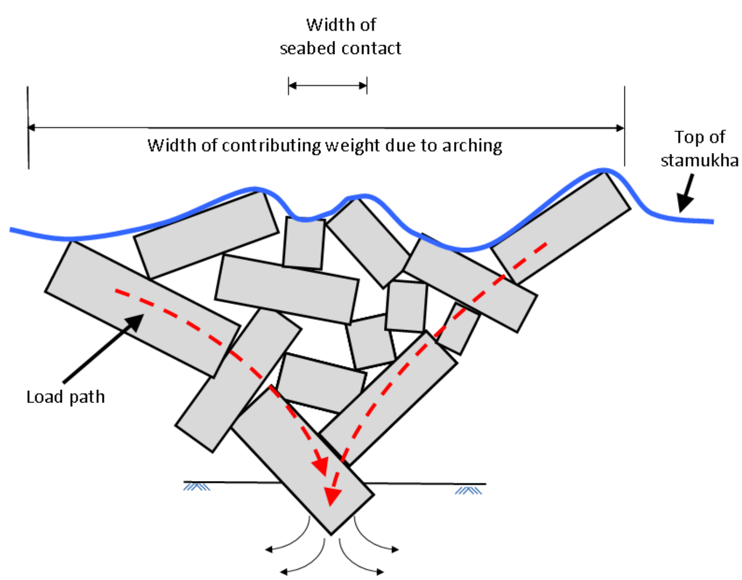

Figure 4. Increased loading associated with bearing pressure due to load concentration effect.

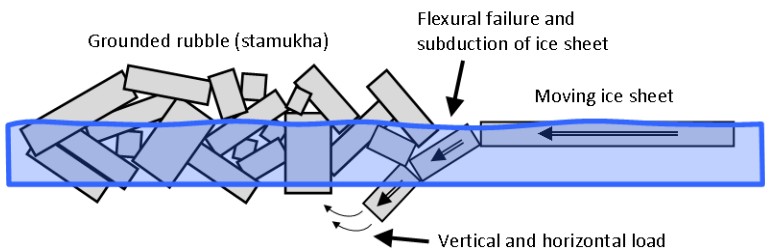

Figure 5. Vertical and horizontal load associated with subduction at stamukha exterior.

A profile of a stamukha footprint determined using a multi-beam echo sounder (MBES) is shown in Figure 6. The stamukha footprint is approximately 200 m long. Four large, deep pits within the footprint are labelled and outlined. In this case the stamukha had been identified and the sail surveyed using a laser mirror scanner (LMS) during the ice season. After the ice had melted, an MBES survey was conducted around the site where the stamukha had been observed. As it is certain that the pits resulted from the stamukha, the characteristics of the pits have been noted and used when trying to determine if other features were stamukha pits.

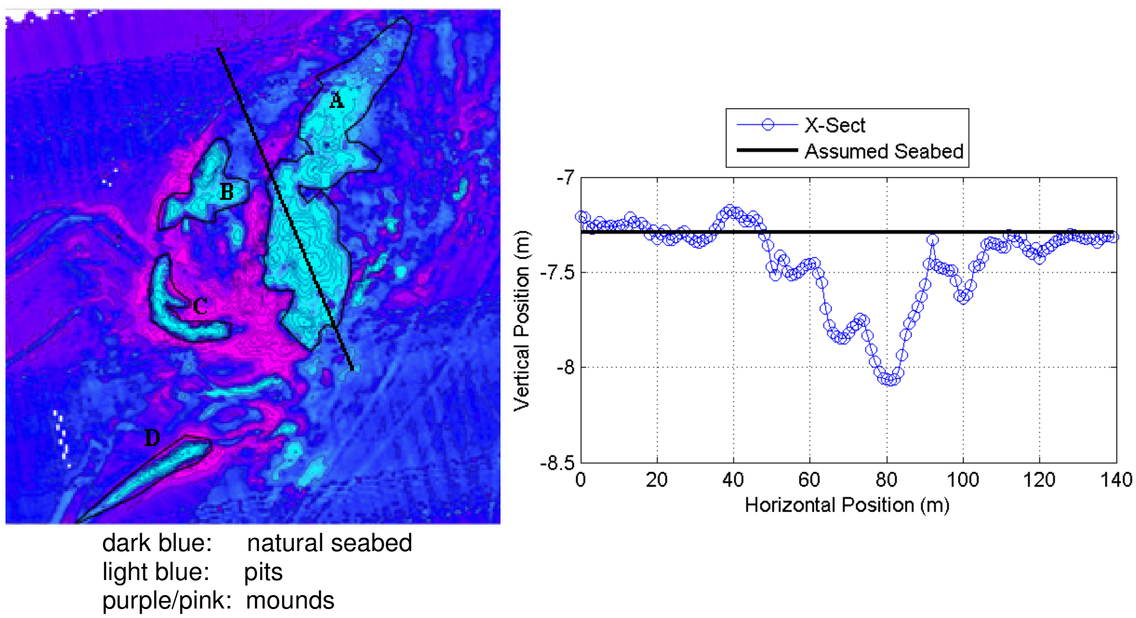

Figure 6. Footprint of a stamukha from 2008 showing 4 deepest pits labelled A, B, C and D and cross section through A.

PROBABILISTIC APPROACH

Significant variations occur in the ice conditions at Kashagan from year to year and there is randomness regarding the locations of pitting, the density of pits, and their dimensions. Estimates of pit crossing rates and distributions of pit depths are required. The annual rate of pitting over a pipeline is analogous to the rate of pit crossings during MBES surveys. It was necessary to extrapolate based on the pit data from the seven years of MBES survey data to the low EL and AL probabilities of exceedance. This required fitting distributions to pit 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.

A lower limit was imposed on the selection of pit depth data in order to improve fits to the data. Furthermore, some limit is required as the number of pits becomes very large as the limit approaches zero, making identification impractical. For the analysis of pit depths and pit encounter rates, a lower limit cut-off of 0.15 m was used.

In fitting pit 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 pits 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:

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

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

To account for the annual variations in conditions, a similar approach was developed for determining EL and AL pit depths as for scour depths (Fuglem et al., 2013). For scour depth, a degree of conservatism was incorporated by adding two standard deviations (based on the annual variation on the mean, and expressed here as a coefficient of variation, *CV*) to the value β determined based on annual regressions:

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

where n is the number of years for which data is available. The main difference between pits and scours is that is that there was less data for pits than for scours, and it was impractical to do regression fits for each year of data. The *CV* based on scour data was, therefore, applied for pit depths, under the assumption that the annual variance is similar, given the same winter conditions and other factors.

DATA ANALYSIS

A pit is defined as a contiguous area of the seabed that has been depressed below the surrounding natural seabed level. A footprint is defined as the entire area disturbed by a stamukha and may include areas higher than the natural seabed depth (mounds) as well as more than one pit. The stamukha footprint shown in Figure 6 includes a number of pits. In some cases, single pits are found that are not part of a larger footprint.

Two types of surveys were carried out to study pit depths. In the first, field personnel used a thermal drill (TD) to vertically penetrate the stamukhi and adjacent sea ice to measure the bottom location of the ice and the position of the sea bed. A jet of hot water from the thermal drill melts the ice. Contact with the seabed was determined when the drill probe stopped penetrating. Thermal drill data was collected from 2001 until 2003, and again in 2010. The TD data was collected along transects (straight lines), so that a 2D dataset is obtained, except for a small amount of TD data that was collected over grids in 2010. The spacing of the TD 2D datapoints varied but was generally about 2.5 m. Figure 7 shows a typical TD profile including the ice (grey), waterline (blue) and seabed (red). A total of 59 TD transects such as the one shown in Figure 7 were collected over the entire program.

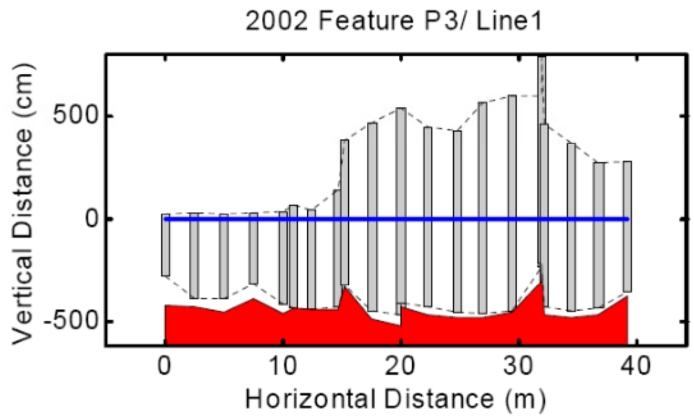

Figure 7. Profile of thermal drill data through a stamukha.

MBES surveys were carried out by Thales Geosolutions in 2003 and GAS (Geological Assistance & Services of Bologna) from 2003 to 2009. The surveys were conducted in the spring after the sea ice and stamukhi have disappeared. The MBES data comprises 3D data points on a grid with 0.5 m spacing. The MBES surveys were conducted along survey lines with swath widths in the range of 25 m. Generally only partial coverage of the pit or footprint was available within a single swath. Complete coverage of a footprint through multiple overlapping passes as shown in Figure 6 was not the norm. The total length of MBES survey was 8427 km.

Pit depths from MBES surveys have been corrected for wave generated erosion occurring between the end of the ice season and the date of 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 specific scours which were surveyed both in the spring and fall.

Pit areas, average depth and maximum depth were obtained from the 3D data set. The average depth is the average of all the points within the pit with respect to the natural seabed level. The maximum is the largest value within the pit. Similarly, the TD dataset was used to obtain average and maximum depths along transects of pits. The natural seabed level is determined by examining the MBES or TD dataset for areas where the seabed is flat and free of mounds and pits.

Some of the pits surveyed with MBES were random encounters along pre-planned survey routes meant to represent likely pipeline locations, areas around structures, or the region as a whole. These surveys are called *unbiased* surveys as they did not target any known stamukha locations or areas known to contain pits. Other MBES surveys targeted locations where stamukhi had been observed. These types of surveys were termed *biased* or *targeted* surveys. The targeted surveys tended to find deeper features since they often went to locations of particularly large stamukhi. During the MBES surveys carried out from 2003 to 2009 a total of 163 pits were encountered and analyzed. Of these, 94 were from unbiased surveys and 69 were targeted.

In addition to targeted and unbiased surveys, pits were classified into two categories based upon the amount of the pit surveyed during MBES surveys. Pits for which the entire pit was surveyed were termed *complete* pits and pits for which only a portion of the pit was surveyed were termed *partial* pits.

Pit Depths

Pit depth data was available from unbiased MBES surveys, targeted MBES surveys and thermal drill measurements. In addition, the MBES surveys included both complete and partial surveys of pits. The best data source for determining an accurate pit depth distribution is considered to be the unbiased multi-beam survey data. As the number of complete observed pits from the unbiased surveys was limited, a comparison of pits depths from the different sources was made.

Figure 8 shows the corrected maximum pit depths for unbiased MBES data with a cut-off of 0.15 m (left) and corrected maximum pit depths for targeted MBES data with a cut-off of 0.15 m (right). The depth parameter beta, for the exponential distribution, is determined from the slope of the regression line. Additional fits were made for including only complete pits as well as complete and partial pits only to determine if there were significant differences. The inclusion of partial pits resulted in larger beta values.

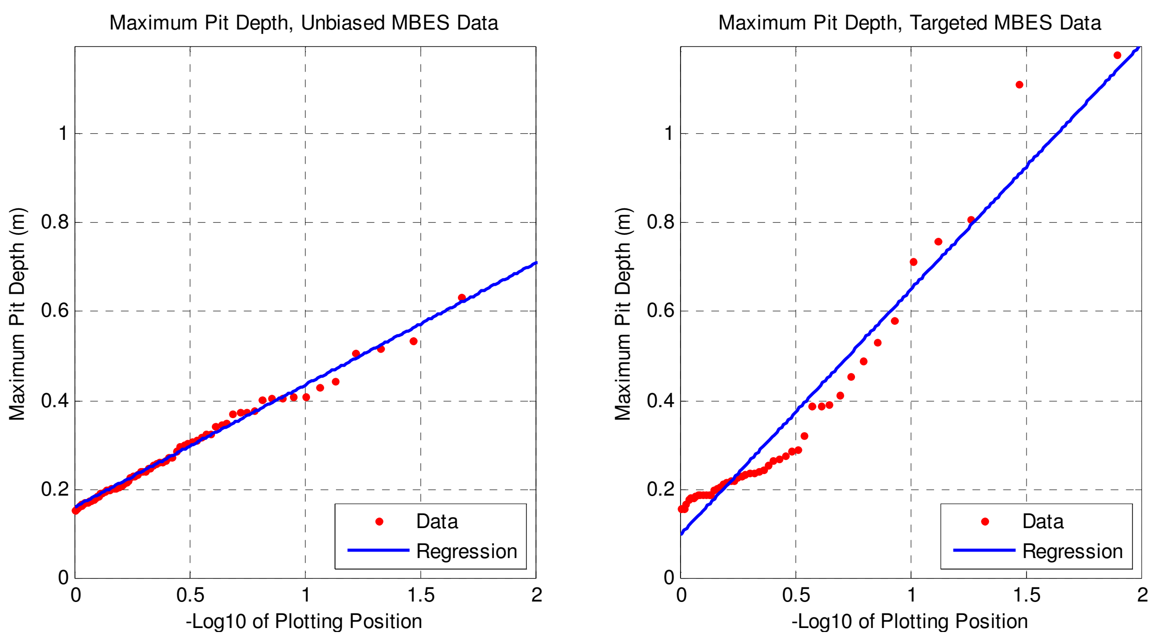

Figure 8. Maximum pit depths for unbiased (left) and targeted (right) MBES datasets.

Thermal drill data from 2001 to 2003 showed much larger depths than the MBES datasets. For the 2010 thermal drill field work, an improved methodology using pressure transducers was used. The resulting depths from 2010 were closer to the values obtained from MBES datasets. A sensitivity study showed that relatively small errors in the thermal drill data could account for the variation in results. On the other hand, there is uncertainty in the MBES data associated with the correction for wave-generated infill and the possibility that pits partially infill due to reworking of the soil as stamukhi form or move away from the area.

Two sources of targeted MBES data were available: pits observed during MBES surveys to sites where stamukhi had been observed; and surveys around structures where presumably large rubble piles had developed. The deepest observed pit occurred adjacent to a structure.

Based on judgment, a final value of beta was chosen based on a combined database including depths from both MBES complete and partial pits as well as the pits in the 2008 footprint (Figure 6) for which a complete profile was available.

Pit Encounter Rates

The *pit encounter rate* ρ is defined as the expected number of pits encountered annually per kilometre of pipeline. Pit encounter rates are based upon unbiased MBES surveys as this is the only dataset that provides truly random pipeline encounter rates. An encounter is defined as the occurrence of any part of the pit within a specified distance of the centreline of the pipeline. Unless otherwise specified, the base case encounter rates are for pits within a distance of 0.5 m of the centreline of the pipeline. Pits forming further away could have an influence on the pipeline due to the movement of soil and associated stresses. The resulting strains will depend on the design of the pipeline. Encounter rates were also determined for larger distances from the centreline of the pipeline. The swath centreline is taken as being representative of the centreline of a pipeline or pipeline bundle.

Encounter rates for pits are estimated from unbiased MBES survey data as follows:

- The numbers of pits that are at least partially within 0.5 m of the centreline of the survey swath and have a maximum depth of 0.15 m or greater are determined.
- The combined length of the unbiased surveys is determined.
- The number of pits are divided by the combined survey length.

The pit encounter rate was calculated for each year that MBES surveys were carried out. The annual average was then used as the design value.

Average pit encounter rates vary with location. Proximity to manmade structures and the shoreline affect rates. Of 163 pits (both targeted and unbiased), approximately 40 were found near installations. Based upon the amount of survey data near installations, the pit encounter rate was approximately 7 times higher than the focus region as a whole. A possible explanation for this increased rate is the increased likelihood of grounding and build-up of ice features near the structures.

Near the shoreline a zone of landfast ice forms. In this area the ice is frozen in place and immobile for much of the ice season. Helicopter surveys of this region showed no stamukhi were present over the course of several ice seasons. Based on the assumption that the rate of pit occurrence was directly proportional to the rate of stamukha formation, an estimate of pit encounter rates in the landfast zone was determined using a Bayesian approach described in Jordaan (2005). The rate of occurrence was estimated to be much lower than in the focus region as a whole. Furthermore, due to the fact that the ice in the region only moves and forms stamukha during the early season when ice is thin and the late season when ice is soft, a lower recommended value of beta was estimated based upon the model for ice pile-up heights described by Christensen (1994) and the assumption that pile-up heights and pit depths are proportional.

Pit Diameter

Pit equivalent diameter is defined as:

$$D = 2\sqrt{A/\pi} \quad (3)$$

where A is the area of the pit in plan as determined from the MBES data grid. A pit equivalent diameter distribution was determined by analyzing profiles of those pits completely contained within the MBES survey swath width. A tendency to smaller diameters results because pits that are large relative to the swath width are less likely to provide complete profiles and so will be under-represented. Furthermore, a large pit is more likely to encounter a pipeline than a smaller pit. A statistical method was developed for correcting the observed diameter distribution to account for these two factors based upon different zones of influence around the pipeline and the MBES survey swath width. The resulting distribution of pits encountered by a pipeline was calculated to be larger than the observed distribution within the MBES data swath.

Check on Distribution

Three areas of uncertainty arise with regard to the pit depth distributions:

- uncertainty in estimating β, given the available number of pits per year
- uncertainty in β as a result of annual variations, and
- uncertainty regarding the shape or type of distribution.

These uncertainties were accounted for by applying the factor $(1+2\cdot CV/\sqrt{n})$ to beta dependent upon the CV for annual scour variation as shown in Equation 2. Two checks were performed which showed that the factor on beta was conservative.

In the first check, the recommended values, determined from a beta based upon all the datasets, were assessed against the deepest observed pits from targeted surveys. Stamukha generated pits were targeted for biased MBES surveys based upon helicopter surveys of stamukha locations. An equivalent unbiased MBES survey effort was calculated in such a way that the probability of finding these deep targeted pits randomly was taken into account. The results showed that the recommended values of EL and AL were not out of line given the estimated exposures for the deeper targeted pits (noting that a decision was made to include the pits from the 2008 complete footprint in the database used to determine beta).

As a check regarding distribution uncertainty, a procedure was implemented that uses a non-parametric distribution for pit depths in determining EL and AL depths. This method (Peek, 2009) was also used for scour depths and is described in Fuglem et al. (2013). The analysis resulted in EL and AL values slightly less than the recommended values, supporting the approach used.

Soil Strength

The distribution of pit depth reflects the combination of soil conditions along the survey routes. In order to estimate pit depths in different soil conditions, a probabilistic stamukha pit model was implemented and calibrated based on the observed distribution of unbiased average pit depths. Soil conditions corresponding to each pit were not known, as a result, the pitting model was run for a distribution of soil conditions representative of the survey route as based on measurements. The pitting model was based on the Vesic model (Bowles, 1988) for bearing capacity of foundations. A model to account for increases in contact area as ice keels penetrate was proposed and calibrated to approximately match the observed distributions of pit sizes. The model tended to give greater depths than observed; this was attributed to increases in soil strength with depth having not being taken into account. The results were considered appropriate to give first-order estimates of relative pit depths for different soils.

For the mixture of soil conditions along the survey route (1/3rd clay and 2/3rd sand), the model resulted in beta values closer to those for 100% clay mixtures than for 100% sand as the pit depths for sand soils were relatively shallow. For cohesive backfill materials with cohesion uniformly distributed from 2 to 12 kPa, significantly higher beta values were estimated. The results for the different cases considered are shown in Table 1.

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

Case	Ratio of beta to survey route value
Survey route: 33.7% clay 66.3% sand	1.00
100% clay (uniform 5-20 kPa)	1.04
100% sand (ϕ uniform 28 to 43 degrees)	0.22
Backfill (uniform 2-12 kPa)	1.47
Clay - minimum strength (5 kPa)	1.51
Backfill - minimum strength (2 kPa)	2.01

CONCLUSION

Inputs for pipeline design in the Kashagan field were determined based upon MBES surveys and TD datasets. EL and AL values for average and maximum pit depths were calculated based upon pit depth distributions and pit encounter rates determined from the data. EL and AL values were found to vary with proximity to installations and the shoreline. Uncertainty in estimating the distribution parameters, annual variation and the choice of distribution have been accounted for by a factor based upon the annual variation in scour parameters. Further analysis on the deepest features found in targeted surveys and an alternate approach to extrapolating depths at low probabilities showed that the approach was sound. The effects of different backfill materials in the pipeline trench were investigated. A corrected pit equivalent diameter distribution was also determined for pipeline design.

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