Large deformation analysis of ice keel-soil interaction in sand

Afrouz Nematzadeh & Hodjat Shiri
St. John's, NL, Canada
Department of Civil Engineering – Memorial University of Newfoundland,
St. John's, NL, Canada

ABSTRACT
The most economical and common way of protecting subsea pipelines from Geohazard issues is to bury them under the seabed. A good understanding of the interactions of the ice, soil, and pipelines is needed to reasonably estimate the burial depth and estimate the impacts of the ice gouging on the pipelines. This study shows that the magnitude of the sub-gouge deformation of the soil is much bigger in the conventional decoupled method in terms of the horizontal and vertical displacements. Although the accuracy of the soil parameters and the constitutive model have great influences on the results, the Coupled Eulerian-Lagrangian (CEL) method is one of the best and accurate method of simulating the ice-soil interaction. Using user-defined constitutive model in this study, generated more realistic results. Further investigations regarding investigating the accuracy of the predictions obtained by CEL is needed.

RÉSUMÉ
La façon la plus économique et la plus courante de protéger les pipelines sous-marins contre les problèmes de Geohazard est de les enfouir sous les fonds marins. Une bonne compréhension de l'interaction entre la glace, le sol et les pipelines est nécessaire pour estimer raisonnablement la profondeur de l'enfouissement et estimer l'impact du gougeage sur les pipelines. Cette étude montre que l'amplitude de la déformation sous-gouge du sol est beaucoup plus importante dans la méthode découplée conventionnelle en termes de déplacements horizontaux et verticaux. Bien que la précision des paramètres du sol et du modèle constitutif ait une grande influence sur les résultats, la méthode Coupled Eulerian-Lagrangian (CEL) est l'une des meilleures méthodes pour simuler l'interaction entre la glace et le sol. L'utilisation du modèle constitutif défini par l'utilisateur dans cette étude a généré des résultats plus réalistes. D'autres études sont nécessaires pour étudier l'exactitude des prévisions obtenues par CEL.

1 INTRODUCTION

Floating icebergs may scour the seabed when they approach shallow waters. This process which is commonly known as "ice-gouging" is the main risk to the subsea pipelines and subsea structures in ice prone regions. The ice gouging event begins with ice and soil interaction. At first, the ice simultaneously penetrates and gouges the soil horizontally until it reaches a steady state situation. When it stops penetrating, then it resumes gouging with approximately constant depth. Studies have shown there are a considerable number of deep gouges which have occurred. Hence, ice gouging is an active hazard for the pipeline industry that can threaten the integrity of the pipeline. Protecting the Arctic subsea pipelines against ice-gouging is a challenging part of engineering design and construction. Burying the pipelines inside subsea trenches is the most popular and economic solution for physical protection of subsea pipelines against ice impact. The main two factors in burying pipelines are the cost and methods of burying them. Therefore, the minimum burial depth that keeps the pipeline safe form the ice-gouging loads should be calculated which dictates the trench geometry, the total subsea excavation volume, and consequently the construction costs.

Simulating ice gouging using numerical methods is more popular since it is easier to implement different soil materials, loading cases and boundary conditions. It can model the most important aspects of the interaction between ice/soil accurately.

1.1 Background

Several research projects have been conducted over the past decades to determine the minimum burial depth of the pipeline to compromise between the construction costs and pipeline integrity against the potential ice scours (Banneyake et al. 2011, Phillips et al. 2005; Kenny et al. 2005; Pike et al. 2011; Abdalla et al. 2008; Barrette 2011).

In addition to that, the effects of ice gouging on clay or sand have been investigated in most of the previous researches (Phillips et al. 2005; Kenny et al. 2005; Pike et al. 2011).

As investigated by Nobahar et al. (2001), soils show nonlinear behavior and for finding accurate results through a numerical simulation, advanced constitutive models are needed. These constitutive models should consist of a large number of parameters and calibration procedures. Soil under ice gouging load is associated with the evolution of shear bands, large deformations, and strains which can reduce the numerical modeling accuracy. The inaccuracies take place more where concentrated shear bands exist, especially with the material strain-softening.

Therefore, for developing an accurate numerical modeling, selecting an appropriate constitutive model for the material is a key factor. In this paper, a user-defined constitutive model has been implanted to simulate the rate-dependent, strain-softening behavior of dense sand more accurately.

2 FINITE ELEMENT MODELING

ABAQUS supports two general analysis procedures which are implicit and explicit analysis. Due to the high accuracy needed for ice gouging event and large displacement in this process, the explicit analysis adopted. This analysis proves to be more accurate for large deformation problems. The geometry of the soil has been considered large enough to prevent the boundary effects problems.

The coupled Eulerian-Lagrangian (CEL) is an alternative solution for large deformation problems such as ice gouging. In this method, the Eulerian mesh is fixed, and the material flows inside the mesh. Therefore, the mesh distortion problem which occurs in the Lagrangian mesh is solved by using CEL approach. All ice gouging simulations contain a moving ice and soil domains, however, depending on the type of the problems the geometry and approaches could be different. In this study, the geometry of soil is assumed to be 70m long, 25m deep and 30m wide. The ice keel attack angle is 30°, and the ice width is 5m. Since CEL analysis has been adopted, some tracer particles have been defined in the model to trace the soil displacement. The first array of particles has been placed at the point that the steady state began and the second one was located where the ice keel stopped. The location of the tracer particles has been shown in Figure 2.

To limit any instabilities in contact between soil and ice, the ice corner has been rounded. The gouge depth has been considered as 1.5m, and the ice keel has been pushed down until it reached the desired gouge depth. Using this approach helped the model to reach the steady state sooner and reduced the simulation time in a considerable way. The ice has been modeled as a rigid body with four nodes, three-dimensional discrete elements, and the Eulerian elements were EC3D8R which are eight node, reduced integration brick elements with hourglassing control.

In the first step of this analysis the geostatic stress has been applied on the soil to generate the initial state of the soil, and in the second step, the ice is pushed down to reach the gouging depth. In the third step, the ice moved horizontally with the velocity of 1 m/s. The gravity was applied to the whole model through this step and the ice continued to gouge at the gouging depth. This paper examines the capability of the constitutive model which has been written by VUSDFLD for dense sand. The soil profile has been defined by the depth for elastic properties. The movement of the ice imposed the gouging load to the soil through the interaction of the soil and keel.

One of the most powerful software in simulating the interaction between bodies is ABAQUS/EXPLICIT. By using a general contact in this software, the interaction between ice/soil can be captured and monitored. There is generally two common behavior for contact between surfaces. One is normal behavior, and the other one is tangential behavior. The normal behavior has been adopted for this study, is a hard pressure-overclosure approach which controls the penetration of ice into the soil which has been investigated by Eskandari et al. (2011) and concluded to be capable of simulating ice gouge more realistic than rough contact. This relationship prevents the tensile forces to be transferred at the interface of the surfaces as soon as the surfaces contact each other. The penalty method has been used for frictional contact with 0.3 friction coefficient.

3 SOIL CONSTITUTIVE MODEL

The elastic properties have been varied through the depth to adopt the Janbu's (1963) approach which increased the initial confining pressure with depth. Equation 2 defines the relationship between the elastic modulus and effective confining stress through the following power series:

$$E_s/P_a = K((K_o*\gamma'*H)/P_a)^n \quad [2]$$

where P_a is the reference atmospheric pressure. K_o is the at rest lateral coefficient, K and n are the power series parameter, H is the depth of the soil and γ' is the effective unit weight.

Table 1. The soil constitutive model parameters

	Parameter	Value
Elastic	K	326
	n	0.86
Plastic	ϕ'_{max}	46.5
	ϕ'_{crit}	35.8
	ψ_{max}	13
Direct Shear Test	D(mm)	44
	δx_p(mm)	1.6
	δx_y(mm)	0.6
	δx_f(mm)	4.3

Modified elastoplastic Mohr-Coulomb model has been adopted from Anastasopoulos et al. (2007) for this study. The authors discussed that by decreasing the mobilized friction and dilation angles, ϕ'_{mob} and ψ_{mob}, respectively, and increasing the plastic deviatoric shear strain, γ^p_{dev}, the strain softening behavior of soil would be simulated. This relation has been shown in Figure 1. The Mohr-Coulomb exists in the ABAQUS library, is unable to capture the strain softening behavior of the material. Therefore, a user-defined model is needed to solve this problem and capture the strain softening behavior of dense sand. ϕ'_{max} and ψ_{max} have been reduced linearly from their peak values to their residual (critical) values which are ϕ'_{crit} and 0. As the result, the plastic behavior determined by the softening of yield surface and the potential of the flow which depends on the deviatoric strains. The octahedral shear strain, largest shear strain, was calculated by the subroutine and associated with all six plastic strain components.

Equation 1 shows the relationship established by Anastasopoulos (2007) to calculate γ^p_f based on the finite element size and direct shear test data.

$$\gamma^p_f = (\delta x_p - \delta x_y)/D + (\delta x_f - \delta x_p)/d_{FE} \quad [1]$$

where D is the height of the direct shear test specimen, d_{FE} is the finite element length, and the horizontal displacement at yield and peak points are δx_y and δx_p respectively. Full softening happens at residual state which has been shown by δx_f.

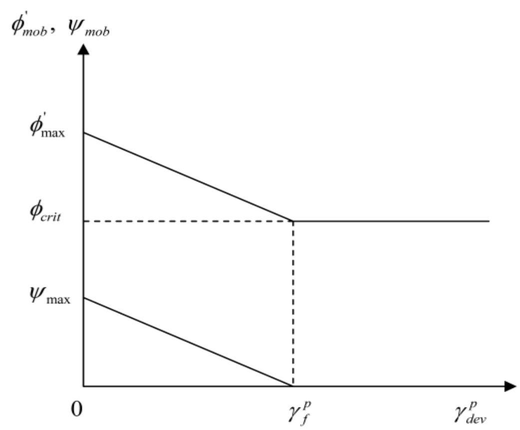

Figure 1. Reducing of the friction and dilation angles from (Anastasopoulos et al., 2007)

4 FINITE ELEMENT MODEL VALIDATION

This model has been validated with published CEL models to ensure the model performs consistently. Philips and Barret (2011) used ABAQUS/EXPLICIT to generate a CEL model for investigating the ice gouge in the sand by considering the varying of dilation angle from 0 to 11 degree and Eskandari et al. (2011) also built the same model as Philips and Barrett (2011) by using a constitutive model for the material and ALE method in ABAQUS/Explicit. A model identical to the medium mesh size of Philips and Barret (2011) and Eskandari et al. (2011) studies has been developed with the exception of using modified Mohr-Coulomb for sand which has been generated for this study. In the reference models, the steady state was initially assumed and has been given to the model, but in the current study, this assumption was not made and instead the model has been pushed down until it reached the gouge depth to create the steady state. The sub-gouge deformation further validated by Pressure Ridge Ice Scour Experiment (PRISE) physical model data for similar conditions which has been conducted by Philips et al. (2005). The test that has been used in this paper is test 1.43 x 10m. The horizontal and vertical reaction forces validated by Pipeline Ice Risk Assessment and Mitigation (PIRAM) test conducted by Yang (2010). The horizontal reaction forces is shown as positive and the vertical reaction forces is shown as negative.

Figure 3 shows the results of reference sub-gouge simulations and the results of the current study. Figure 4 compares the results of the centrifuge test and developed model and Figure 5 represents the comparison of reaction forces.

The start of the vertical axis in Figure 3 represents the mud line and also the depth and deformation has been normalized by the gouge depth. Since the gouging depth is equal to 1.5m, the depth below “1” shows the sub-gouge displacement.

5 RESULTS AND DISCUSSIONS

The most important result in ice gouging modeling is sub-gouge deformation, therefore, the result of this model has been compared with two other CEL models and centrifuge test result separately.

As presented in Figure 3, the results are very consistent with published data. It shows that the constitutive model has high accuracy.

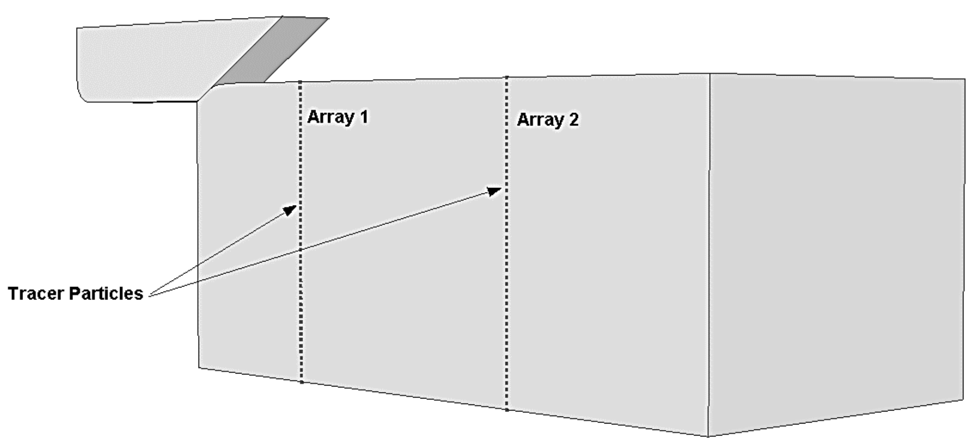

Figure 2. Initial ice and seabed

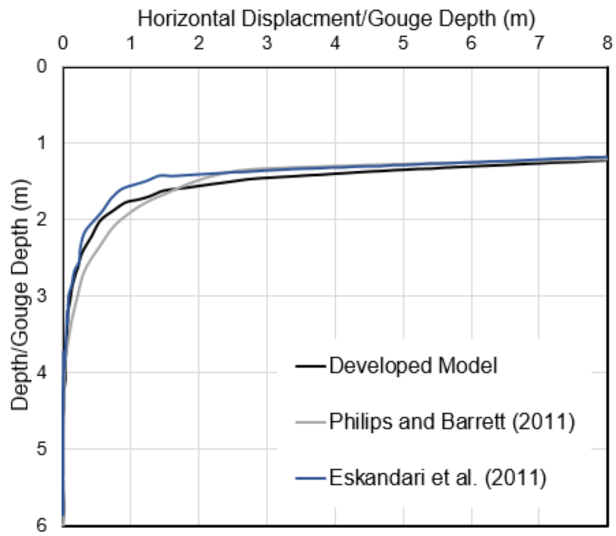

Figure 3. Comparison of sub-gouge deformation of the developed model and the reference FEA models

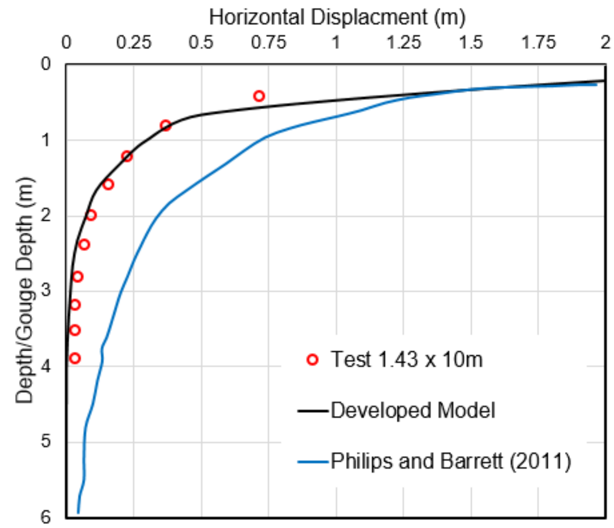

Figure 4. Comparison of sub-gouge deformation of the PRISE test and developed model

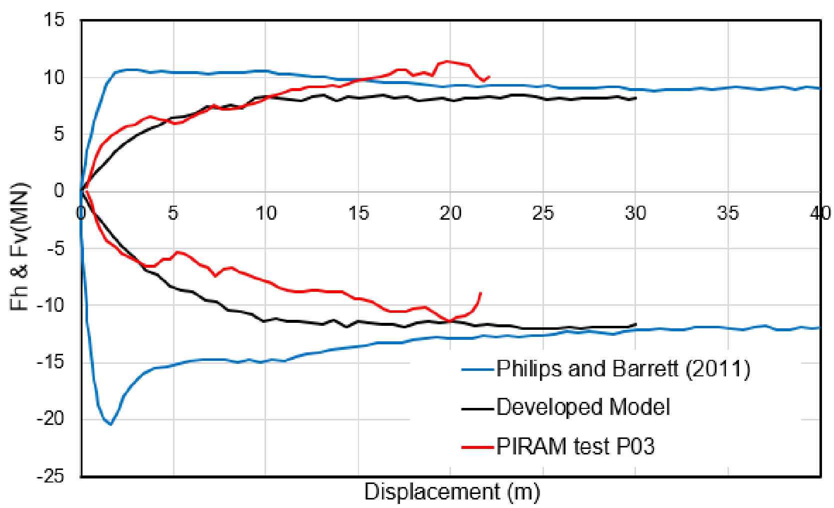

Figure 5. Comparison of horizontal and vertical reaction forces with FEA reference model, PIRAM test, and developed model

By comparing the results from the current study and test data, it can be seen that the developed model was able to capture the soil behavior well and it could simulate the dense sand behavior more realistically.

As Figure 4 shows, the current study is in more agreement with the test results than Philips and Barret (2011).The deformation below the gouge depth (below "1") are consistent with the test results. Since the elastic modulus has been applied more realistically through the depth in the current study, the results in depth show better agreement with the test data.

Figure 5 represents the consistent between the horizontal reaction forces of developed model and both the FEA model and the test data. However, since the initial condition of the reference FEA model is different from the current study and also the contact definition would be different, the start of the reaction forces are different ,therefore, after reaching the steady state the results are quite close. In the same way, around the steady state, the test data and developed model results overlapped.

The results suggest that the past studies on ice gouging event resulted in an unrealistic sub-gouge deformation. The conventional sub-gouge deformations were much bigger than the test results. However, the current study has shown that using appropriate constitutive model can simulate the ice gouging process more accurately.

6 CONCLUSION

The available built-in Mohr-Coulomb constitutive model, within Abaqus, cannot capture the post-peak shear stress response due to friction softening, nor can it limit the volumetric expansion with increased axial strain due to dilation softening. Therefore, the user subroutine is essential for capturing realistic soil behavior. In this paper, an effective stress analysis has been conducted on cohesionless soil. Mobilized effective dilation and friction angles along with plastic deviatoric strain and variation of friction angle with mean effective stress have been implemented using VUSDFLD subroutine and CEL approach.

It can be concluded that the modified Mohr-Coulomb model that has been used in this paper, developed consistent results with the centrifuge test and was able to capture the expected failure mechanisms. It could simulate ice gouging event in the dense sand with low pressure condition by considering the strain softening behavior of dense sand. It is important to consider the pressure effects related to pipe/soil interaction in cohesionless material, since pipeline burial depth are usually shallow enough to be under low pressure conditions.

Applying the elastic parameters through the depth, strengthened the model to capture the deformation under the gouge depth more accurately as it appeared in the results. Moreover, it has been illustrated that basic properties of the sand are very effective in seabed behavior under gouging events.

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