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An ALE FEM Model of Ice Scour

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ABSTRACT: A Finite Element (FE) model of the ice scour process is developed to study the soil deformation and transport process around the scouring ice and to investigate the effects of the ice scour on pipelines buried in or installed on the seabed. The effect of the ice ridge angle and the ice scour depth on the sub-scour (boundary layer) and the ice reaction forces is analyzed. The developed FE model is an application of the Arbitrary-Lagrangian-Eulerian (ALE) method to a soil mechanics problem involving very large deformations.

1 Introduction

The ice scour process takes place when an ice ridge frozen into an ice sheet starts to move towards shallower water. The evidence indicates that initially some of the loose pieces of ice get dislodged from the ridge (Liferov 2004). It is also observed (Blasco 2002) that after a transient initial phase, the scour profile and the scour depth remain somewhat constant for the rest of the process. During this steady state phase, long scours exceeding several kilometres are generated on the seabed. As it was shown in an earlier paper (Konuk et al. 2004), this is most likely due to the fact that the cutting process generates larger vertical force than the ice sheet can maintain vertically and the ice ridge consolidates in the initial phase of the scour. The ice scour process can, therefore, be reduced to the problem of soil cutting by a rigid indentor. This problem is similar to the soil moving processes generated by earth moving equipment such as excavators and ploughs.

Both in the field of scour research and in other fields, the problem was studied mostly by experimental methods. As shown by Palmer et al. (2005), the results were quite inconsistent. As mentioned by Palmer (2005), there is no direct full scale data on the soil deformations and on the forces involved. There is also significant uncertainty on the geometry of ice ridges. The development of reliable and accurate numerical or analytical methods is therefore an important need for both designing and constructing offshore pipelines in arctic regions. The objective of this paper is to develop a numerical model to study the significance of some of the important aspects of the scour process, the sub-scour deformations and the soil-ice interaction forces.

The paper starts in the next section with the review of numerical models developed by other authors to solve the ice scour problem. A brief review of applicable computational methods is also presented in Section 2. Section 3 describes the ALE FE model developed in this paper. In Section 3, computational aspects of the model as well as material modelling will be discussed. Section 4 presents the results for different ice ridge angles and for different ice scour depths. Sub-scour deformations and ice ridge-soil interaction forces are presented and discussed in Section 4. Section 5 presents the conclusions.

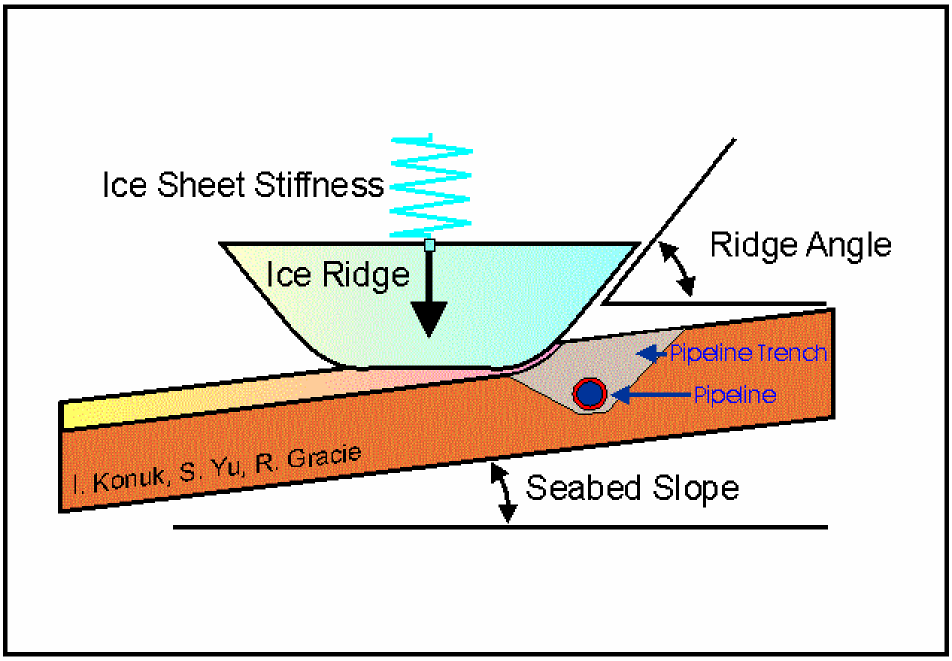

Figure 1. Illustration of Elevation View of Ice Scour Process.

2 Review of Literature on the Application of the Numerical Methods

An accurate numerical solution to the problem requires that the computational algorithm used must be able to accommodate very large soil displacements while maintaining all laws of mechanics. At the same time, a proven soil constitutive model, which can accommodate the stress-strain paths that the soil undergoes throughout the model, has to be employed. Several numerical models based on Lagrangian FE method were developed in recent years by different authors to analyse the ice scour process. The limitations of the Lagrangian FE method is well known (Belytschko et al. 2000) due to convergence problems and also most importantly due to extreme mesh distortions when large deformations are involved. Woodworth-Lynas (1996) reports convergence problems in their attempt to model the scour process numerically. Other papers utilize Lagrangian FE methods with remeshing (Lach 1996, Yang 1997). As shown by Belytschko, remeshing of Lagrangian meshes introduces errors duo to the need to project the nodal variables to the nodes of the new mesh. It is especially difficult to maintain mass conservation during the projections from the old mesh to the new mesh. ALE method overcomes this by using the continuity equation which is the partial differential equation equivalent of the mass conservation equation. Lagrangian method uses normally an algebraic version of the mass conservation equation where, in principle, a constant mass matrix is maintained. The major difference between the updated Lagrangian and the ALE methods is in the inertial term. The ALE method utilizes a non-constant mass matrix.

The first of the mentioned FE models (Lach 1996) relies on a static two dimensional representation of the process. As it will be later discussed, it is important to generate a steady state scour in the modelling of the scour process. It is not feasible to reach to a steady state condition with a two dimensional model. The paper by Yang (1997) utilizes a static "updated" Lagrangian approach with remeshing. Yang provides an algorithm to update the stiffness matrix for the new mesh. However, no algorithm is presented to update the mass matrix. It is, therefore, not clear if the conservation of mass is maintained by the Yang model.

Coupled FE and discrete element methods were utilized by Horner et al. (2000) to solve a similar problem that arise in soil excavation processes. In this paper, the excavation machine structure is modelled using an FE model and the soil mass is represented by discrete elements. It is known that soil behaviour observed in conventional laboratory tests for complex stress paths can not be accurately modelled by the discrete element methods. Due to this limitation, although the approach can qualitatively describe soil displacement fields, the loads and especially the stresses computed are not accurate in the soil domain solved by the discrete element method.

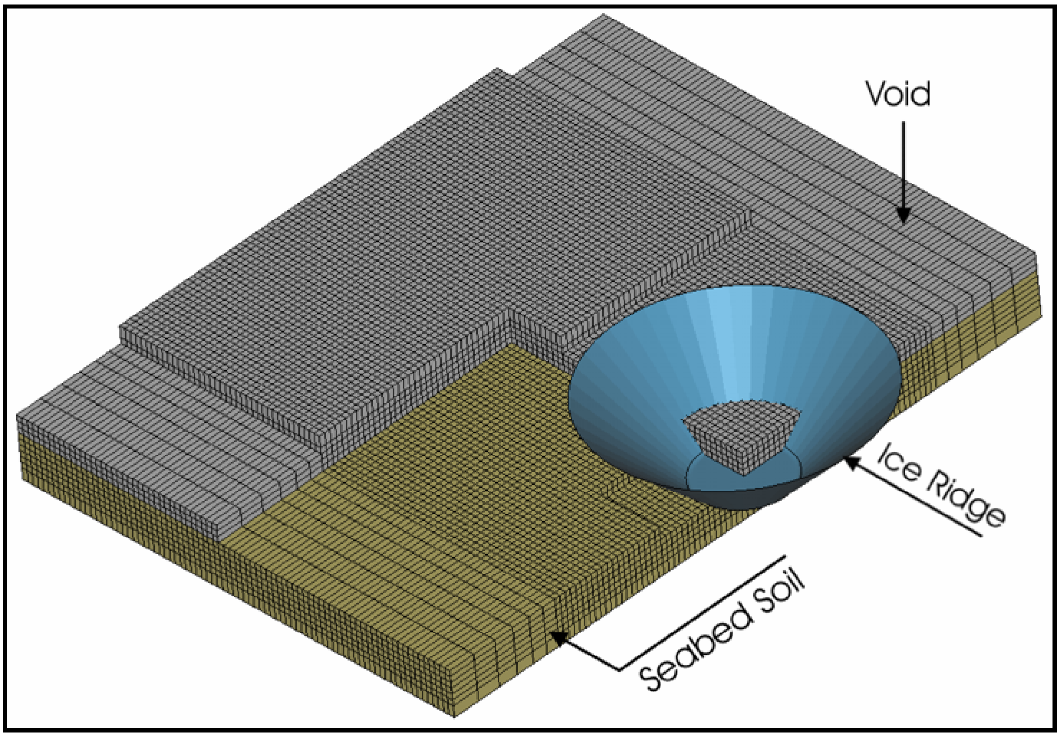

Figure 2. Illustration of of the FE Model.

Two main FE approaches that can accommodate very large deformations while accepting complex soil constitutive models were considered to solve the ice scour problem. One is the meshless method developed in recent years. Application of this method can be found in Chen et al. (1999) and Wu et al. (2001). The other FE method that has become popular for fluid structure interaction problems is the ALE FE method (Belytschko). In this method, the analysis undergoes three major steps. In the first step, a standard large deformation explicit Lagrangian FE analysis is conducted. In the second step, the FE mesh is remapped based on some smoothing criteria. The remapping algorithms can be based on the stresses and the deformations obtained in the previous time step or on the mesh topology. The third step in the ALE approach is the advection phase. In this step, the discretized strain, mass, and momentum parameters are computed for the nodes of the new mesh using laws of conservation. A detailed description of the algorithm used in the ALE model developed in this paper can be found in Souli et al. (2000) and Aquele et al. (2003). LS-DYNA explicit software (Hallquist 1998) which implements these algorithms was utilized in this paper to model the ice scour process.

3 Finite Element Model Description

ALE FE method is chosen to model the ice scour process as this approach provides more flexibility in comparison to meshless methods both in terms of memory requirements as well as the ease of exploitation of the existing proven soil constitutive models in LS-DYNA. Memory requirements for meshless methods were found to be too great. In the special application of the ALE method adopted in the ice scour model, the mesh is kept stationary (Eulerian mesh), thus avoiding the second step of the ALE method. In order to provide space for the berm and the soil mound expected to accumulate in front of the ice ridge, a third component consist of “void” material is laid over the soil part.

Finite element discretization is done using LS-DYNA (Version 970) Explicit FE software (LSTC 2003)]. All analysis is conducted as a dynamics problem incorporating inertia effects. Ice ridge is idealized as a rigid conical indentor. Typical finite element mesh used for implementing the model is illustrated in Figure 2. Various versions of the cone indentor are developed with the ridge angle varying from 15 degrees to 45 degrees (See Figure 1). In all models presented in this paper, the ice scour width is 15 m.

The essential parts of the developed model are the soil, the void and the ice ridge. Soil is modelled using 8 node constant stress (one point integration) solid elements. The seabed is assumed to be horizontal. The void consists of solid 8 node constant stress elements that initially contain no material. The depth of the void layer is chosen to accommodate the berm on the sides of the ice ridge and the soil pile expected to develop in front of the ridge. The ice ridge is modelled using shell elements. The ice ridge motion is defined by prescribing its velocity. The soil and the void elements are defined as “Eulerian” elements. Thus, the soil and the void element nodes are fixed. Soil mass is allowed to move through both the soil and the void meshes. The ice indentor moves through these Eulerian meshes. A penalty based contact with friction between the soil and the ice indentor induces the plowing of the soil as the ice indentor moves through the soil and the void elements.

All degrees of freedom for the nodes at the bottom of the model are fixed. The vertical degrees of freedom for nodes at the sides are left free. The depth and width of the model are selected to ensure that the boundary effects are negligible. The length of the model is selected to ensure that the scour process can reach to a steady (almost periodic) state. The steady state condition is determined by monitoring the contact forces and the soil particle trajectories.

The CAP soil constitutive model used in the model was originally developed by Simo et al. (1988).
Soil mass is taken initially to be stress free. In order to prevent artificial hardening, initial CAP position is moved forward for each layer corresponding to the surcharge load due to the weight of the soil layers on top. The important aspect of the soil constitutive model is that it handles the corner between the CAP and the failure surface in a consistent way, allowing a continuous transition from hardening to failure. This is quite important as most of the soil in front of the ice spend long time in this corner while being pushed first forward and then up the mound in front of the ice. In the model developed, soil mass is assumed to be a single phase material which implies an undrained process. A summary of the CAP soil parameters used in the ALE FE model is given in the Appendix.

The loads and displacements are imposed in three stages. In the first step, gravity is applied.

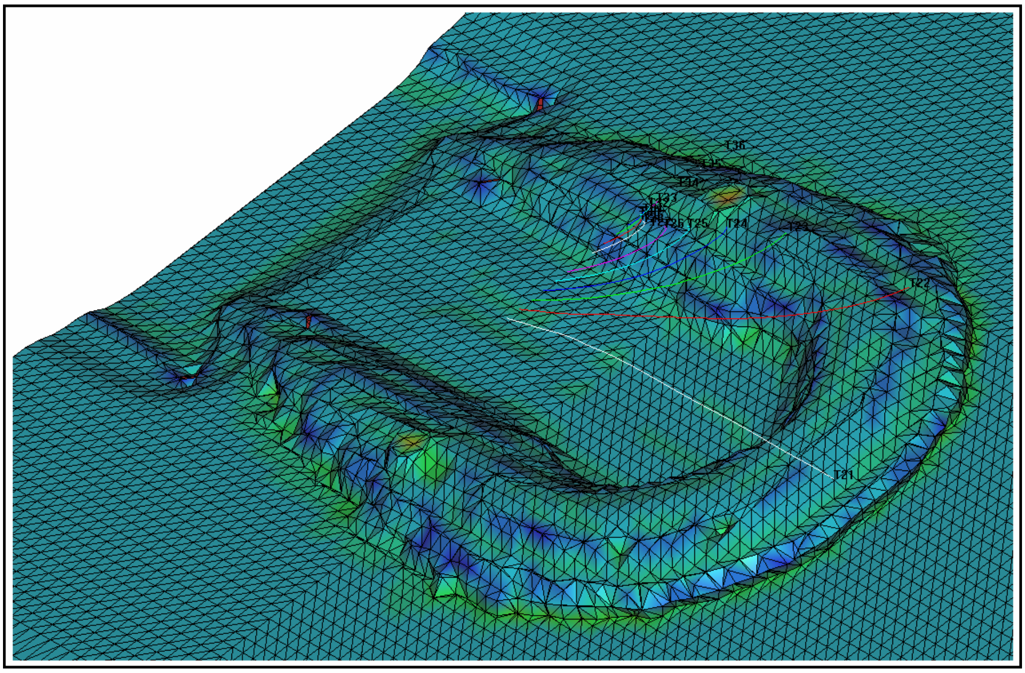

Figure 3. Typical Output from the FE Model with 45 Degree ice ridge with trajectory of Trace Particles that were originally placed at 20 m from the start and at 0.5 m depth

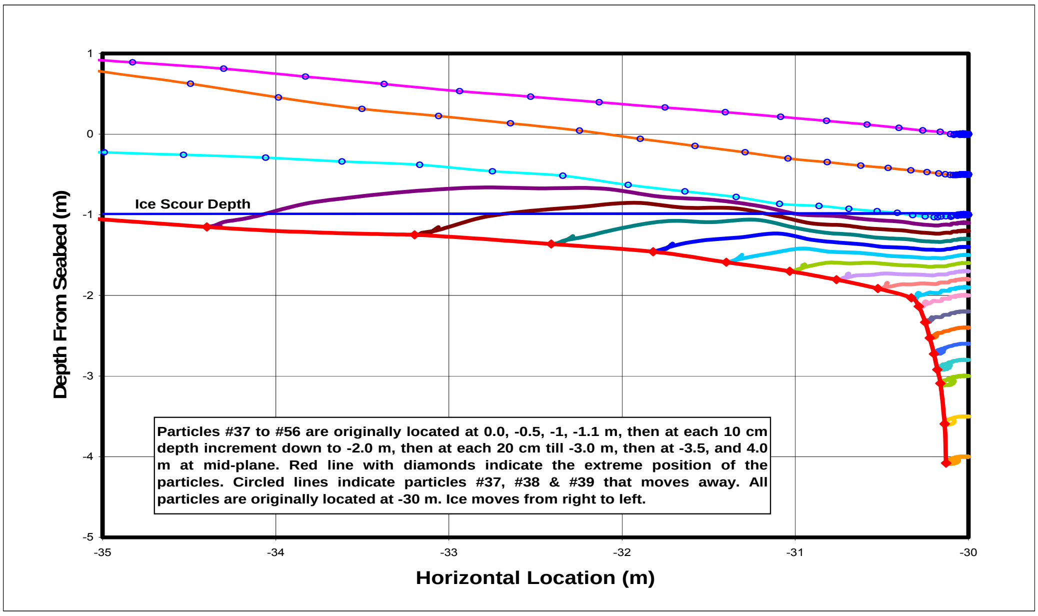

Figure 4. Example of particle trajectories and sub-scour soil deformation – 45 Degree ice ridge and 1 m scour depth – in this figure, ice moves from right to left

Sufficient time is allowed to ensure that the soil stresses reach a stationary state. This step ensures that the stress state in the soil is representative of the natural conditions and is mechanically admissible with the soil constitutive model used in the analysis. Initially, ice ridge is placed outside the soil. In the second step, the ice ridge is accelerated using a sinusoidal ramping function starting with zero velocity. In the third step, once the indentor contacts the soil boundary; it is moved across the model at a constant speed until a steady state condition is reached. All translational and rotational degrees of freedom of the indentor, other than translation in the direction of the scour, are constrained. In all analyses presented, indentor speed is taken to be 1 m/Sec.

4 Discussion of Results

A typical graphical model output is illustrated in Figure 3. Here, colour fringes indicate the soil density, and only partially or completely full soil elements are shown. This figure also contains the trajectory of the Trace Particles placed at 0.5 m depth and at a distance of 20 m from the edge of the model. Figure 4 shows the trajectories of the particles placed at 30 m from the seabed surface to a depth of 4 m in the mid-vertical-plane. Figure 4 shows that the particles underneath the scour initially move slightly down and then rise up. The initial downward movement is induced by the formation of the “mound” in front of the indentor. The subsequent upward movement is generated by the stress field in front of and underneath the indentor. Once the indentor is above the particles position, the particles are forced down again due to the increasing vertical stresses. After the indentor moves over, the particles somewhat rebound. Figure 4 also indicate that a relatively thin layer of particles near the seabed are forced out of the scour zone. This mean that the resulting scour depth does not exactly match with the ice keel position.

Figure 5 presents soil deformation profiles for different indentor angles and scour depths ranging from 15 Degree to 45 Degree and 1 m to 2m respectively. Table 1 summarizes the sub-scour deformation at 1m below the scour depth for all combinations. As can be seen from Figure 5 and Table 1, sub-scour deformation appears to have a logarithmic relationship with the ridge angle. The change in sub-scour deformation from 30 to 15 Degree is exponentially higher than the change between 45 and 30 Degrees. On the other hand, the subscour magnitude increases proportionally with the scour depth.

Table 1. Sub-scour deformation at 1 m below the scour depth

Scour Depth (m)	Ridge Angle 45 Degree	Ridge Angle 30 Degree	Ridge Angle 15 Degree
1	0.4 m	0.7 m	1.5 m
2	0.8 m	1.1 m	2.8 m

However, Figure 6 indicates that the vertical reaction force on the indentor increases by a rate similar to the rate of increase in subscour deformations. This means that the depth of scours created by shallow sloped ridges would tend to be significantly lower because the vertical reaction force applied by the ice sheet does not depend on the ridge geometry and the buoyancy contribution is relatively small.

The results shown in Figures 4, 5, and, 6 typically require a simulation period of 60 Seconds or about 70 m ice ridge movement before a steady state conditions are reached. This period increases significantly as the ridge slope decreases. For 15 Degree ridge angle, a simulation period of 80 Seconds is required.

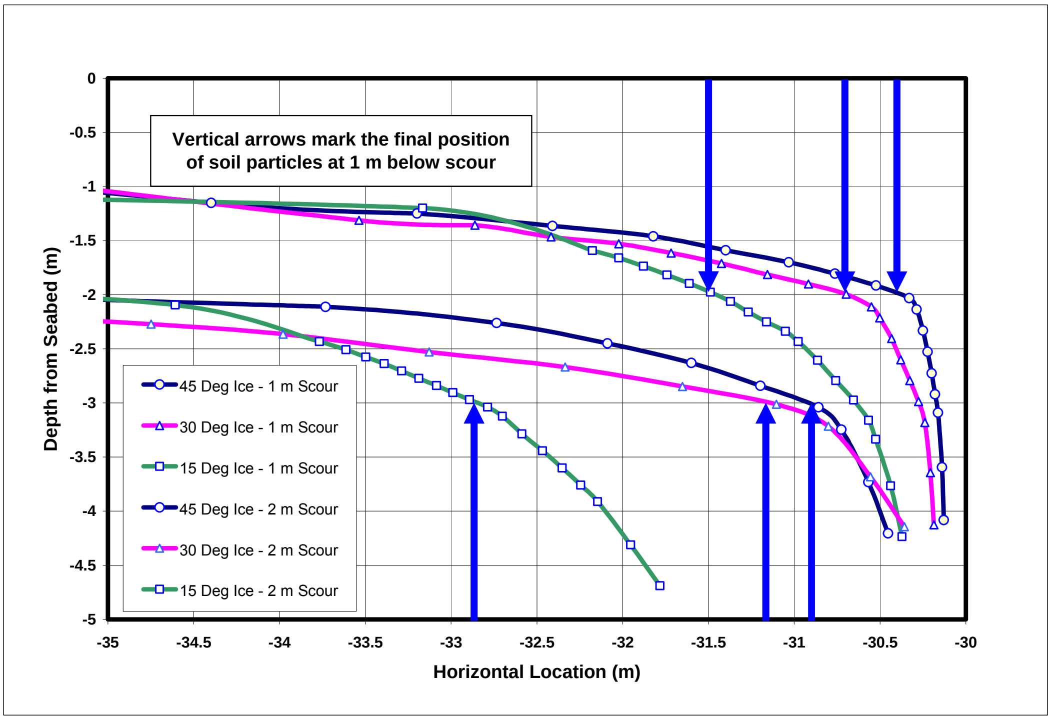

Figure 5. Comparison of Soil Deformations at 30 m from the model edge - Ice Angles vary from 15 to 45 Degrees and Scour Depth from 1 to 2 m.

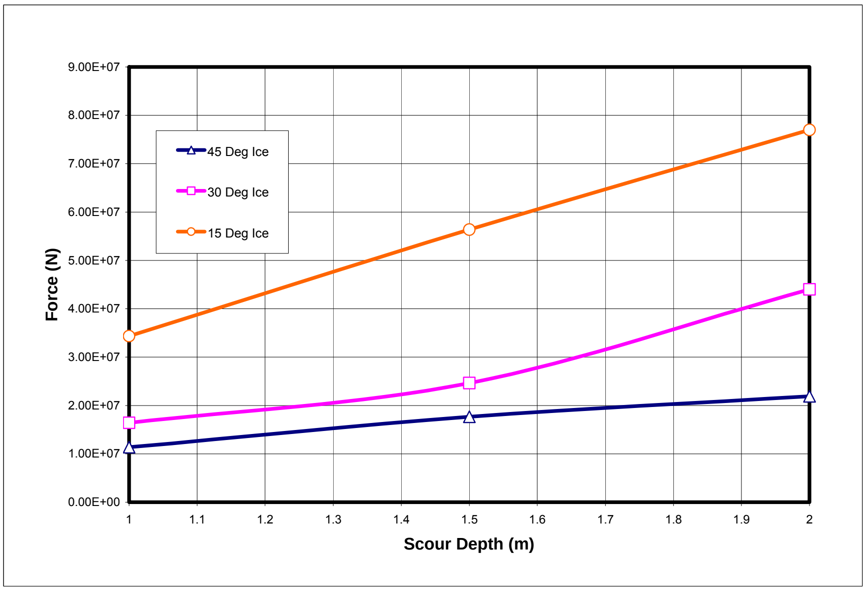

Figure 6. Vertical Ice Lift Force vs. Scour Depth.

5 Conclusions

It is shown that ALE FE technique is ideally suited for the solution of the ice scour problem. The results show that at lower ridge angles, the sub-scour deformations and the ice-soil reaction forces are very sensitive to the ice ridge angle. This implies a correlation between the scour depths and the ridge angles. It is likely that deeper scours are formed by higher slope ridges. This has to be verified in the field. However, if it is proven, for a given area, one can establish scour depth limits using information about the ridges. In order to reach to a steady state process, a simulation distance of about 4 to 5 times the scour width is required. This raises questions on the accuracy of the results obtained by static FE simulations which involve only few meters of ice ridge movement.

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Appendix: Soil CAP Constitutive Parameters

The following constitutive soil model parameters are used in this paper:

K = 10 MPa, G = 1 MPa, α= 500 Pa, γ= 0.0 Pa, β= 0.0 Pa^{-1}, θ=0.1, R= 4, W= 0.06, D= 1.26 E^{-06} Pa^{-1}, ρ= 1400 kg/m^3.

The notation used here is similar the notation used by Simo (1988).