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Practice for Pipeline Design in Ice Scoured Environments: Application to the Kashagan Project

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ABSTRACT

The Kashagan project in the North Caspian Sea, when fully developed, could include as much as 1000 km of buried pipelines, umbilicals and power cables. Since the North Caspian freezes each winter, these structures are subject to loads from ice scouring and stamukha formation associated with moving ice. The high cost of deeper burial to reduce risk of damage to pipelines means that considerable effort has been put into the data collection and design methods for pipeline during the various stages of the project.

An approach to pipeline design for ice loads has evolved during ten years of data collection, studies and engineering design for the Kashagan Project. This paper describes the criteria developed for Phase II of the project. The design process starts with determining the probability of exceedence appropriate for the design load cases. However, the loads are never measured, but have to be determined based on observed effects of ice scouring and stamukha on the seabed. Then the mechanism by which the ice interacts with a buried pipeline is considered so that the design scour width and depths can be translated into soil displacements which are applied to the pipeline (in a pipe – spring model). The interactions between stamukha pits and a pipeline are different from scours. If the pit depth is greater than the burial depth, direct contact between the ice and pipeline can occur and ice crushing pressures may need to be considered as well as soil displacements.

Additional complications to the design include the geometry of the pipeline trench and the difference in soil strength within the trench and the surrounding seabed. Combinations of scouring events at the same location, as well as a single extreme event also need to be considered in terms of accumulated plastic strains in the pipeline. Upheaval buckling could also be triggered at a scour or pit location

INTRODUCTION

The Kashagan project involves development of an offshore oil field in the North Caspian Sea, Figure 1. Verlaan & Croasdale (2011) describe the ice conditions in the North Caspian and the related design issues for structures and pipelines. When fully developed, the project could include as much as 1000 km of subsea pipelines (flow lines, trunklines, injection lines), umbilicals and power cables. Subsea pipelines, umbilicals and cables are buried to mitigate the effects of ice scouring and stamukha loads. Minimising the burial depths is an important economical and engineering design challenge.

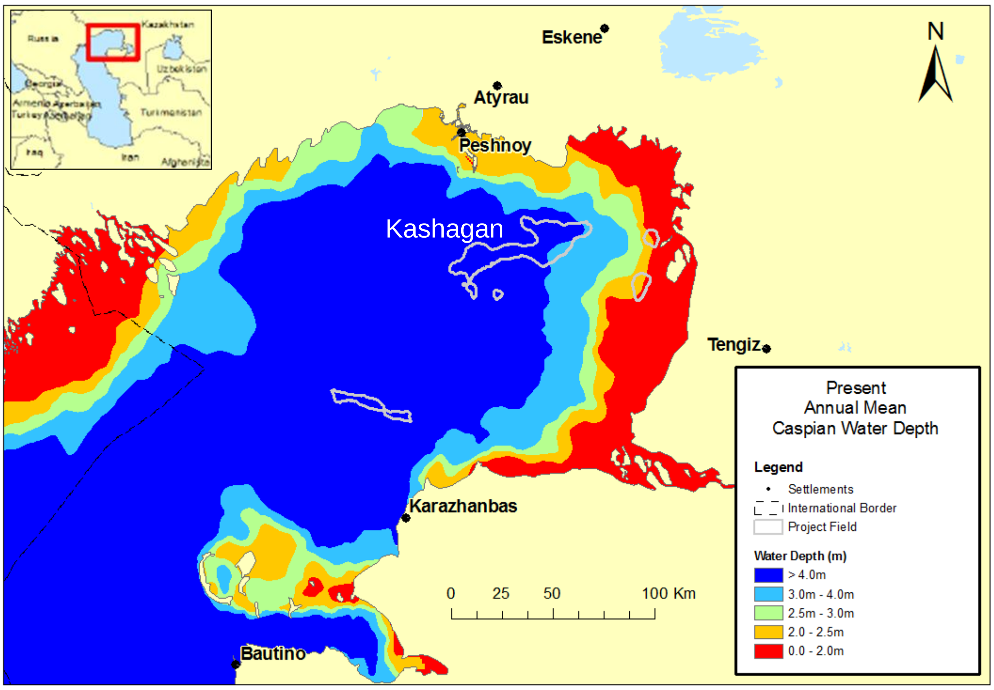


Figure 1. Kashagan Project in the North Caspian Sea.

Over the past ten years, considerable resources have been put into pipeline burial depth studies for the Kashagan project. This work has included field data collection, physical and numerical modelling of the key physical processes and engineering design. The high level the design process is very simple, Figure 2, but at the detailed level has evolved significantly as more data have been gathered (e.g. Nilsen & Verlaan, 2011) and understanding has increased. In this paper we describe the approach that is now current, along with the logic supporting this methodology. Reference is made to several companion papers providing greater detail of particular aspects of the analyses supporting the design method.

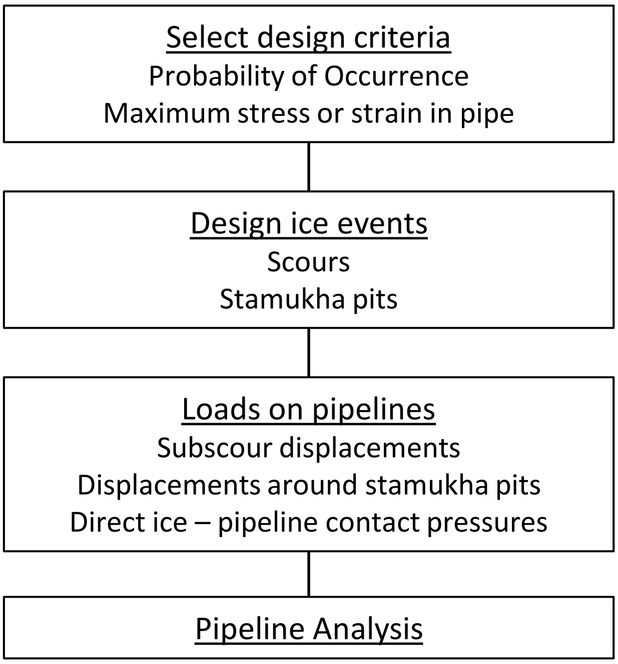


Figure 2. Design Process for Buried Pipelines in Ice Scoured Environments.

DESIGN CRITERIA

The Kashagan pipeline design team adopted probabilistic design criteria, and an early question was whether the failure probability should be "per km" or "per pipeline". The latter could lead to two similar pipelines, of different lengths, having different burial depths (or alternatively a different wall thickness) while the former results in a notionally different reliability for a long versus short pipeline. We also noted that data from actual offshore pipelines in the North Sea (AME, 1998) indicated a higher probability of failure than the design (nominal) probability of failure in offshore design codes, specifically DNV (2007). One of the reasons for this higher failure rate is that many failures are the result of loading or events that are not considered in the structural design of the pipeline.

The logical extension of this observation is that designing a pipeline to ever lower probabilities of structural failure will not necessarily decrease the actual failure probability. Our approach was therefore to select design ice loads on the pipeline that would be consistent with nominal probabilities of failure approximately one order of magnitude less than the observed failure probabilities of offshore pipelines. Since there is additional conservatism between the application of the design loads and calculation of stresses and strains and strains to failure, this approach means that structural failure of the pipeline due to ice loads is much less likely than due to other causes. Within this framework, two design loading levels for ice loads were specified as indicated in Table 1. Whether the environmental or accidental load case governs the burial depth depends on the operating conditions of the pipeline as well as the load factors that are applied to the environmental load.

Table 1. Ice Load Design Criteria for Kashagan Phase II Pipelines.

Design Load	Probability of being exceeded
Environmental Load	10^{-3} / km / year
Accidental Load	10^{-5} / km / year

During the project, analysis of pipelines under ice scour loading indicated that each pipeline had a critical width of loading. For a given scour depth, the maximum strain the pipe occurred when the soil displacements due to ice scouring were applied over a specific width. This critical width is different for each pipe, and Figure 3 illustrates this for two pipes. Critical widths were found to vary between about 4 m and 20 m, but depended on factors such as operating temperature and pressure as well as soil properties and ice scour loading.

This dependence of pipeline strains on scour width has interesting implications for design, because there is logically a relationship between scour depth and scour width. Wide scours are shallower on average than narrow scours, but wide scours also tend to have narrow deeper sections within them.

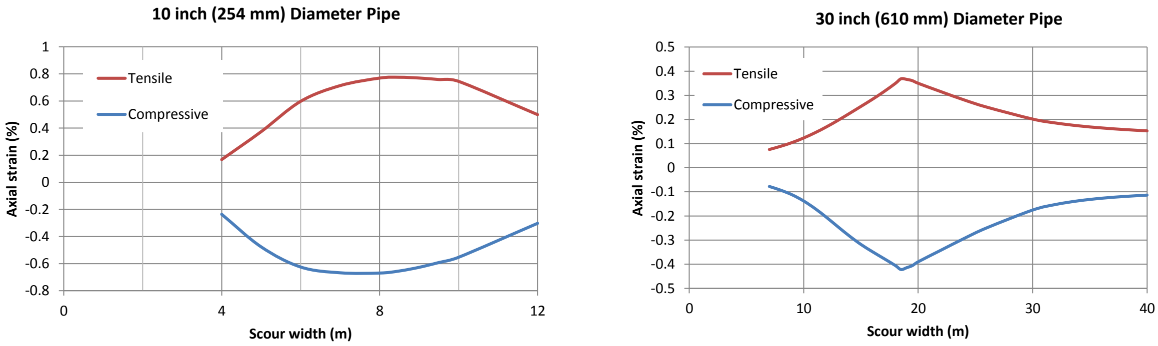


Figure 3. Critical Width for Two Pipelines under Ice Scour Loading (Been et al. 2011)

DESIGN ICE EVENTS: ICE SCOURS AND STAMUKHA PITS

Two types of ice loads need to be considered; scours and pits. Ice scours (or gouges) are caused by moving ice being dragged along the seabed. Analysis of such data to produce a design scour depth and width is addressed in a companion paper, Fuglem et al. (2013). Stamukha are stationary grounded ice features and form pits in the seabed. Scours and pits are considered separately, but in reality pits may occur at the end of a scour (as the scouring ice feature comes to a standstill) or even within a scour if the ice stops moving temporarily. Calculation of design pit depths is described by Parr et al. (2013). In general scours result in greater burial depths than pits.

LOADS ON PIPELINES

There are several loading scenarios to consider when developing design load cases for pipelines due to ice. Table 2 lists the loading scenarios considered at Kashagan. An overarching concept is that moving ice scouring the seabed should not come into contact with a pipeline, cable or umbilical.

Since pipelines are buried below the deepest scours to avoid contact with the ice, the pipeline loading from ice scours is through subscour displacements of the soil. However, we found that design pit depths could exceed the burial depths to avoid extreme scours, especially when considering very soft backfill or incomplete backfilling of pipeline trenches. Rather than force burial depths to exceed extreme pit depths, we considered load cases from stamukha where direct contact between stationary ice and the pipeline can occur. These interaction scenarios between pits and pipelines are discussed in more detail by Croasdale et al. (2013).

Subscour Soil Displacements

Accepting that the pipeline will be buried below the deepest scour depth, the loading on the pipeline is due to soil displacements caused by ice scouring, so called subscour displacements. Figure 4 is an illustration of the ice scouring problem, showing that the subscour displacements reduce with depth below the scouring ice feature. Consideration must also be given to the distribution of subscour soil displacements away from the centreline of the scour, which as illustrated on Figure 4 is typically taken as a sine function of the maximum (centreline) value.

Subscour soil displacement is a much researched topic although reliable and agreed models do not yet exist. In a companion paper, Been et al. (2013) provide a review of research and project related studies to determine subscour soil displacements.

The seabed soils in the North Caspian are highly variable, and consistent of a range of sands, silts and clays. As described in Fuglem et al (2013) we were able broadly to determine that scour depths in sands were significantly less than average while scour depths in soft clays were greater than average. Based on the surveyed soil type along the pipeline alignment or in a particular segment of a trunk pipeline, we were able to refine the design burial depth accordingly. This resulted in a reduced burial depth requirement in sands compared to early in the project when we used the same scour depths in sands and clays. For a given soil displacement, however, the load from a sand is higher than from a clay because the sand is much stiffer.

An added complication arises from the fact that any buried pipeline is placed within a trench, and the trench backfill is unlikely to have the same strength as the surrounding natural seabed. There is therefore the possibility that an ice feature scouring over a buried pipeline will drop into the trench as it crosses the pipeline. This is particularly important in cases where multiple pipelines, umbilicals or cables are to be laid in the same trench with a minimum separation between each structure. Trenches in these cases may be tens of metres wide.

Using the same relationships between scour depths in sands and clays discussed above, the design scour depths in wide trenches were increased to reflect the potential increase in scour depth resulting from soft backfill. The depth increase is somewhat mitigated, however, in that displacement of soft backfill results in lower forces on the pipeline.

Table 2. Design Load Cases for Ice Action on Kashagan Pipelines.

Consideration	Load Case	Comment
Ice regime	Landfast or mobile ice	Design scour and pit depths reduced in landfast ice zone
	Proximity to structures	Observed scour frequency increases near existing structures
Ice Scouring: Subscour Soil Displacements	Clay soil or sand soil	Design scour depths as well as subscour displacements are different in sands and clays
	Trench width	Where multiple pipelines are placed in a single wide trench, scour depths are increased because backfill is softer or looser than natural seabed
Stamukha Pits	Vertical loads	Soil displacements or ice pressure (when pit depth is greater than burial depth)
	Lateral soil displacement	Pit is adjacent to pipeline (not directly above)
	Subduction of ice sheet during stamukha formation	Soil displacements or ice pressure (when pit depth is greater than burial depth)
	Trench slope failures	Heavily grounded stamukha forms adjacent to trench in soft clay
	Concentrated ice loads	Individual ice blocks crushing against pipeline
	Ice sheet ramping during stamukha formation	Special case of vertical loads
	Transition of deep pit to ice scour	Stamukha can break up or start moving, but this case is a subscour displacement loading
	Sand backfill in soft clay paleochannel	Design case avoided through construction control on backfill type
	Punch through failure – sand layer above soft clay	Design case avoided through construction control on backfill type
Upheaval Buckling	Reduced cover due to removal of material by ice scouring	Vertical imperfection and scour or pit overlap
Multiple Load Events	Plastic strain accumulation	Overlapping scours during design life of pipeline

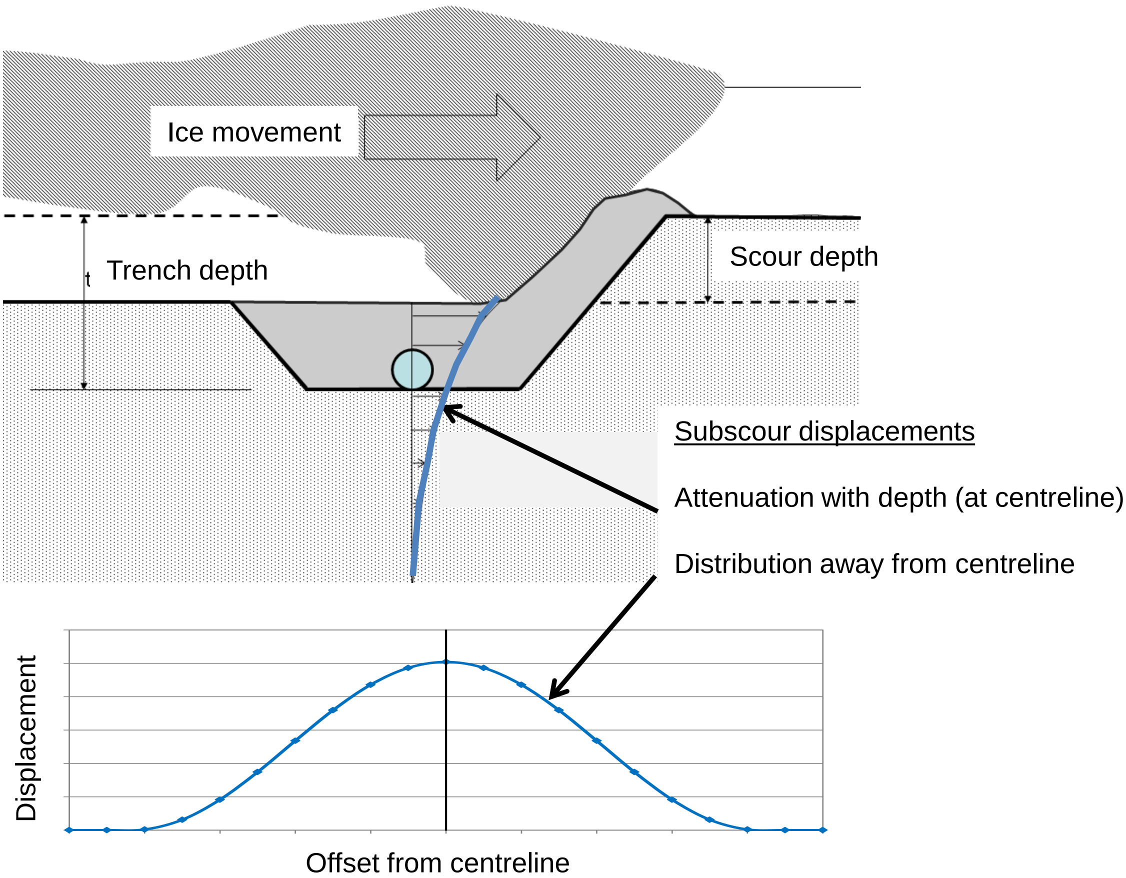


Figure 4. Ice Scour and Subscour Soil Displacements.

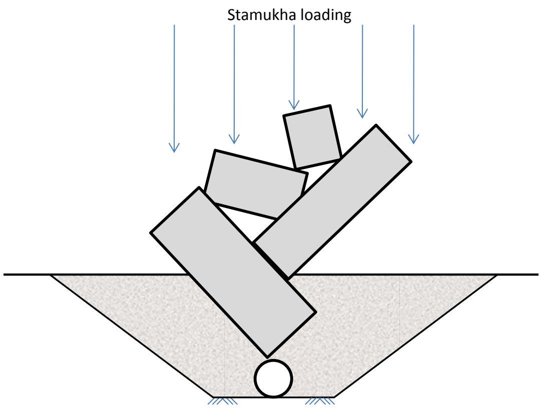
Soil Displacements around Stamukha Pits

The pit – pipeline interaction scenarios and resulting load cases for pipeline design are listed in Table 2. As discussed earlier, both soil displacement loading and direct ice – pipeline contact loading scenarios were considered.

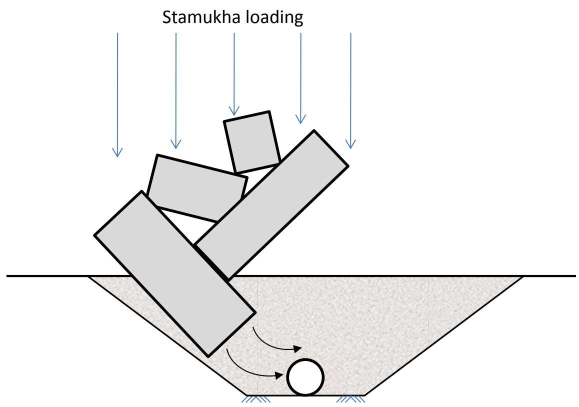
Only the interactions that give rise to the largest loads or displacements need to be considered as design load cases. The design stamukha load cases for Kashagan pipelines are shown on Figure 5. Vertically downward soil displacements when a stamukha is directly over the pipeline are excluded, because the loading from direct ice contact with the pipeline is the more critical loading in this case. If the design pit depths were less than the burial depth, then vertical soil displacements would have been considered.

Figure 5d illustrates an unlikely mechanism but one that should nevertheless be considered. If the trench is backfilled with very soft clay, a heavily ground stamukha on the seabed adjacent to the trench could induce a failure of the trench wall, resulting in lateral displacement of the soils around the pipeline over a significant length of pipeline (since stamukhi can be large). Rather than design the pipeline for this failure mode, a design requirement was imposed to carry out stability analyses for the anticipated seabed strengths. This mechanism does not occur for typical seabed strengths and stamukha heights in the North Caspian, but potential mitigation measures include changing the trench geometry (flatter slopes) or increasing the strength of the backfill.

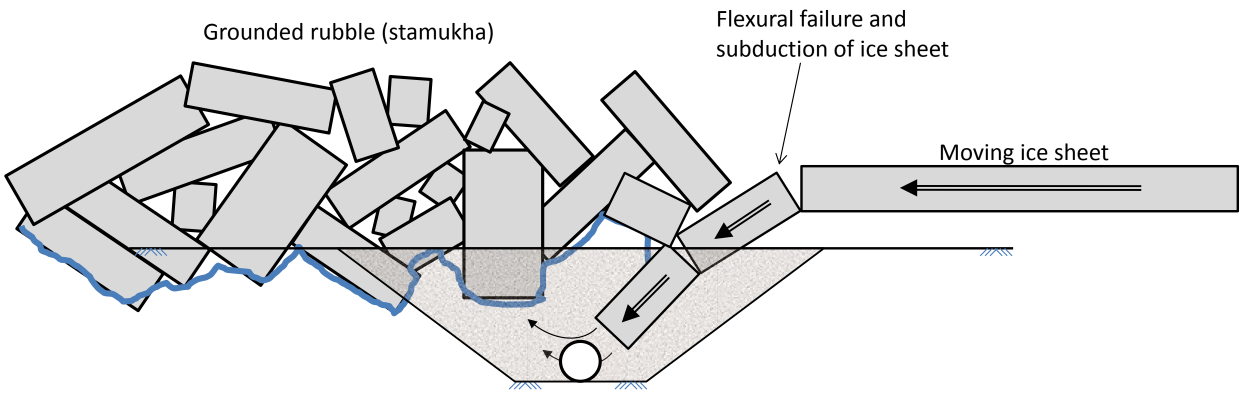
The soil displacements around a stamukha pit (Figure 5b) can be modelled with sufficient accuracy using finite elements or even analytical solutions. The numerical problem differs from ice scouring in that continuous movement of the ice, pore water drainage, rate effects and very large strains need not be considered. Further, we have not yet found a pipeline design case where pit related soil displacements were a more critical load case than direct ice contact or ice scouring.



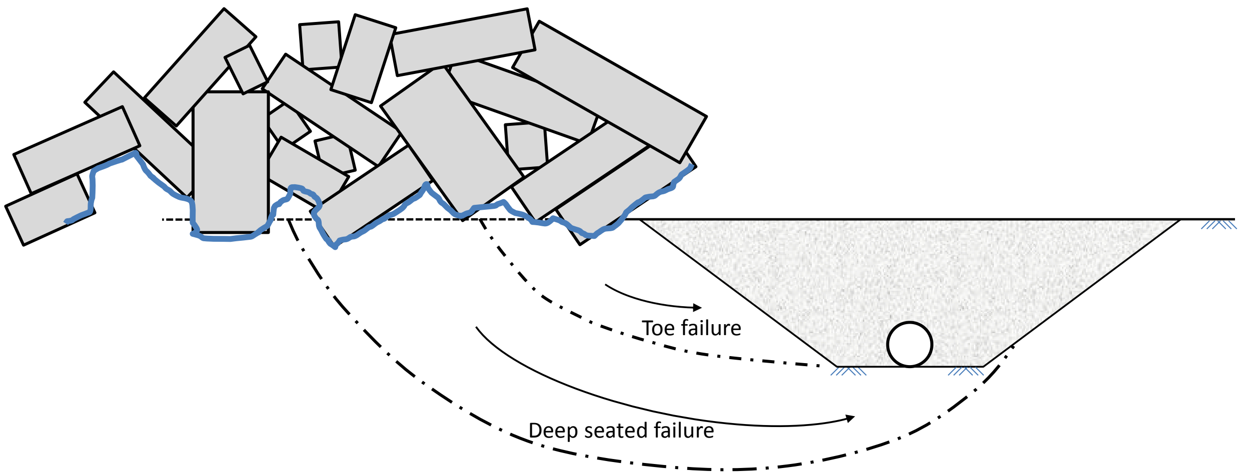
a) Vertical Loading (Direct Contact



b) Lateral Soil Displacements (Pit Adjacent to Pipeline)



c) Ice Subduction During Stamukha Formation



d) Trench Slope Failure due to Stamukha Loading

Figure 5. Stamukha Load Cases for Buried Pipelines at Kashagan.

Direct Contact Ice Loads

In the direct ice contact loading cases (either vertical from the weight of the stamukha above the pipe, or from subduction of the ice sheet during stamukha formation), the strength of the ice rubble is a key parameter determining the load on the pipeline. The load on the pipeline depends on the loaded area or length of pipeline, with the contact pressure dependent on the area of contact as described in Croasdale et al. (2013). The design requirement is therefore to apply the ice rubble crushing pressure to lengths of pipeline ranging from 1 m (small contact area, higher pressure) to 20 m (large contact area, lower pressure).

An additional direct contact case is the possibility of a concentrated load over a small area of the pipeline, as a result of crushing of a single ice block within the grounded rubble. The effect on the pipeline would be one of denting or local buckling of the pipe wall. Pinching might occur in a buried cable or umbilical. This load case results in relatively high stresses (the crushing strength of ice) but the stresses are area dependent and the actual loads on the pipeline are limited. In addition, the design operating pressures of the pipes act in the opposite direction and are of the same order as the ice stresses.

ICE-SOIL-PIPELINE INTERACTION ANALYSIS

Interaction between ice, the seabed and buried pipelines is a sufficiently complex and three-dimensional problem that a full 3D finite element analyses is warranted. The most successful 3D models to date have been using an Arbitrary Lagrangian Eulerian (ALE) or Coupled Eulerian Lagrangian (CEL) formulation in order to capture the large displacements that occur during scouring (e.g. Konuk et al. 2005, Abdalla et al. 2009, Lele et al. 2011). These analyses are not, however, at the stage of being practical for engineering purposes. In addition to the time and resources required for a single analysis, the simplifications required to obtain convergent solutions result in key processes not being modelled. Dilation in dense sands, partial drainage of pore water pressures and the strength and flexibility of the ice feature are typical examples. Further, there are large uncertainties around the ice features causing the loading, ice strength, soil properties, trench geometry and backfill properties for any given case.

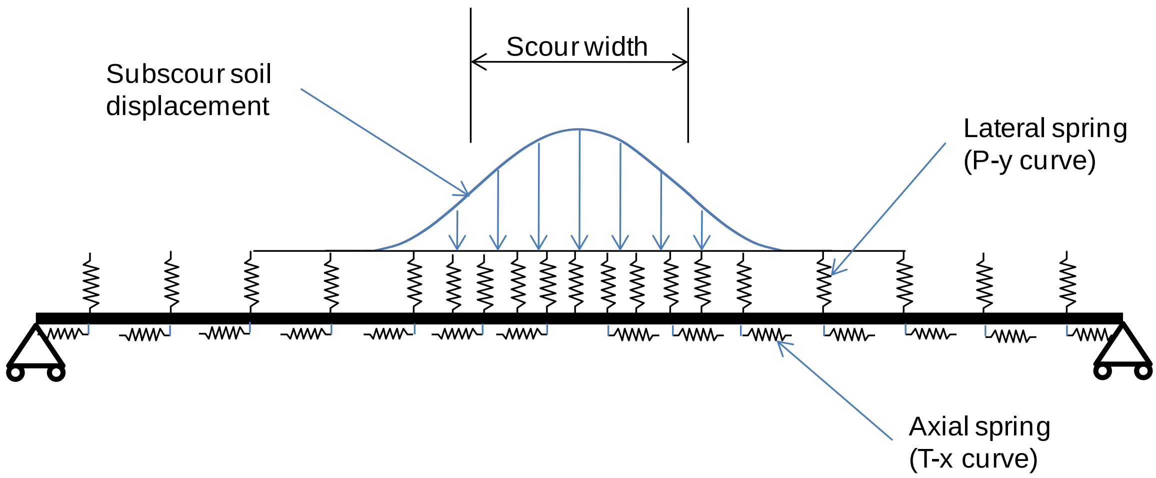


Figure 6. Winkler Spring Model for Pipeline Bending under Ice Scour Loading (similar models would be set up for stamukha pit loading).

The design practice therefore remains to rely largely on Winkler type spring models for pipeline analyses, as shown on Figure 6. Here the ice – soil interaction is separated from the soil – pipe interaction. In this approach it is conservatively assumed that the ice is a rigid body having the same underside shape as the scour trace on the seabed. Similarly, the free field soil displacements are greater than the actual soil displacements in the presence of the pipe. This allows a pipe-spring model to be a conservative calculation of stresses and strains in the pipe.

A full 3D finite element analysis should nevertheless be considered for a few critical load cases to confirm that the pipe-spring model is indeed conservative. The model should be validated against physical tests, a topic of ongoing interest and current research in the industry, for example Peek et al. (2013) and Phillips et al. (2010).

COMBINATIONS OF LOAD CASES

So far we have considered ice scour loading or pits as separate load cases. In the Kashagan project the scour and pit frequencies are such that scours or pits could occur at the same location more than once during the operational life of the pipelines. It is relatively simple to show that two abnormal load events at the same location have a sufficiently low probability that this scenario need not be considered. However, consideration was given to combinations of frequent events. The approach was firstly to consider the probability of occurrence of an ice load event that might lead to plastic strains the pipeline. For example, an ice event with return period of 50 years might take the pipe to its elastic limit in bending. We then considered the probability that two ice events with a return period greater than 50 years could occur at the same location within the 30 year design life of the pipeline. If this probability is greater than the nominal probability of failure of the pipeline, then further analysis of cumulative strain effects on the pipeline would be required.

A second, and more important, load combination considered was that of upheaval buckling at a scour location. The scouring removes a certain amount of overburden, and if this coincides with a vertical imperfection in the pipeline then upheaval buckling may be triggered. An analysis was carried out to determine the probability of overlap between scours and vertical imperfections. The minimum soil cover depth to avoid upheaval buckling was increased by 0.1 m for environmental load cases up to 0.4 m (for the accidental load case). This does not increase the burial depth for ice scouring – it would only increase the burial depth if the minimum depth was determined by considerations of upheaval buckling.

CONCLUSIONS

Design of offshore pipelines in ice scoured environments requires detailed consideration of the load effects from ice scouring and stamukha pits. This paper describes the design practice that has evolved over a period of about ten years for the Kashagan project. Many loading cases, soil types, ice regimes, pipelines and interaction mechanisms have been considered. We have learnt much during the project, but there are still unknowns and uncertainties that require further work. Conservative loads or assumptions are applied during the design to compensate for these unknowns.

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