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Subscour Displacements for Pipeline Design: State of Practice for Kashagan Project

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ABSTRACT

The Kashagan field is located in an area of the Caspian Sea that is subject to ice scouring of the seabed. Offshore pipelines are buried to mitigate the ice loads arising from scours, and the optimum burial depth is an important design consideration. Within the design process, it is the displacements in the soils below the scouring keel (subscour displacements) which need to be estimated as inputs to the pipeline design.

Quantifying subscour displacements has been the subject of intense study for the Kashagan project in the last 10 years, involving physical tests at a range of scales, advanced numerical modelling and several join industry research projects. This paper describes the development of subscour displacement models for sands and clays for the Kashagan project. It starts with a background to the work that has been done in a broader context before describing the specific relationships defined for Phase 2 of the project, as well as some of the uncertainties involved. There is still much work to be done to refine the models that are still a work-in-progress.

INTRODUCTION

The Kashagan field in the North Caspian Sea (Figure 1) is located in about 4.5 m of water that is typically frozen for about 3 months of the year. Movement of this ice causes scouring of the seabed as well as formation of stamukha, both of which may result in significant loads on buried pipelines. Pipelines are buried to mitigate the ice loads, and the optimum burial depth is an important design consideration, balancing the cost of deeper burial against increased safety margin. Considerable effort has been put into developing methods of pipeline design for ice scouring on the Kashagan project, which is described in a companion paper by Been et al. (2013). This paper considers one aspect the design: estimating the soil displacements below a scouring ice keel, the so called subscour displacements.

The problem is illustrated simplistically on Figure 2. The moving ice causes the soil around the gouge to be displaced, which can be considered as a profile of displacement in the direction of ice movement at the centreline that reduces with depth below the ice, as well as attenuation of that displacement in the "out-of-plane" direction (i.e. perpendicular to the direction of ice movement). Quantifying subscour displacements has been the subject of study since the 1980s, involving physical tests at a range of scales (including in a geotechnical centrifuge) and advanced numerical modelling. However, given the nature of the problem, involving both large strains and potentially high shearing rates in the soils, there is still much uncertainty which needs to be covered by conservatism in the design approach.

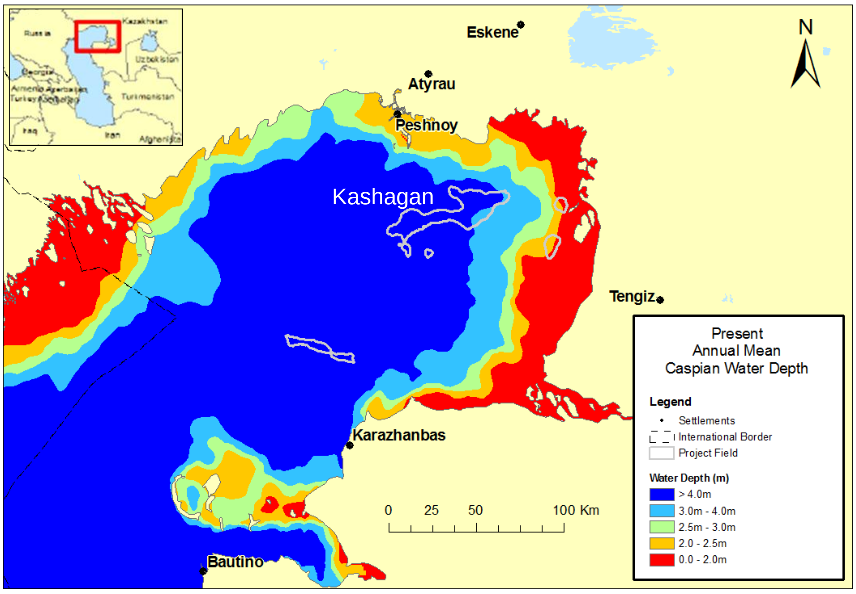


Figure 1. Kashagan Project in the North Caspian Sea.

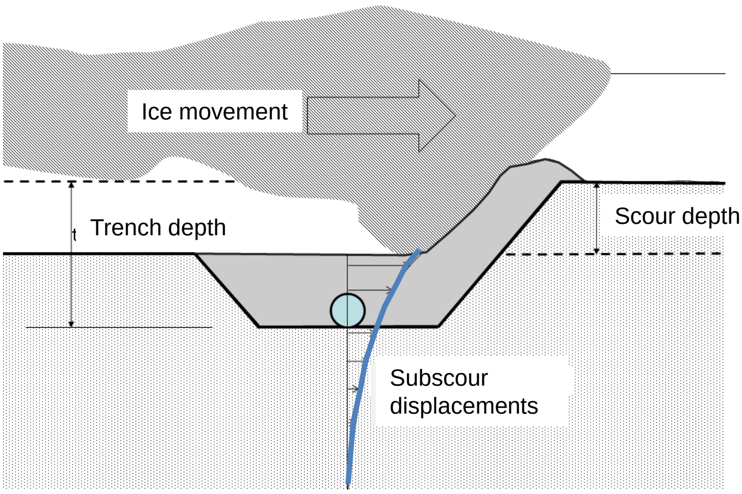


Figure 2. Ice Scour and Subscour Soil Displacements.

In this paper we first discuss some of the assumptions and simplifications around physical and numerical models of the real ice scouring process. We then consider subscour displacements separately in sands and clays, as there are key differences in how well each soil type can be modelled both physically and numerically.

MODELLING OF SUSBCOUR DISPLACEMENTS

Both physical models and numerical methods have been used to understand subscour displacements. Early work was largely physical modelling to better understand the mechanisms of failure in soils supplemented by analytic methods to calculate the forces associated with scouring processes (Been et al. 1990, Palmer et al 1990). However, it soon became apparent that the soil displacements were key to pipeline design, rather than forces, and this sparked an extensive effort at C-Core in the 1990s with the PRISE joint industry project as well as several university theses on the topic. PRISE included extensive centrifuge model testing, resulting in an empirical basis for subscour displacements in clays published by Woodworth-Lynas et al (1996). Finite element modelling was also carried out at that time (e.g. Yang et al. 1996), but with limited success, partly because computing power and software development were insufficient for 3D problems involving large strains and complex soil behaviour.

Pipelines for Sakhalin Island projects and the Kashagan Project involved significant lengths of buried pipelines and the conservatism inherent in the PRISE models became problematic. This sparked renewed interest in physical testing, particularly at a larger scale than previous work. Medium scale testing was carried out in a dredging flume at Delft Hydraulics Laboratory in the Netherlands (Vershinin et al. 2007, Been et al. 2008) and large scale testing in a field in Texas (Sancio et al. 2011). Centrifuge testing remained part of the mix, both within the PIRAM project (Phillips et al. 2012) and at Delft (Allersma & Schoonbeek, 2005).

Advances in large strain finite element modelling and computing power in the last ten years have allowed sophisticated 3D continuum modelling of ice – soil – pipeline interactions and subscour displacements (e.g. Konuk et al. 2005, Kenny et al. 2005, Abdalla et al. 2009, Phillips et al. 2010, Phillips & Barrett 2011, Lele et al. 2011, Eskandari et al. 2011 & 2012, and others). These models generally provide good insights into factors that affect subscour displacements and point to lower subscour displacements than the PRISE models. However, even these state-of-the-art numerical models may not capture significant physical phenomena, such as the full complexity of soil behaviour at large strains, effect of complex strain history or scale effects that remain even after appropriate scaling of gravity forces in centrifuge tests. Therefore the design should not rely on such models alone.

Figure 3 summarizes many of the simplifications within the physical and numerical models used to date, and compares them to real ice scours. It is expected that many of these simplifications will cease to be necessary as software improves, while more complex physical tests are possible given sufficient resources. An example is that all of the soil models consider that the ice is rigid and essentially infinitely strong. This aspect of limiting ice strength is discussed in Croasdale et al (2013).

Some model simplifications are inevitable. The keel geometry and scour shape, for example, vary randomly in the real world, and it is therefore reasonable to assume a regular shape in the models. However, considering a rectangular scour shape of the maximum scour width and depth will result in higher subscour displacements than for a typical scour where the maximum depth occurs only over a small portion of the width. A solution adopted for the Kashagan project is to consider the cross sectional area of the scour, or the average depth, when computing subscour displacements.

Numerical models typically include simplifications imposed by limitations of the numerical code, and these can be important. For example, some coupled Eulerian-Lagrangian models do not easily accommodate material property changes that occur between the natural soil and trench backfill. In addition, scouring in sands is typically too fast to be drained but also too slow to be altogether undrained. A coupled stress and flow model is required to capture this behaviour adequately, but none of the currently available large strain numerical codes (Abaqus, LS-Dyna) have this capability. Finally, strain localisation of the soils subject to large strains near the scouring feature is expected to occur in reality, and appears to occur in physical tests as well. Under certain conditions this localisation can be captured by numerical models, but requires very fine mesh sizes and great care by the modeller to ensure that the modelled strains are a result of material behaviour rather than mesh size. Localization is further complicated by local drainage effects. Even when conditions are essentially undrained at a global scale, drainage effects at surfaces or zones of localized deformation can play an important role. Capturing this in a coupled stress and flow model requires a mesh that can also capture localized flow phenomena.

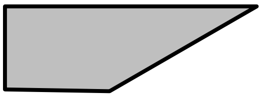
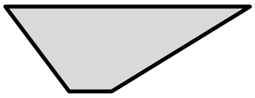
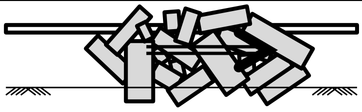
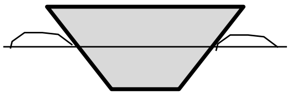
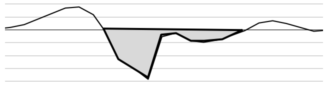
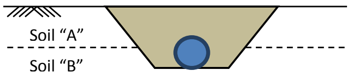
	Physical Model	Numerical Models	Ice Scours
Ice	 • Regular shapes • Rigid, infinite strength	 • Regular shapes (truncated cones, trapezoidal, etc.) • Rigid (ice properties not modelled)	 • Irregular keels (ice rubble) • Ice rubble strength and compressibility
Ice Motion	• Constrained, generally horizontal • Soil-ice contact forces can be high as a result of constrained motion	• Some constraints imposed for numerical simplicity	• Unconstrained, except by surrounding ice • Vertical motion occurs in response to soil-ice contact forces
Scour shape	 • Rectangular	 • Rectangular or trapezoidal (truncated conical keel)	 • Irregular shape • Typically also varies along length of scour
Velocity	• Generally constant, but could be varied	• Velocity independent	• Unknown – varies between zero (when ice feature may come to a halt) and ice drift speeds (up to 1 m/s)
Trench	• Generally none, but could be included	• Generally none • Numerical / software issues with boundary between natural soil and trench backfill	 • Natural soil variations, and trench backfill
Soil	• Sand and clay soils • Uniform soil properties • Soil layers have been modeled	• Single soil type • Uncoupled behaviour (pore pressure drainage and rate effects not considered)	Real soils • Strain hardening and softening • Layering • Shear localisation

Figure 3. Model Simplifications Used to Date for Ice Scouring.

Models thus provide good insights and a sound basis for estimating subscour displacements for engineering design, but judgement is also a key component and inevitable uncertainties must be covered by design margins and/or conservative approximations.

SUBSCOUR DISPLACEMENTS IN CLAYS

The empirical equations from PRISE, Woodworth-Lynas et al (1996), were initially used for the early production phase of the Kashagan Project because they provided a consistent and simple set of equations that were believed to be conservative. There was also nothing better at the time, but the project sponsored a series of tests in the dredging flume at Delft Hydraulics laboratory. The equipment and test results are described in Been et al. (2008), and despite some limitations in the test conditions, they provide valuable new information on scouring mechanisms in clays.

Most of the PRISE tests were carried out on 15° keels, with a few tests on 30° keels. The flume tests included 15°, 30° and 45° keels and identified that the failure mechanism changed as a function of keel angle. For shallow (15°) angles, the scoured soil tends to move predominantly outwards and up into the side berms whereas for steeper (30° and 45°) keels the soil first moves upward into a frontal mound before clearing sideways. This difference and how it affects the subscour displacements is explained by Been et al (2008), while Figure 4 shows the subscour displacements at the scour centreline observed through a glass panel at the assumed axis of symmetry as well as some of the measured displacements.

Limitations of the flume tests related largely to the soil bed preparation. Clay was prepared by mixing at fixed water content and then producing "bricks" which could be placed in the flume. Different coloured dyes were also used on the outer surface of some bricks as illustrated on Figure 4. Although the clay bed was then loaded to close the gaps between clay blocks, there is inevitably a slight difference in the strength of the clay and on the contact between blocks. In addition, the preparation method does not achieve 100% saturation of the clay. This may not be a serious limitation, but it does mean that there is negligible increase in clay strength with depth, that the clay may be more compressible than if it were fully saturated and pore water pressure due to capillary effects is unknown. We also identified an effect of surface roughness of the indenter on displacements and the effect that a pipeline has on the soil displacements during scouring.

While the flume tests strongly indicated reduced displacements compared to the centrifuge test data on clays, larger scale tests were subsequently carried out to avoid the scaling issues with centrifuge and flume tests, to reduce the constraints on keel motion and to allow realistic pipeline sizes and cables to be included in the test setup. Sancio et al (2011) summarize these tests, called the “Texas tests” as that is where they were carried out. Figure 5 shows the test set-up, consisting of a keel weighing about 450 kN towed by a D-11 dozer / tractor over a prepared soil bed containing a buried pipeline. The keel was shaped to avoid a flat base, thereby simplifying the test measurement system and modelling needs. (In the field there is unlikely to be a flat horizontal keel base, but there is no hard information on what the base of a scouring keel looks like after some abrasion and re-adjustment of the ice rubble through contact with the seabed.)

The scale and cost of the Texas tests was such that few tests could realistically be carried out. The intention was to provide a basis for verification of numerical models which would be used in design. Some numerical verification has been carried out, e.g. Lele et al (2011) and Peek et al (2013). At the time that engineering for the full field development phase of Kashagan was halted and postponed, numerical simulations of ice scouring in clays indicated a large difference between the subscour displacements as a function of undrained shear strength and stiffness of the clay. This finding is consistent with the analysis and results of the flume tests, however testing of very soft materials was not practical for the Texas tests to

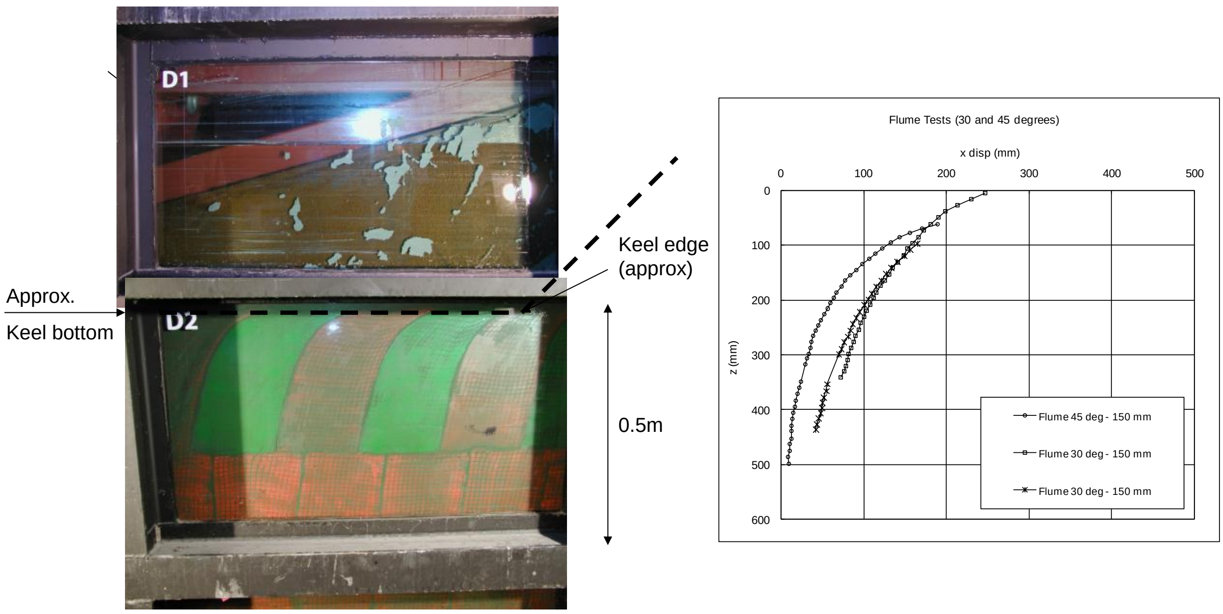


Figure 4. Typical Subscour Displacements in Clays observed in Flume Scale Tests (Been et al. (2008).

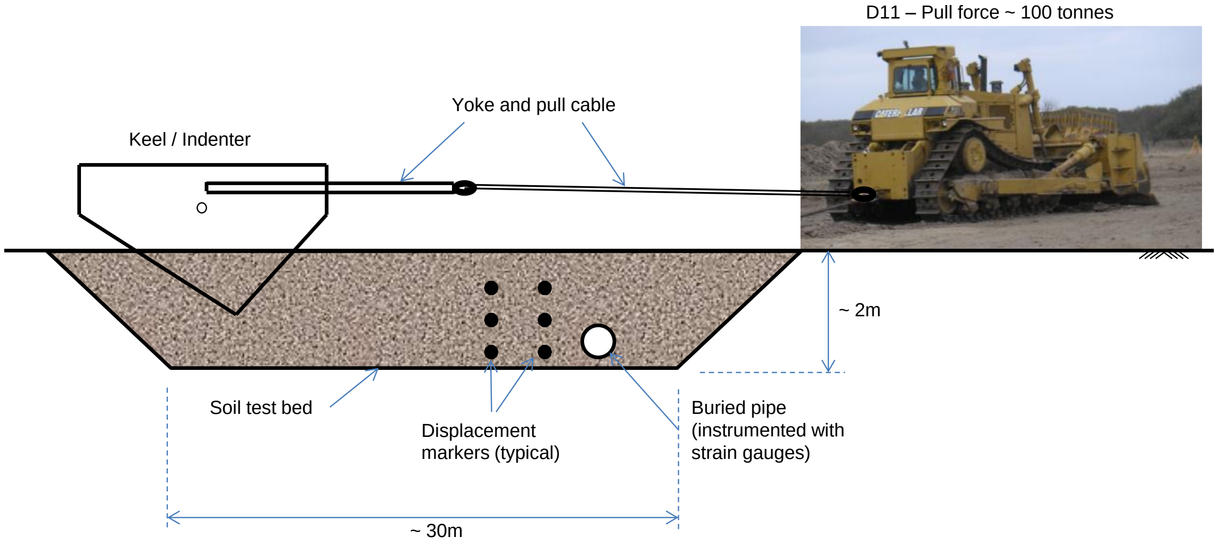


Figure 5. Test Setup for Large Scale Texas Indenter Tests

verify this result. The simulations overpredicted the measured values for stiff clays in the Texas tests, and a subscour displacement model based on the simulations was considered to be conservative and therefore adopted.

Based on the simulations, the subscour displacement for clays was approximated as:

$$x_z = x_o \exp(-n \cdot z) \qquad z \geq 0.5\ m \qquad (1)$$

where x_z is the subscour displacement at depth z below the keel (at the centreline of the scour), and x_o and n are curve fitting parameters. Attenuation of displacements away from the centreline is described for stiff clays by:

$$x = x_z \qquad y < 0.075\ W \qquad (2a)$$

$$x = x_z \times 0.5\left[1 + cos\pi\left(\frac{1.6y}{W} - 0.12\right)\right] \qquad 0.075\ W < y < 0.70\ W \qquad (2b)$$

$$x = 0 \qquad 0.70\ W < y \qquad (2c)$$

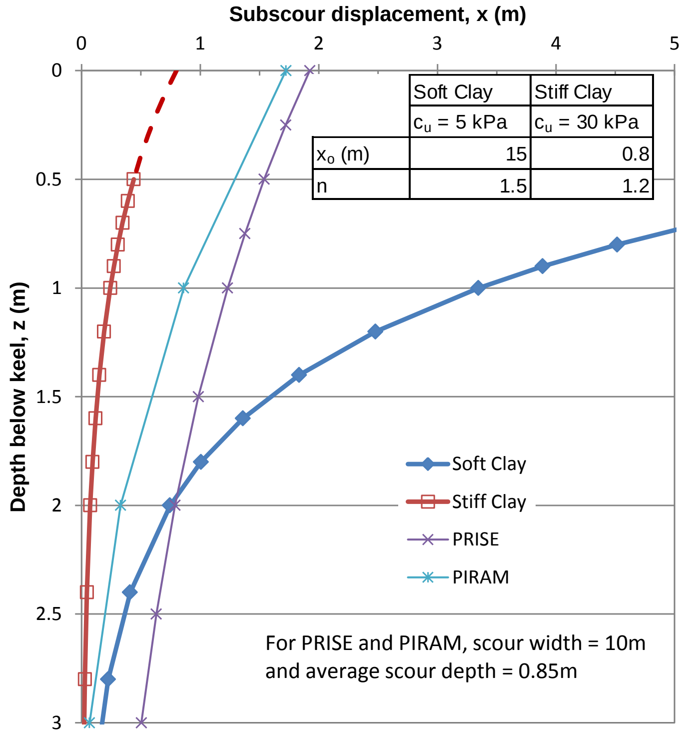
and for soft clays by:

$$x = x_z \times 0.5\left[1 + cos\pi\left(\frac{1.2y}{W}\right)\right] \qquad 0 < y < 0.83\ W \qquad (3a)$$

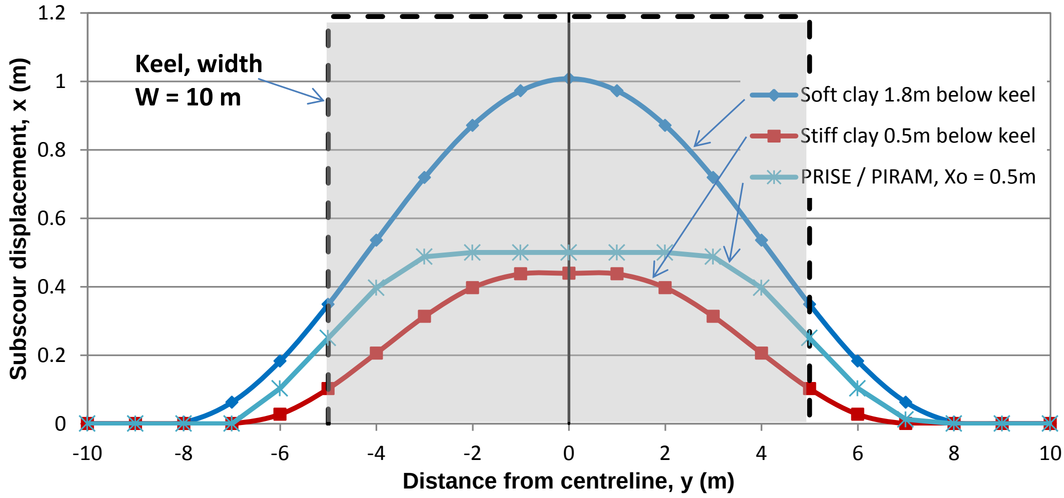
$$x = 0 \qquad 0.83\ W < y \qquad (3b)$$

where y is the distance from the centreline of the scour, W is the width of the scour or keel and x_z is the centreline displacement from equation (1).

Figure 6 illustrates this subscour displacement model. The Kashagan project, supported by physical and numerical modelling, has substantially reduced the subscour displacements for stiff clays compared to the earlier models based mainly on centrifuge test data. For very soft clays (undrained shear strength of 5 kPa), however, much larger displacements are indicated. The transition from soft clay (typically a disturbed backfill) to a stiff clay (natural seabed or controlled backfill) is not clear based on the work to date and is expected to depend on the stress-strain behaviour of the soil. Since the maximum observed undrained strength of clay backfills for the project was less than about 12 kPa, this value was selected as the upper limit for "soft clay" displacements. Note that the actual loading on a pipeline by very soft clays is limited by plastic flow of the clay around the pipeline and the large subscour displacements in soft clay backfills are not necessarily an onerous design requirement.



a) Horizontal Displacement at Centreline of Ice Keel



b) Attenuation of Displacement away from Centreline

Figure 6. Subscour Displacement Model for Kashagan Project

The attenuation of displacements away from the centreline is seldom discussed in papers, but Figure 6b shows the curves developed for the Kashagan project, based on the large scale physical and numerical models. There is more work to be done to evaluate how these curves may change with depth below the keel – currently they are considered to be depth invariant.

SUBSCOUR DISPLACEMENTS IN SANDS

As with clays, for sands the starting point for the Kashagan project was the centrifuge test data from PRISE, as well as insights gained from the Sakhalin projects reported by Vershinin (2007). Key elements of the sand subscour model compared to the clay model were:

- Recognition that the $\sqrt{\text{Depth x Width}}$ function within the PRISE model was not supported by the data (Figure 7a).

- Subscour displacements are a function of the sand density – denser sands would have less subscour displacement than loose sands (Figure 7b).
- Centrifuge tests on sands are essentially drained, i.e. negligible pore water pressures exist in the sand during scouring in the centrifuge, but field scale scouring cannot be considered drained for a reasonable range of scour velocities and sand permeability.
- Dilatant sands tend to shear in localized “shear bands”, and scaling of centrifuge displacements in sands to field scale cannot be done with conventional approaches.

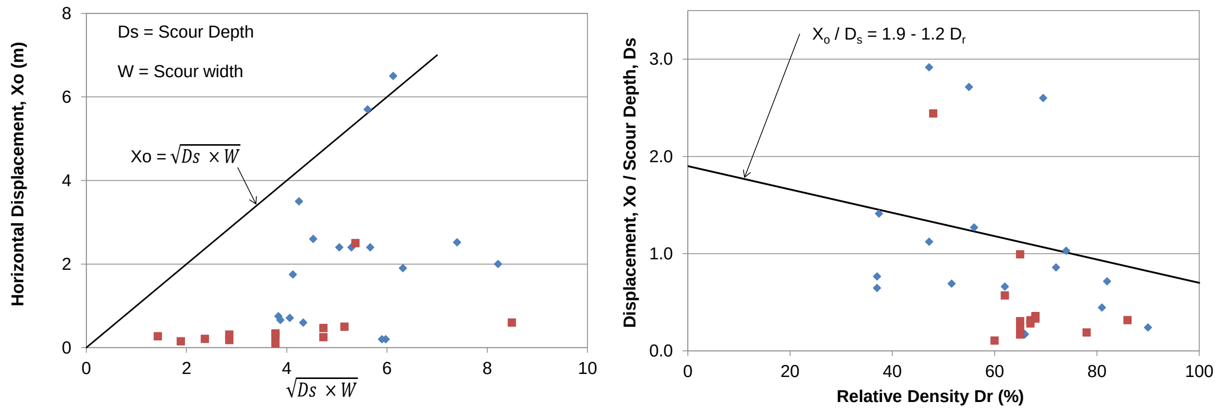


Figure 7. Subscour Displacements from Centrifuge Tests in Sands

The function relating the maximum displacement (at the keel centerline at the scour depth) to sand density illustrated on Figure 7 is a conservative bound on the centrifuge tests rather than a data fit. There are data that lie above the line, but we were able to justify the selected line on detailed inspection of the particular tests that gave those large displacements. We also found that the attenuation of displacements with depth below the scour appeared to depend on the sand density, as would be expected, and formulated a depth dependent subscour displacement relationship for sands as follows:

$$x_z = D_s \cdot (1.9 - 1.2 \cdot D_r) \cdot exp\left(-n\frac{z}{D_s}\right) \qquad (4)$$

where x_z is the centreline displacement at depth z below an ice keel scouring to a depth D_s, D_r is the relative density of the soil expressed as a ratio between 0 and 1 and n is a decay coefficient:

$n = 1.4$ for $D_r \geq 0.5$

$n = 1.0$ for $D_r < 0.5$

These values of n create a discontinuous function of relative density, but in practice this is unlikely to cause a problem. If the sand is dense, it will have high negative pore pressures and stiffness, while if it is loose it will show positive pore pressures and reduced stiffness. The transition from dense to loose usually occurs over a small range of densities. For lateral attenuation from the centerline displacements the curve identified as “PRISE / PIRAM” on Figure 6b was used.

The Texas indenter test program illustrated on Figure 5 included large scale tests on sands, to address the concerns related to drainage and scaling issues in the centrifuge tests. In fact, subscour displacements in the Texas tests as well as flume test data were generally smaller than the relationship indicated above, but the number of tests and range of test conditions were limited. Figure 8 shows the subscour displacement profile for a scour depth of 0.35 m using the above equation as well as the range of data from the physical tests (for which the deepest scour was 0.35 m). The relationship appears to be conservative compared to the test data at shallow depths, and very similar at depths greater than 0.3 m below the keel. A possible explanation for the difference in the upper 0.3 m is that this is the zone of high shear strains where centrifuge scaling is poor, while below below 0.3m the displacements are determined by mainly elastic strains, for which the centrifuge data would be expected to be reliable. However, this theory has not yet been tested and validated by numerical models.

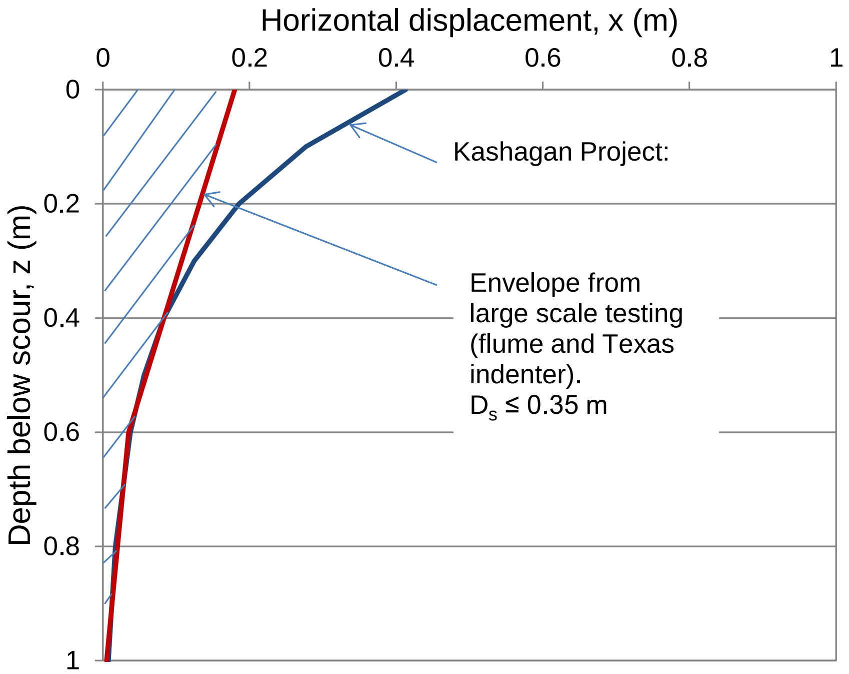


Figure 8. Subscour Displacements Model and Large Scale Test Data for Sands

THE FUTURE

The key to pipeline design for ice scouring in the future will almost certainly involve advanced 3D numerical models. The models must be validated against physical tests, a topic of ongoing interest and current research in the industry. Additional large scale physical model testing is the subject of a current joint industry project in Canada, and should provide the necessary validation data for subscour displacements and keel-soil-pipeline interactions.

The key advances required in numerical modeling appear to be the ability to include, within large strain CEL or AEL formulations, coupled stress and flow in the constitutive behaviour and different soil types in a geometry that is representative of a backfilled trench and layered soils.

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