THE RESPONSE OF DENSE SAND TO THE ICE GOUGING EVENT

by

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ABSTRACT

The integrity of subsea pipelines in the Arctic regions are threatened by ice-related subsea geohazard. A common practice for physical protection of the pipelines against the ice loads is to burying them inside the subsea trenches. However, determining the minimum burial depth of the pipeline to minimize the construction cost is a challenging design aspect of Arctic offshore pipelines. This requires an in-depth understanding of the ice-soil-pipe interaction, which in turn is significantly affected by ice-soil interaction and the foucuse of this thesis.

Mohr-Coulomb soil model is conventionally used for continuum modeling of dense sand by adopting the constant friction and dilation angles. However, this approach neglects the pre-peak hardening and the post-peak softening behavior of dense sand. In this study, two smart self-correcting soil models were incorporated into an advanced Coupled Eulerian-Lagrangian (CEL) analysis to automatically update the shear strength parameters by the magnitude of plastic strains.

The analysis was conducted using ABAQUS/ Explicit scheme incorporating the soil model that was coded into a user-defined subroutine. The soil strength parameters are self-corrected to model the nonlinear hardening, softening and pressure dependency behavior of dense sand by considering the ice keel bearing pressure and octahedral shear strain. The pre-peak hardening, and post-peak softening behavior of dense sand were captured through a series of free-field ice gouging analysis. Tow comprehensive parametric studies were conducted, one investigated the ice properties and anther one was foucued on the soil parameters.

The sub gouge soil deformation and ice-soil contact pressure were extracted and compared with the results of the original Mohr-Coulomb model, the published numerical model, and test data. The study showed the significance of incorporating the strain rate dependency of dense sand on seabed response to ice gouging.

The methodology was found to be a strong but simple framework that can be used in daily engineering analyses. It was observed that the magnitude of the subgouge soil deformation is overestimated by the conventional decoupled methods. Also, the required burial depth was found to be smaller than those recommended by conventional methods, which in turn can significantly reduce the construction effort.

The parametric studies showed that the higher attack angles produce lower reaction forces, smaller subgouge deformation, and smaller side/front mounds. The deeper gouge depth creates higher reaction forces, more substantial subgouge deformation, and frontal mound. The wider keel base produces higher reaction forces, larger subgouge deformation, and frontal mound. The geometry of ice does not affect the subgouge deformation significantly; however, it has considerable influence on reaction forces and the formation of the mound. The conical keel shape results in larger reaction forces than the rectangular one. The mound on the side and in front of the rectangular keel is sharper than the conical one. In terms of parametric soil study, the sand with higher relative density creates more significant subgouge deformation and sands with higher density have the same effects on the ice gouging process.

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List of Abbreviations and Symbols

Abbreviations

ALE	Arbitrary Lagrangian Eulerian
CEL	Coupled Eulerian-Lagrangian
MC	Mohr-Coulomb
MMC	Modified Mohr-Coulomb
TX	Triaxial
PS	Plane Strain
DS	Direct Shear
PIRAM	Pipeline Ice Risk Assessment and Mitigation
PRISE	The Pressure Ridge Ice Scour Experiment

Symbols

A	Slope of $(\varphi_P'^{TX} - \varphi_C'^{TX})$
m, C_1, C_2	Soil parameter
I_R	Relative density index
k	Slope of $(\varphi_P'^{TX} - \varphi_C'^{TX})$
E	Young's modulus
Q, R	Material constant
p'	Mean effective stress
μ	Friction coefficient between the ice and soil

φ'	Mobilized angle of internal friction
φ'_{in}	φ' at the beginning of plastic deformation
φ'_P	Peak friction angle
φ'_c	Critical state friction angle
φ'_μ	Ice-soil interface friction angle
ψ	Mobilized dilation angle
ψ_{in}	ψ at the beginning of plastic deformation
ψ_P	Peak dilation angle
γ^P	Engineering plastic shear strain
γ_P^P	γ^P required to mobilized φ'_P
γ_c^P	Strain softening parameter
γ	Unite weight
K, n	Material parameter
ϕ'_{max}	Maximum friction angle
ϕ'_{crit}	Critical friction angle
ψ_{max}	Maximum dilation angle
D	Height of the direct shear test specimen
δx_p	Displacement at peak point
δx_y	Displacement at yield point
δx_f	Softening at residual state
γ^p_{dev}	Plastic deviatoric shear strain,

$\gamma^p{}_f$	Plastic shear strain at maximum friction angle point
P_a	Atmospheric pressure
$K_\circ$	At rest lateral coefficient
H	Depth
γ’	Effective unit weight

Chapter 1

Introduction

1.1. Overview

One of the most significant risks to subsea pipelines crossing the Arctic offshore territories is ice-induced scour in the seabed. As a cost-effective solution, pipelines are usually buried for physical protection against ice impact. Estimating the minimum reliable burial depth to obtain a sufficient level of pipeline protection is still a challenging design aspect due to uncertainties associated with the ice gouging characteristics. The response relies on deep understanding and proper modeling of the ice keel-soil interaction during the scouring process. In the past 20 years, a significant amount of research has been conducted on ice gouging event in cohesive and granular seabed sediments to advance the offshore industry's understanding of ice scour characteristics (NRC-PERD 2014, BSEE-WGK, 2015).

1.2. Original contribution

The classical Mohr-Coulomb (MC) soil model has been conventionally used for numerical modeling of the ice gouging in sandy seabed, which is widely observed in Arctic offshore regions. UsingMC model is a simple and fast approach with an acceptable level of accuracy for situations where constant values of angles of internal friction (φ') and dilation (ψ). However, the MC model does not consider the characteristics of the non-linear stress-strain behavior of dense sand including non-linear pre-peak hardening, post-peak softening, dependency on density and confining pressure (Hsu and Liao, 1998), and the mode of shearing (e.g., triaxial versus plane-strain) (Bolton, 1986). These simplifications result in some level of inaccuracy in the estimation of seabed response to ice scour within the basal shear zone underneath an ice keel. Consequently, the subgouge soil deformation, the keel reaction forces, and the heave formation in front of the moving ice keel are all affected because shear bands and failure planes underneath, and in front of, the ice keel develop progressively (Philips et al., 2005). In addition, the failure planes are relocated with displacement of the ice keel. Therefore, the simple limit equilibrium approach with constant soil strength parameters cannot properly represent this complex process. Therefore, the progressive formation of failure planes that can accommodate the variation of mobilized shear resistance along these planes needs to be incorporated in numerical models to better simulate the ice-seabed interaction mechanisms. There are advanced constitutive soil models like NorSand that consider some of the non-linear stress-strain features of dense sand behavior that have been used for ice gouging (Eskandari et al., 2011). However, a significant amount of complex coding of material model and computational effort along with calibration of a large number of parameters are required.

In this study, a series of key features from some existing and recently developed non-linear models were adopted through a simplified approach to incorporate all of the aforementioned non-linear effects into a modified Mohr-Coulomb (MMC) model (e.g., Roy et al., 2015; Bolton, 1986). Large deformation analyses were conducted in ABAQUS/ Explicit using Coupled-Eulerian-Lagrangian (CEL) approach. The seabed soil model was coded into a user-defined subroutine (VUSDFLD) that was called by ABAQUS in every time increment to update the shear strength parameters of the sand based on accumulated plastic shear strain, loading condition, density and confining pressure. A comprehensive parametric study was conducted using the MMC model by examining different seabed parameters and ice keel configurations one at a time. The comparison was made between the results produced by MC and MMC models, and also some of the key published experimental and numerical studies (Eskandari et al., 2015; Yang, 2009).

1.2.1. Organization of the Thesis

This thesis is a paper-based thesis which is divided into three parts. The first chapter is the introduction which discusses the organization of the thesis. The second chapter is the literature review which explains the history of ice gouging modeling in detail.The effects of geohazards Arctic areas on the integrity and safety of subsea pipelines have been investigated. The focus of this part is on ice gouging event and the previous studies in this area and the related implications for buried pipeline and the seabed soil. Recent discoveries in this area and different methods of modeling ice gouging phenomena have been reviewed. In the third chapter of the thesis a conference paper which was published in Geoedmonton 2018 is presented. . Different soil model was used in this paper and the constitutive model is explained in detail, and its advantages are highlighted. The application of a user material model in ABAQUS/Explicit is shown. The results were sufficient, but the mound formation was exaggerated by the software.

In the fourth chapter of the thesis, a journal paper is presented, which discusses the MMC model and development of the VUSDFLD subroutine in detail. The model advantages and results were explained. The CEL model was examined deeply, and two comprehensive groups of parametrics were studied. The first parametric study considers the main features of ice and gouge mechanisms and the second one investigates the soil parameters which contributes in ice gouging model.

At the end of the thesis, the conclusions of this study are summarized, and some suggestions for future work are offered. Another paper which was submitted for Congress on Numerical Methods in Engineering (CMN 2019) is illustrated in Appendix A. It sumerise the journal paper which has been presented in chapter 4 and the key points of the research.

Chapter 2.

Literature Review

2.1. Arctic Geohazards

The most probable geohazards that can happen in an offshore project are fault planes, scour and sediment mobility, seabed subsidence, earthquakes, submarine slope stability, shallow gas, and liquefaction.

The specific geohazards of Arctic area are more challenging, such as ice gouging, permafrost thaw, strudel scour and upheaval buckling (Abdalla et al., 2008).

The literature review shows the empirical and analytical solutions, physical modeling, laboratory testing and numerical methods that structure the motivation and framework for the current study . Reliability on progressing finite element procedures to model the complicated, nonlinear coupled ice/soil interactions requires a deep understanding of parameters affecting soil constitutive model and behavior, subgouge soil deformation and failure mechanisms during free-field ice gouge events.

This thesis focuses on the large deformation ice/soil interaction in cohesionless soil for improvement of finite element tools for appropriate application to regions with natural soil changeability.

2.2. Ice gouging phenomena

2.2.1. Icebergs and Ice Ridges

Ice bodies that scour or goug the seabed generally are in two categories: icebergs, and ice ridges. Ice ridges are the ice created by environmental agents such as wind and currents. In the Alaskan Beaufort Sea, ice ridges are the dominant reason for ice scouring whereas in the east Arctic and Labrador icebergs usually gouge the sea floor.

An iceberg is a large part of the glacier or an ice sheet that has been detached from them and float in the ocean. Icebergs are made of freshwater. Hence, 90 percent of their body submerged (the keel) and the rest floats above the water (the sail) (Barrette, 2011).

The ice ridges are formed by saline water, and their submerge density is higher than the icebergs'. They are mostly found in frozen lakes. The ice ridges can have a great depth below the water as well as a great height above the water. In the case of high horizontal forces, such as wind, the icebergs might gouge the seabed.

2.2.2. Ice gouging process

The main hazard to subsea pipelines is ice gouging in the Arctic area. When ice reaches to the shallower water or shoreline, the ice gouging takes place. There are several scenarios that can happen by the contact between the ice and soil. Ice gouging occurs when the driving forces such as wind and currents are large enough to penetrate the ice into the soil. The ice first starts to penetrate the seabed and advances horizontally. After that, the ice reaches a steady state in which it moves with an approximately with a constant gouge depth and velocity which depends on the seabed shear strength and also environmental conditions. In the Springdale M-29 scour located in Grand Banks, the speed of 0.5 m/s was recorded (McKenna, Crocker, and Paulin, 1999). The ice that is in contact with the soil revolves over the point of contact to keep its equilibrium. The attack angle is the angle between the ice and seabed which is dependent on the local interactions between ice and soil. Figure 2-1 shows a schematic view of ice gouging.

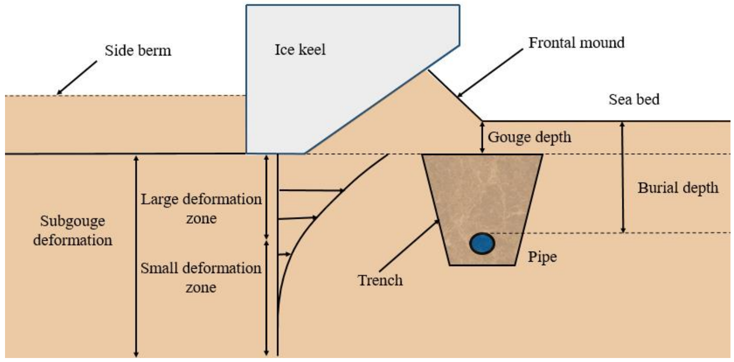

Figure 2-1. Ice gouging mechanism

The distribution of the ice gouges along with the gouge depths have been investigated. Most of the gouge depths are less than one meters; however, gouges with five meters of depth have been recorded. The gouges with more than two meters of depth have been considered an extreme occurrence. The gouge widths in extreme cases can be between a few meters to tens of meters wide. Figure 2-2 shows the marks of ice gouging on the seabed.

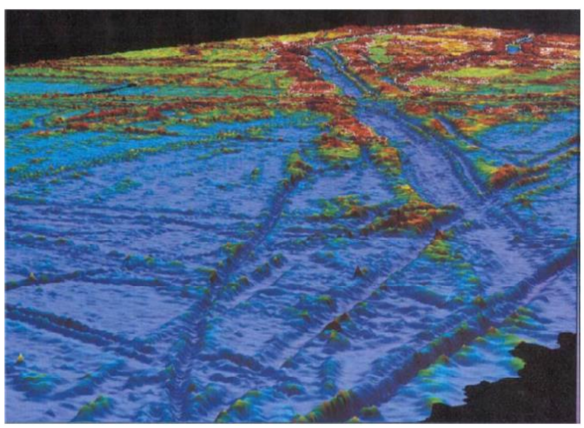

Figure 2-2. The ice scours on the Canadian Beaufort Sea (S. Blasco, NRCan)

Some of the damages from ice gouging can be seen in the literature (Grass, 1984; Noble and Comfort, 1980; Vershinin et al., 2008).

2.2.3. Gouge geometry

The seabed gouges are the most crucial issue threatening the integrity of the subsea pipeline in cold areas since the pipeline design and route selection both are affected by this problem in offshore projects.

Generally, the deeper gouges happen in deeper water about 20 meters and smaller one in water about 5 to 10 meters deep. A typical relation between the water depth and gouging depth has been developed by Rearic and McHendrie, 1983 and is shown in Figure 2-3 which is based on the surveys in the Beaufort Sea.

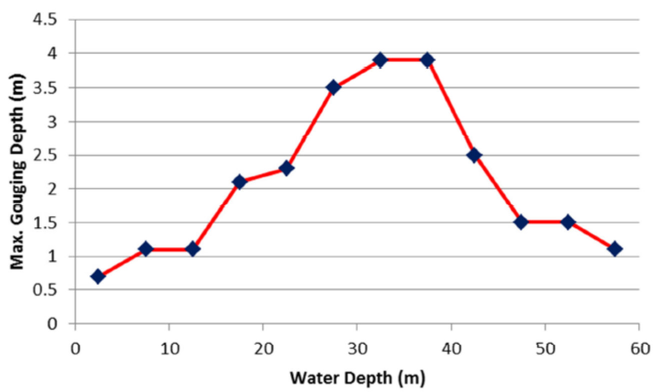

Figure 2-3. Water depth and maximum gouge depth (Eskandari, 2014)

It was hoped that the extreme gouges happened in the past and did not take place contemporarily; however, more studies showed that even deep gouges are being scoured at present (Palmer et al., 1990).

2.2.4. Ice/Soil interaction

The ice gouge can create a considerable challenge for pipelines in cold areas. The extent of soil deformation is divided into three zones as shown in Figure 2-4.

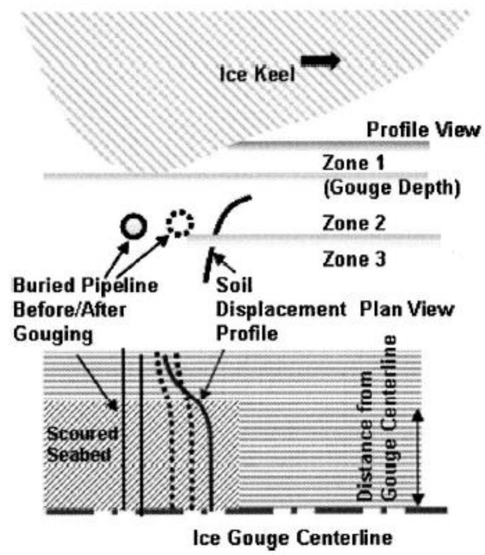

Figure 2-4. The division subgouge deformation (Nobahar, et al., 2007)

Zone 1 is the closest layer to the seabed. The ice keel enforces significant large deformation in this part which leads to potential failure of the pipeline because of the direct contact. Thus, the pipeline should not be placed in this zone. Below zone 1, zone 2 is located. It was assumed that by preventing direct impact between the ice and the pipeline, the risk of failure of the pipeline had been solved; however, the findings from Pressure Ridge Ice Scour Experiment (PRISE) project and other studies proved that zone 2 also bears large deformation in soil under the ice (Philips et al., 2005). Therefore, even without direct contact between the pipeline and ice, there is a good chance of failure for the subsea pipeline in this zone, too. Zone 3 is the layer with small strain. Placing the pipelines in this layer is safe; however, it is not economical. The pipeline used to be placed in twice the maximum gouge depth or more in the past. Due to the nature of ice gouging which is a displacement-controlled phenomenon, it is sufficient to consider an ultimate state in which the pipeline deforms plastically, and the integrity of the structure is kept (Nobahar et al., 2007).

2.3. Previous studies about ice gouging

There are four methods for investigating the ice gouging phenomenon:

1. Physical examinations
2. Laboratory tests
3. Theoretical studies
4. Numerical analysis

Historical events present that ice gouging inducing large deformations to the soil creates scours in the seabed and forces soil materials into berms at two sides of the trench, (Woodworth-Lynes et al., 1996). Laboratory tests and numerical analyses prove that a mound would be shaped in front of the keel. This illustrates that the nature of ice gouging event is a three-dimensional process (Palmer et al., 1990). There is comprehensive information on ice gouging, and some unresolved issues in this field have been raised by Palmer and Niedoroda, 2005.

2.3.1. Physical examination

Despite the accurate information that can be found by conducting physical tests, the technical challenges involved in operating these tests are very significant. One of the reasons for conducting real ice gouging tests is to investigate this event in a natural environment. These tests can produce a valuable understanding of how the ice gouging mechanism works. These studies contain information about the area where scouring might happen, anticipating the drift path of ice, arrangement of the drift path, ice feature properties and specification of seabed soil properties. The program of the Dynamics of Iceberg Grounding and Scouring (DIGS) was one of these natural ice gouging studies in

1985 on the Labrador continental shelf (Hodgson et al., 1988; Lever et al., 1991; Woodworth-Lynas et al., 1991).

Lanan and Ennis, (2001) conducted some offshore pipelines studies which investigated the ice scour in cold regions of North Star in the Beaufort Sea.Pipes were placed at 2.2 meters deth. In Lake Erie, the Millennium project was conducted to transport Canadian natural gas to the United States. Pipe was trenched to a depth of 3.4 meters (Lever, 2000); however, it was never built. A test project was conducted in the east coast of Canadian arctic islands using the Hibernia, the Terra Nova and White Rose facilities in Grand Banks to explore the feasibility of gas transportation in these areas. Similar projects were conducted in other cold areas including Kashagan field in the Caspian Sea, and Sakhalin projects 1-4 in the Sea of Okhotsk (Kenny et al., 2007).

Another group of physical studies focuses on real ice features. To anticipate the maximum gouge depth, it is crucial to have sufficient knowledge of ice and soil properties of a geographical location. In the case of ice ridges with complex internal structures, this becomes more essential (Croasdale et al., 2005; Croasdale et al., 2001; Liferov et al., 2002).

The next significant group of physical field studies is seabed mapping. The information about the nature of ice gouging has been gathered by these studies. The data, such as gouge depth, width, length, orientation, density, and frequency, can be taken from these studies (King, 2011).

The other aims of physical studies are the gouge relicts which exist currently on land that used to be the seabed of ancient lakes or seas. These studies can provide perfect information about the subgouge deformation of the soil (Woodworth-Lynes et al., 1996).

Liferov and Pavel (2005) published the outcomes of a series of tests conducted to capture the failure of seabed soil and ridge keel.

Since operating in situ, full-scale gouging tests are complicated, the small scale test and numerical analyses are being employed for designing purposes (Liferov et al., 2007).

2.3.2. Laboratory test

Due to the complexity of ice gouging events such as the large deformation, shear band, and cracks, simulating of ice gouging process is difficult and need special attention. The laboratory tests are being used to understand the ice gouging phenomenon accurately and more precisely. The large scale ice gouging testing is difficult since, in addition to the technical problems associated with these tests, the subgouge deformation can be very hard to capture and measure. Therefore, the real scale tests are impracticable, and consequently, laboratory tests become more favorable. Ice gouging is a process with high-stress level, and in cohesionless soil, the soil particles may crush during this event and sand may show cohesive behavior different with the low-stress levels that its response is mainly frictional The centrifuge test provides the chance of solving these stress level problems.

The research which utilizes the laboratory test data employ the results of these tests to the actual real-scale process. Sometimes the scaling can be ignored to validate or calibrate a numerical model (Barker and Timco, 2002; Barker and Timco, 2003; Barrette and Timco, 2008; Stava et al., 2008; Vikse et al., 2007). The other approach is applying a centrifuge to model high gravity (Phillips et al., 2005).

C-CORE research on ice scour focuses on cultivating phenomenological data of ice scouring, direct monitoring of gouges from manned submersibles, investigate the results of the scours in the Canadian Arctic and Lake Agassiz, Manitoba, conducted small-scale iceberg gouging events in the St. Lawrence River and Laboratory simulation of the gouging process. From the tests in cohesive soil, it resulted that in fine materials considerable subgouge deformations can occur while the surface deformations are relatively small (Poorooshab and Clark, 1990).

Chari and Green, (1981) used a flume of 14 x 4 meters. This study showed the motion of soil ahead and below the gouge. They put a pipe in front of the ice and under the keel to measure the induced pressure and later Green et al., (1983) concluded that a keel with an attack angle of 30 degrees shows 30% enhancement in pressure on the pipes in comparison with a keel with a vertical face.

Paulin, (1991) conducted gouging tests on the sand in dry and fully saturated soils. They used two attack angles of 15 and 30 degrees. They realized that displacements in loose sand were more substantial than a dense one.

Kioka et al., (1999) performed many tests and investigated the influence of attack angle and scouring velocity. The experiments resulted in that the gouging force is affected by the speed but not by the attack angle.

Nevertheless, the attack angle influences the gouge depth, and the upward displacement of the model ice rises with the decline of the attacking angle (concerning horizon).

Vikse et al., (2007) executed scouring tests associated with pipelines. They reported that by passing over the pipeline a cyclic motion path pursues, and the maximum pipeline deformation happens by the lower attack angles of the ice.

By using the scour tank facilities in Memorial University on Newfoundland some laboratory tests were conducted by Clark et al., (1990) in which they investigated the ice gouge in very soft silt soils, and later Clark et al., (1994) studied the ice gouge in sands.

These tests showed that the vertical force of ice keel is considerable and can be large enough to lead to failure and deformation in the soil under the gouge, unlike the previous assumption that laboratory research made that the ice scour mostly a ploughing action on the seabed with a small vertical force.

Barrette and Timco, (2008) operated an experimental project to examine the mechanism of ice gouging of a coarse sand seafloor. They tried to eliminate many problems which were associated with the test set-up and did not exist in a real situation. In this project, the gouging process was simulated in a flume of 6 x 2.6 meters with a height of 1.2 meters and real ice was employed to gouge the soil. Their outcomes confirmed the previous studies and also, they found out that at the initiation of the study the ice penetrated the seabed fairly suddenly beside the horizontal movement until halfway where the steady movement parallel to the seabed begins.

Centrifuge tests are perfect resources for solving some of the scaling problems of small scale test results to full-scale conditions. Palmer et al., (2003) conducted a comprehensive set of tests and compared them with full-scale data of buried pipelines and reported that there are hesitations in scaling the displacement field of the test results to full-scale situation. Woodworth-Lynes et al., (1996) have conducted centrifuge tests to study the scaling problems that happen.

Schoonbeek and Allersma, (2006) did some initial centrifuge test on some scouring and the scouring of the remolded soil. They investigated ice scouring of the soft soil overlying by an overconsolidated layer. This research concentrated on the scouring in clays.

The PRISE project was an internationally funded, interdisciplinary program that C-CORE was also part of it. This program motivated to prepare a guideline for the safe design of the pipeline and other seabed installation in areas that are disposed to the ice gouging. PRISE contained a wide variety of research including data collecting, centrifuge, and numerical simulation, model development and installation of test pipeline in the area influenced by the ice gouge. The experimental project of PRISE has been summarized by (Phillips et al., 2005).

Woodworth-Lynes et al., (1996) conducted a series of tests on sands and clays with scales of 1/75 and 1/150 which were analyzed by Walter and Phillips, (1998) and resulted in some empirical equations to find the forces. In these studies, no buried pipeline was used, and the keel was simulated as a rigid indenter. The study was a section of a joint industry program known as PRISE. The empirical function extracted from these tests are important in ice gouging investigation; however, using them in a situation other than the test needs special attention since the subgouge deformation resulted from these formulas are independent of the material properties. The PRISE's results were reported in 2005 (Kenny et al., 2005; Phillips, et al., 2005).

2.3.3. Theoretical studies

The ice gouging can be studied by geotechnical theories. As these theories work with the most important aspects of a mechanism, they can demonstrate a simple solution as the initial guideline for more evaluations.

Chari and Green, (1981) investigated the horizontal movement of ice gouging the seafloor by using the equilibrium of forces on the body of the material ahead of the iceberg and the predicted failure surfaces and finally calculated the forces on the iceberg. The momentum balance equation was employed after that to anticipate the iceberg movement distance. Other research has used the same approach to find the force and gouge length (Kioka et al., 1999). A comprehensive parametric study of such models that apply force equilibrium or energy balance to calculate the forces and scour length was conducted by Nilsen, (2003). These studies resulted in a deeper understanding of the effects of kinetic energy, attack angle and other important parameters on soil deformation.

2.3.4. Numerical analysis

Iceberg scours models are generally characterized in two methods. One approach applies a range of plastic limit analysis. Schoonbeek et al., (2006) conducted detailed research using this approach. Also, they explored the formation of possible failure planes comprehensively to enhance the prediction of the forces.

The other method is using finite element modeling. The finite element approach is able to apply available codes which were constructed and validated to answer soil mechanise problems. It also provides the prospect to apply a different kind of constitutive models for numerous types of soils (Kenny et al., 2005).

Despite advancement in this area, there are still some complications. Plastic limit analysis cannot find the map of the strains, stresses and void ratio. Moreover, it is not able to anticipate the displacement and stresses of the model below the considered slip lines. The nonlinear deformation like the gouging problem creates many difficulties when finite element method is employed. Further, the finite element with mesh reconstruction is computationally costly, and hence their use is narrow. Palmer and Niedoroda, (2005) explained some of the issues associated with the modeling.

Nevertheless, the numerical methods are considered a strong approach to investigate the mechanism of ice scouring and finding the soil behavior and pipeline to the gouges. For instance, Konuk et al., (2006) present that the deformation path of particles in the subgouge area is oval since the ice forces the soil down and moves forward. As the keel passed, the soil particles improve their deformations to some degree, but because of the plastic deformations, they do not recover completely.

Numerical simulation enables the researchers to model the problems in various boundary conditions and loading cases or soil materials in general.

One of the key points of accurate numerical modeling is choosing a suitable constitutive model. These model should be capable of finding different stress paths. Also, they should be simple to finding the input parameters with a few common tests. They should be founded on the realistic explanations of material stress-strain behavior of the ice scouring phenomenon. Kenny et al., (2005) presented the finite element analysis that could capture the main points of ice/soil/pipe interaction sufficiently. Continuum models are supposedly exact simulation of the real problems they have been defined for; however, practically they are not exact, and their response relies on the constitutive model and simplifications applied in the method.

Numerous methods are used and explained in literature to tackle the ice gouging problem. Some of these approached are more well-known such as pure Lagrangian, updated Lagrangian, Pure Eulerian, mesh free and Arbitrary Lagrangian Eulerian. The strength of the pure Lagrangian is the accurate definition of the ice-soil interface as the nodes are attached to a material., However as explained before, the nonlinear nature of deformation in scouring event can lead to not properly analysied in a Lagrangian reference method and consequently it may not be stable. The mesh distortion has been reported by Woodworth-Lynas et al., (1996) and therefore it possessed convergence problems. Konuk and Gracie, (2004) also explained that the method of assigning the nodal values to the nodes of the new mesh in the updated Lagrangian method creates errors in the simulation. To eliminate the large deformation problems and following numerical instability and also enhance the results of the numerical modeling the Arbitrary Lagrangian-Eulerian method is used in ice gouging finite elements analysis (Jukes et al., 2008; Kennyet al., 2004; Konuk et al., 2007; Lele et al., 2011; Liferov et al., 2007; Nobahar et al., 2007; Pike and Kenny, 2016). In addition to the ALE approach, the latest method of tackling the ice gouging problems is Coupled Eulerian-Lagrangian (CEL) method which has been proved to be both accurate and straightforward to use (Pike and Kenny, 2016; Lele et al., 2011).

To simulate the ice scouring problem, both 2D and 3D models were developed. However, the best model as discussed before is the 3D models which mimic the conditions more realistically.

During the PRISE project, a large number of studies were conducted to model the ice gouging event numerically. Yang, (1993), Yang and Poorooshasb, (1997) employ an elastic-perfectly plastic, non-dilatant Drucker Prager model. They utilized the small strain formulation and simulated the pipe with beam elements with an undrained condition soil. Yang and Poorooshasb, (1997) validated their model with the centrifuge results for clay for a 2D model in undrained condition. The model overestimated the centrifuge results.

Lach, (1996) developed a 2D model using modified Cam-Clay constitutive material. The 2D model encountered limitation because of the idealization and mesh distortion.

Jukes et al., (2008) conducted a 3D finite element analysis that used the CEL method to tackle the mesh distortion problem using Prager Cap soil model. They move the ice horizontally to mimic the steady state condition. ABAQUS software 6.7 was employed, and the pipe and ice ridge were made of Lagrangian elements and soil were modeled as

Eulerian body. They proposed that generally, ice scouring in dense soils results in higher deformations for the pipeline. The soil deformation also enhances with the gouge depth. They suggested that the pipeline moved downward as the ice passes through it because of the vertical load induces to the pipeline, and then it comes back to its place. The recovery time of the pipeline is directly related to the gouge depth.

Abdalla et al., (2009) developed a CEL model in ABAQUS software to investigative the ice scouring event. The developed 3D model anticipated the enforced stresses and strains in the pipeline under the ice scouring load. The model validation was conducted by the results of the centrifuge tests and other published FE developed models by other researchers. They came up with relations of pipeline burial depth and pipeline strains for different ratios of pipeline diameter to thickness.

Eskandari et al., (2011) studied an ice gouge event in cohesionless soil by developing a NorSand soil model and implementing it in a numerical finite element model. They used the critical state of sand and depression of the dilation of sand to capture the strain softening behavior of cohesionless soil behavior and came up with a 3D ALE model. The results of this paper presented that the developed NorSand model was able to eliminate the excessive dilation of sand which is produced by the commercial finite element packages and improve the modeling behavior of sand for different loading conditions, especially in an ice gouging event, it was able to capture the subgouge deformation more realistically.

El-Gebaly et al., (2012) utilized complicated numerical methods which limited the simplification in the conventional numerical methods such as decoupled ice-soil and pipe-soil approaches and investigated the ice gouging. The CEL method was employed to simulate the process and was validated by the available centrifuge and full-scale test results. It has been reported that the CEL subgouge deformation results are smaller than the compared data.

Peek et al., (2013) simulated the large scale tests of Texas. The soil was a 3D dimension body of clay and was meshed by Eulerian elements. A constitutive soil model was proposed which was an invariant of Von Mises yield surface that relied on time for its elastoplastic feature to calculate the yield strength. This study was able to simulate the strain hardening of the soil and stress-strain curves which were resulted from unconfined compression laboratory tests.

Been et al., (2013) explained an approach for designing pipeline against ice gouging load which was proposed during the Kashagan project in the North Caspian Sea. In this approach, the ice interacted with the subsea pipe and found the subgouge deformations in regard to soil properties, keel geometry and the then applied the subgouge displacements loads on the pipe.

Been et al., (2013) came up with a new empirical relationship for subgouge displacements in clay. These relationships were developed the past studies that were conducted by PRISE program and eliminated some of the simplifications that were expensive in enormous projects such as the constructing of Kashang. The developed relationships were considered numerical analyses, centrifuge tests, and flume tests data. They added keels with attack angles of 30º and 45º to the PRISE attack angle which was 15º. The new empirical relationships were for both clay and sand. Some parameters such parameters which included the material properties were added, and they improved the PRISE formulations significantly.

Barrette and Sudom, (2014) prepared a comprehensive study on the centrifuge tests that have been conducted to understand the ice gouging mechanism. The database included about 500 physical tests, and it contains different keel geometries, the degree of freedom of ice, soil and pipe features. There are some important problems and gaps that have been mentioned in this study which should be paid more attention in the future.

Pike and Kenny, (2012) studied on some issues in designing offshore pipeline under the ice gouging load. This study concentrated on modeling of contact and defining the interface parameters. The paper resulted that the employing of simplified interface conditions can create a reasonable method to simulate contact mechanisms, subgouge deformations, soil cleaning, and failure mechanisms.

Pike and Kenny, (2012) worked on describing of the soil resistance to axial pipe displacement in cohesive soil material for enforced loading. Parametric studies were conducted to evaluate the sensitivity of the model to interface shear stress limit and friction coefficient. The results showed that the interface shear stress limit has a significant impact on the tangential shear behavior and consequently on the axial pipeline reaction force. A method was proposed which applies a rational drained friction coefficient in addition to an interface shear limit based on the remolded undrained shear strength of the soil to employ in numerical simulations of enforced pipe/soil interaction in clay.

Chapter 3

Large deformation analysis of ice keel-soil interaction in sand

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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 subgouge 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 methods 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.

3.1. 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 industr 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 safe pipeline from 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.

3.1.1. 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 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 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.

3.2. 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 .

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 a steady state sooner and reduce 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 nodes, 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 a 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 from being 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.

3.3. 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 3-1 defines the relationship between the elastic modulus and effective confining stress through the following power series:

$$E_s/P_a = K\left(\frac{K_o \times \gamma' \times H}{P_a}\right)^n \tag{3-1}$$

Where P_a is the reference to 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 3-1. 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 . The Mohr-Coulomb model 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 ψmax have been reduced linearly from their peak values to their residual (critical) values which are ϕ'critical and 0. As a 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 3-2 shows the relationship established by Anastasopoulos (2007) to calculate $\gamma^p{}_f$ based on the finite element size and direct shear test data.

$$\gamma_f^p = (\delta x_p - \delta x_y)/D + (\delta x_f - \delta x_p)/d_{FE} \tag{3-2}$$

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.

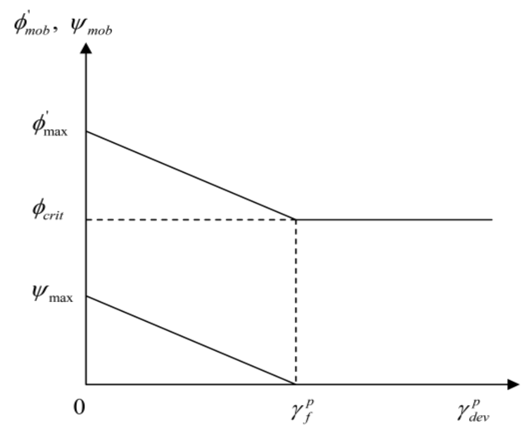

Figure 3-1. Reducing of the friction and dilation angles from (Anastasopoulos et al., 2007)

3.4. Finite element 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 except 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 subgouge deformation further validated by Pressure Ridge Ice Scour Experiment (PRISE) physical model data for similar conditions which have been conducted by Philips et al., (2005). The horizontal and vertical reaction forces validated by Pipeline Ice Risk Assessment and Mitigation (PIRAM) test conducted by Yang (2010). The horizontal reaction forces are shown as positive, and the vertical reaction forces are shown as negative.

shows the results of reference subgouge simulations and the results of the current study. compares the results of the centrifuge test, and developed model and represents the comparison of reaction forces.

The start of the vertical axis in Figure 3-5 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 subgouge displacement.

3.5. Results and discussions

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

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

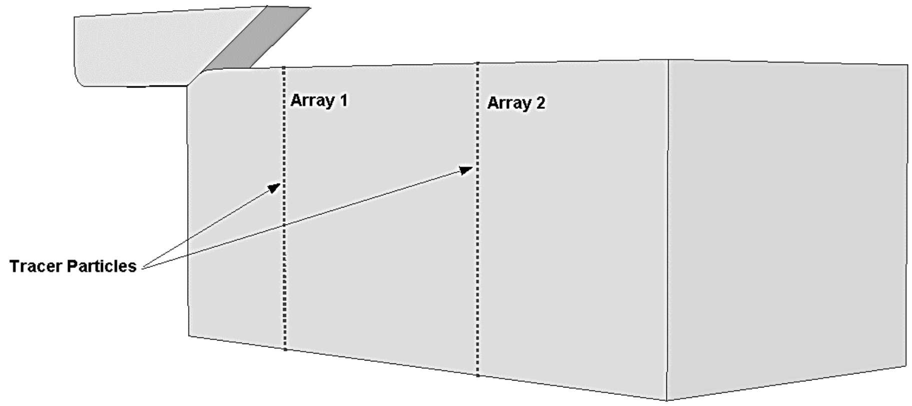

Figure 3-2. Initial ice and seabed

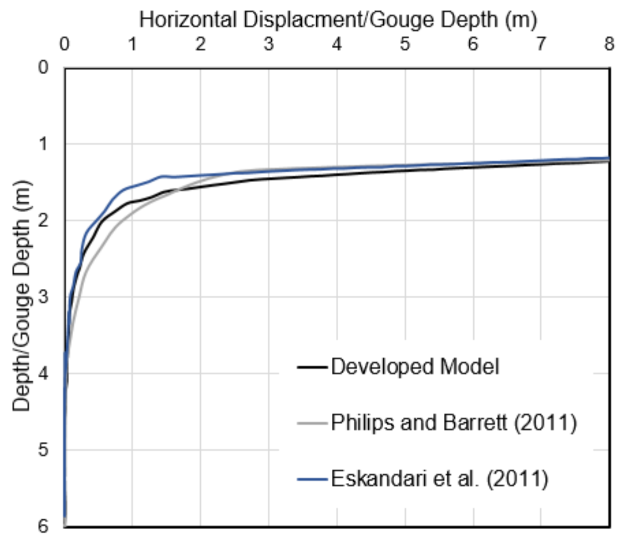

Figure 3-3. Comparison of subgouge deformation of the developed model and the reference FEA models

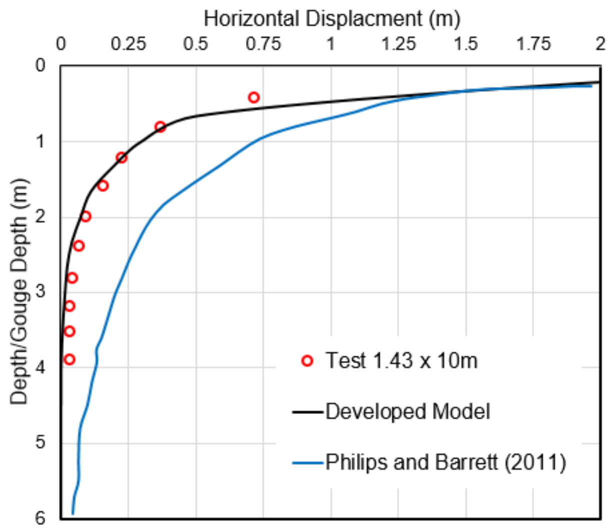

Figure 3-4. Comparison of subgouge deformation of the PRISE test and developed model

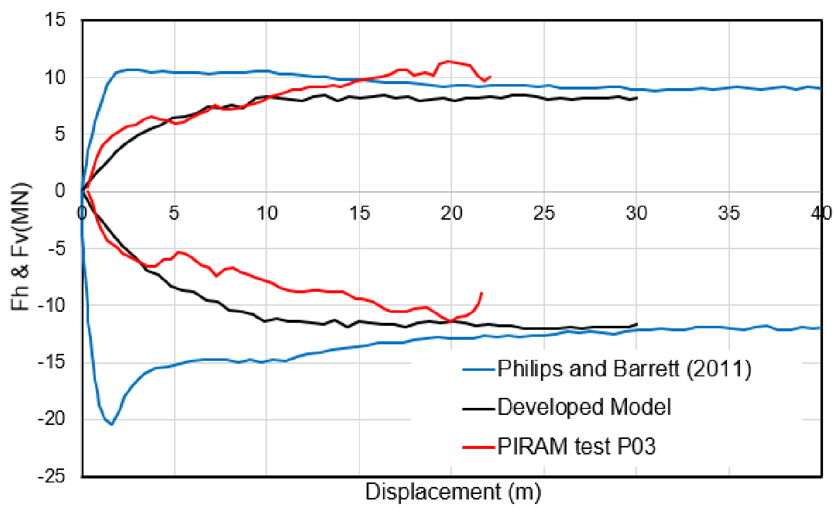

Figure 3-5. Comparison of horizontal and vertical reaction forces with FEA reference model, PIRAM test, and developed model

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 3-4 shows, the current study is in more agreement with the test results than Philips and Barrette (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 3-5 represents the consistent between the reaction forces of the 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 subgouge deformation. The conventional subgouge 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.

3.6. 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 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 is 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 the basic properties of the sand are very effective in seabed behavior under gouging events.

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Chapter 4

The Influence of Non-linear Stress-Strain Behavior of Dense Sand on Seabed Response to Ice Gouging

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Abstract

Large deformation analyses were conducted to simulate the ice gouging process in dense sand. A modified Mohr-Coulomb model was adopted to incorporate the non-linear stress-strain features of dense sand including the plastic shear strain accumulation, loading condition, density and confining pressure. Coupled Eulerian-Lagrangian methodology was used in a series of dynamic ABAQUS/Explicit analysis with the soil model implemented as user-subroutine. A comprehensive parametric study was conducted to examine the effect of ice keel configuration and soil model parameters on keel reaction forces and subgouge soil deformations. The proposed model prevented excessive dilation and better predicted the seabed response to ice impact.

Keywords: Ice gouging; Large deformation analysis; dense sand; constitutive soil modeling; Numerical modeling; subgouge soil deformation

4.1. Introduction

One of the most significant risks to subsea pipelines crossing the Arctic offshore territories is the ice-induced scour in the seabed. As a cost-effective solution, pipelines are usually buried for physical protection against the ice impact. Estimating the minimum reliable burial depth to obtain a sufficient level of pipeline protection is still a challenging design aspect due to uncertainties associated with the ice gouging characteristics. The response relies on deep understanding and proper modeling of the ice keel-soil interaction during the scouring process. In the past 20 years, a significant amount of research has been conducted on ice gouging event in cohesive and granular seabed sediments to advance the offshore industry's understanding of ice scour characteristics (NRC-PERD 2014, BSEE-WGK, 2015).

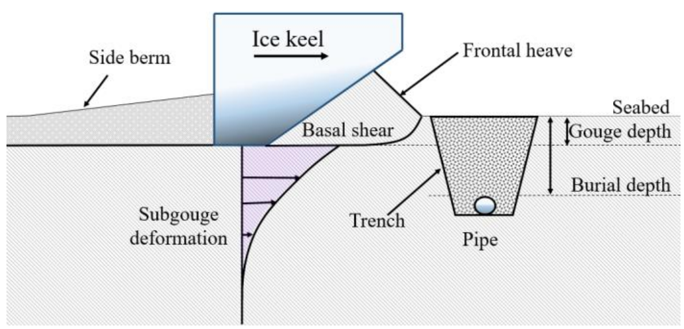


Figure 4-1. Ice gouging process and subgouge deformation

The classical Mohr-Coulomb (MC) soil model has been conventionally used for numerical modeling of the ice gouging in the sandy seabed, which is widely observed in Arctic offshore regions. The MC model is a simple and fast approach with an acceptable level of accuracy in many occasions that considers constant values of angles of internal friction (φ') and dilation (ψ). However, the MC model does not consider the characteristics of the non-linear stress-strain behavior of dense sand including non-linear pre-peak hardening, post-peak softening, dependency on density and confining pressure (Hsu and Liao, 1998), and the mode of shearing (e.g., triaxial versus plane-strain) (Bolton, 1986). These simplifications result in some level of inaccuracy in the estimation of the seabed response to ice scour within the basal shear zone underneath the ice keel. Consequently, the subgouge soil deformation, the keel reaction forces, and the heave formation in front of the moving ice keel are all affected. As for instance, the shear bands and failure planes underneath and in front of the ice keel develop progressively (Philips, et al., 2005). In addition, the failure planes are relocated with a displacement of the ice keel. Therefore, the simple limit equilibrium approach with constant soil strength parameters cannot properly represent this complex process. Therefore, the progressive formation of failure planes that can accommodate the variation of mobilized shear resistance along these planes needs to be incorporated in numerical models to better simulate the ice-seabed interaction mechanisms. There are advanced constitutive soil models like NorSand that consider some of the non-linear stress-strain features of the dense sand behavior that have been used for ice gouging (Eskandari et al., 2011). However, a significant amount of complex coding of material model and computational effort along with calibration of a large number of parameters are required.

In this study, a series of key features from some of the existing and recently developed non-linear models were adopted through a simplified approach to incorporate all of the aforementioned non-linear effects into a modified Mohr-Coulomb (MMC) model (e.g., Roy et al., 2015; Bolton, 1986). Then, large deformation analyses were conducted in ABAQUS/ Explicit using Coupled-Eulerian-Lagrangian (CEL) approach. The seabed soil model was coded into a user-defined subroutine (VUSDFLD) that was called by ABAQUS in every time increment to update the shear strength parameters of the sand based on accumulated plastic shear strain, loading condition, density and confining pressure. A comprehensive parametric study was conducted using the MMC model by examining different seabed parameters and ice keel configurations one at a time. The comparison was made between the results produced by MC and MMC models, and also some of the keys published experimental and numerical studies (Eskandari et al., 2015; Yang, 2009). It was observed that the classical MC model overestimates the subgouge soil deformation, front heave formation, and the keel reaction forces. The adopted simplified approach using the MMC model resulted in a higher level of accuracy with a lower computational cost compared to the conventional MC model and the previously hired modeling approaches. The proposed model resulted in considerably lower magnitudes of the seabed response, which is well close to the test results. The cyclic oscillation of the keel reaction force was also captured that have been reported in experimental observations but had never been produced by numerical simulations in the past.

4.2. Numerical Modelling Framework

4.2.1. Overview

Two different approaches have been historically used to model the soil-structure interaction: i) the simplified beam-spring approach, and ii) Continuum finite element (FE) analysis using constitutive soil models. The current state-of-practice for assessment of the ice impact on buried pipelines combines the simplicity of the beam-spring approach with an accuracy of the continuum approach through decoupled analysis. In this approach, first, a free-field ice gouging analysis is conducted by using continuum FE analysis, and then, the subgouge deformations are transferred to the simple beam-spring model to obtain the corresponding pipeline response (Barrette 2011; Been et al., 2013; Kenny et al., 2000, 2005, 2007b; Nixon et al., 1996; Philips, Clark and Kenny, 2005; Woodworth-Lynes et al., 1996). This conservative approach is computationally more attractive than the fully coupled large deformation finite element analysis (LDFE) but still suffers from the superposition of idealization errors and directional load decoupling effects through discretized soil media (Pike and Kenny, 2016).

Improving the accuracy and the computation efficiency of the free-field ice gouging analysis can consequently result in improved efficiency and accuracy of the decoupled method. This was the key objective of the current study, in which an MMC model was coded into a simplified user-defined subroutine (VUSDFLD) and incorporated into an advanced CEL/LDFE analysis.

Ice gouging is a large deformation event, where also the small classical strain exists. The lagrangian approach is not able to sufficiently model the large plastic soil deformations due to mesh distortion. Conventional remeshing technics cannot solve the problem because of imposing unreasonably high computational costs and accumulated errors (Belytschko et al., 2000; Lach et al., 1993; Woodworth-Lynes et al., 1996; Yang and Poorooshasb, 1997). The Arbitrary Lagrangian-Eulerian (ALE) approach resolved some of the limitations of the Lagrangian method, but it is still suffering from limited allowable mesh distortion (Banneyake et al., 2011). The Coupled Eulerian-Lagrangian (CEL) method that was adopted in this study, has been successfully used in LDFE analysis of the ice gouging process by allowing an independent material flow inside the mesh and eliminating the mesh distortion issues (Konuk and Gracie, 2004; Lele et al., 2011; Phillips and Barrett, 2011; Pike and Kenny, 2012).

The dynamic explicit analysis handles the severe deformation problems and difficult contacts by adopting small time increments (ice-soil contact or soil-pipe contact). Care should be taken to maintain the model stability and accuracy at the same time by setting appropriate simulation setup, mesh refinement, solution control parameters, and a solid post-processing practice (Konuk and Gracie, 2004; Lele et al., 2011; Phillips and Barrett, 2011; Pike and Kenny, 2012).

4.2.2. Finite Element Model

A half-space ice-soil model ($76 \times 22 \times 40$ m, L × W × H) was constructed to facilitate the validation of the model against the published numerical (Eskandari et al., 2012) and experimental studies (Yang, 2009) (see Figure 4-2) and to mitigate the potential boundary effects. The seabed soil was modeled as the Eulerian domain with 31.5 m depth to allow for a free material flow inside the Eulerian mesh and extreme deformations during the gouging process. The Eulerian domain was meshed using 8-noded linear reduced integration hexahedral elements (type EC3D8R).

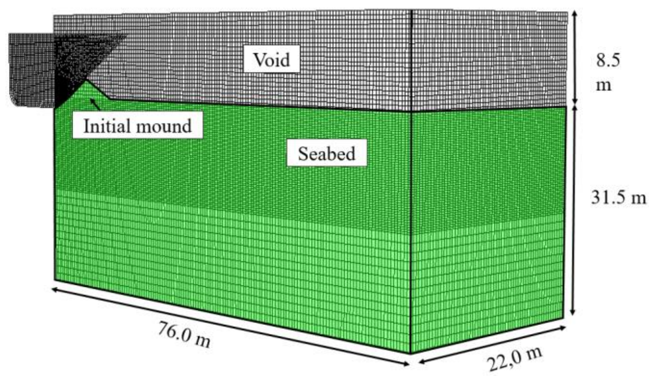


Figure 4-2. The constructed FE model configuration

The ice keel was modeled as a Lagrangian domain with vertical displacement restrained to simulate a horizontally moving rigid indenter (Eskandari et al., 2012; Fadaifard and Tassoulas, 2014). A void part with a total height of 8.5 m was assumed on top of the seabed surface to allow for the heave formation in front of the ice keel. The ice-soil contact was defined using the ABAQUS built-in general contact. A penalty based contact was also applied for the frictional behavior with a friction coefficient (μ) of 0.7 (i.e., $\tan(\varphi_{\mu})$). The parameter φ_{μ} are the ice/soil friction angle and lies between $\varphi'_{P}/2$ and φ'_{P} of sand (Yimsiri et al., 2004).

The model was initialized by setting the velocity boundary conditions to secure the Eulerian mesh and prevent the ice keel rotation. The geostatic stress was applied to model the soil column pressure (Lele et al., 2011). In the first analysis step, the gravity load was applied, while the initial geostatic step was contributing to the mitigation of the dynamic sudden load effects. In the second step, using the velocity boundary condition, the ice was horizontally displaced over a large displacement domain, while the other the degrees of freedom of ice was constrained. The velocity was gradually increased from zero to the target magnitude to prevent the generation of dynamic effects due to sudden loading. To minimize the computational effort, a finer mesh was used in gouging affected area, and a coarse mesh was used in the rest of the domain. Tracer particles were used in a 3D space and in different distance from ice keel to monitor the subgouge deformation and the soil displacement trajectories throughout the scouring process. The dense sand model was incorporated by coding the MMC model to a user-defined subroutine (VUSDFLD) that is further explained in the next section.

4.2.3. The Adopted Constitutive Soil Model

The classical Mohr-Coulomb (MC) is a simple soil model that has been used in its original or improved form in the past for modeling the ice-gouging in dense sand (e.g., Hossain et al., 2011; Panico et al., 2012). The experimental studies show that the plastic strain is developed well before failure, whilst the MC model assumes that the plastic strains develop only when the stress state is on the failure (yield) surface. In addition, the soil deforms at a constant dilation angle once the stress state reaches the yield surface, and any change in stresses within the yield surface results in only elastic strain. In order to capture this behavior, constitutive models of different forms have been proposed in the past (Prevost 1985; Gajo and Wood 1999; Dafalias and Manzari 2004). In this study, the non-linear models proposed by Vermeer and de Borst (1984), Bolton (1986) and Roy et al., (2015) were adopted through a simplified approach to incorporate the effect of non-linear stress-strain behavior that is not considered by built-in MC model in ABAQUS.

4.2.3.1. Flow rule

Bolton (1986) conducted an extensive number of triaxial tests to investigate the dependence of the peak friction angle (φ'_P) on mean effective stress (p') and also the relationship between the peak dilation angle (ψ_P), peak friction (${\varphi'}_P^{TX}$), and critical friction (${\varphi'}_C^{TX}$) angles. The author proposed the following flow rule for the behavior of dense sand:

$$\varphi'^{TX}_P - \varphi'^{TX}_C = AI_R \tag{4-1}$$

$$\psi_P = ({\varphi'}_P^{TX} - {\varphi'}_C^{TX})/K \tag{4-2}$$

$$I_R = I_D(Q - \ln p') - R \tag{4-3}$$

$$I_D = Dr(\%)/100 \tag{4-4}$$

where I_R is the relative density index, I_D is the relative density (Dr), Q and R are equal to 10 and 1 respectively, which are the best fit for most of the field tests (however; they may swing with the type of sand and p′). The subscripts P and C describes the peak and critical state, respectively. A is a constant equal to 3 for the triaxial condition and 5 for plain strain condition. ${\varphi'}_C^{TX}$ is the critical friction angle and is taken as $\approx 33^{\circ}$(Bishop, 1961; Cornforth, 1964). K is equal to 0.5 for the triaxial and 0.8 for the plain strain. A three-dimensional version of this flow rule was adopted in this study to suit the 3D nature of the ice gouging event.

4.2.3.2. Strain hardening and softening

Vermeer and de Borst (1984) proposed the following equations to approximate nonlinear hardening of the mobilized friction angle as a function of accumulated plastic strain. It was assumed that the mobilized friction angle would increase from 29.0° to ${\varphi'}_P$) when γ_P^P is reached.

$$\varphi' = \varphi'_{\mathrm{in}} + \sin^{-1}\left[\left(\frac{2\sqrt{\gamma^{\mathrm{P}}\gamma_{\mathrm{P}}^{\mathrm{P}}}}{\gamma^{\mathrm{P}} + \gamma_{\mathrm{P}}^{\mathrm{P}}}\right)\sin\left(\varphi'_{\mathrm{P}} - \varphi'_{\mathrm{in}}\right)\right] \tag{4-5}$$

$$\psi = \sin^{-1}\left[\left(\frac{2\sqrt{\gamma^{\mathrm{P}}\gamma_{\mathrm{P}}^{\mathrm{P}}}}{\gamma^{\mathrm{P}}+\gamma_{\mathrm{P}}^{\mathrm{P}}}\right)\sin(\psi_{\mathrm{P}})\right] \tag{4-6}$$

The parameter φ'_{in} is the initial friction angle corresponding to the beginning of the plastic response. During post-peak softening, the mobilized friction angle can be expressed as follows (Vermeer and de Borst, 1984; Hsu and Liao, 1998):

$$\varphi' = \varphi'_{\mathrm{c}} + (\varphi'_{\mathrm{P}} - \varphi'_{\mathrm{c}}) \exp\left\{-\left(\frac{\gamma^{\mathrm{P}} - \gamma_{\mathrm{P}}^{\mathrm{P}}}{\gamma_{\mathrm{c}}^{\mathrm{P}}}\right)^2\right\} \quad \text{(BC line, Figure 4-3)} \tag{4-7}$$

$$\psi = \psi_{\mathrm{P}} \exp\left\{-\left(\frac{\gamma^{\mathrm{P}}-\gamma_{\mathrm{P}}^{\mathrm{P}}}{\gamma_{\mathrm{c}}^{\mathrm{P}}}\right)^2\right\} \quad \text{(EF line, Figure 4-3)} \tag{4-8}$$

The geometrical form of the equations is illustrated in Figure 4-3 for various magnitudes of relative density and effective mean stress, where the post-peak softening inflection point is located at a shear strain of $\gamma_{\mathrm{c}}^{\mathrm{P}}/\sqrt{2}$ which is greater than $\gamma_{\mathrm{P}}^{\mathrm{P}}$.:

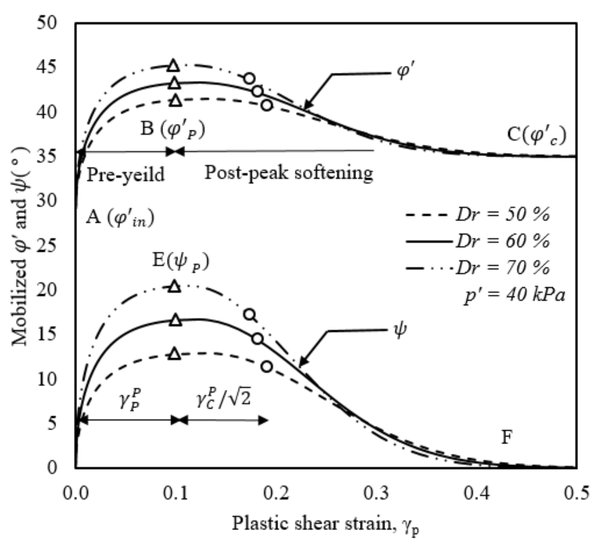


Figure 4-3. The mobilized $\varphi'$and ψ

The initial part of the plots shows the strain hardening that starts from the pre-yield zone in which φ' and ψ enhance from φ'_{in} and ψ_{in} to φ'_P and ψ_P at γ_P^P.

The peak strengths are mobilized at relatively smaller strain levels for dense sands under low confining pressures; hence, the plastic shear strain corresponding to peak friction angle can be expressed as a function of both the relative dilatancy and confining pressure (Lee et al., 1965; Tatsuoka et al., 1986; Hsu and Liao, 1998; Lings and Dietz, 2004). Roy et al., (2015) adopted the above approach and proposed the following equations to capture the effect of density and stress level on γ_P^P:

$$\gamma_P^P = \gamma_P^c \left(\frac{p'}{p'_a}\right)^m \tag{4-9}$$

$$\gamma_c^P = C_1 - C_2 I_D \tag{4-10}$$

where γ_c^P is the strain softening parameter and p'_a is the atmospheric pressure (100 kPa). The parameters m, C1 and C2 are soil parameters, which could be obtained from a set of triaxial or simple shear tests at different confining pressures and densities.

For modeling the elastic response, a Poisson's ratio (ν) of 0.2 was considered as a suitable value for dense sand (Jefferies and Been 2006). The Young's modulus (E) was considered constant through the model.

ABAQUS does not offer any direct way of applying the aforementioned features of non-linear stress-strain behavior of dense sand. Therefore, a simple user-defined subroutine (VUSDFLD) was developed and incorporated into explicit CEL analysis. The stress and strain components are passed through a subroutine in every time increment. First, the subroutine uses the stress components to calculate p'. Then the principal strain components are obtained using the VSPRING utility, and their gradient are calculated as the difference of the minor and major components of principal plastic strain. The γ_P was calculated as the sum of the $\Delta\gamma_P$ during the analysis time. The parameters γ_P and p' were defined as field variables (FV1 and FV2) and then, using the MMC model equations, the mobilized φ' and ψ were defined as a function of FV1 and FV2 in a tabular form in the model input file. The program updated the φ' and ψ with the field variable by reading the subroutine during the analysis and automatically incorporated the non-linear stress-strain response of the seabed material.

4.3. Verification of Numerical Model Performance

A series of LDFE ice gouging analyses were conducted using CEL method combined with the coded MMC seabed soil model to assess the performance of the constructed numerical model. The subgouge soil deformation, keel reaction forces and, the front soil mound were extracted and compared with the results of classical MC model and two published resources: ii) advanced numerical ice gouging studies using NorSand model (Eskandari, 2014), and iii) centrifuge model tests conducted at C-CORE under the "Pipeline Ice Risk Assessment and Mitigation (PIRAM)" JIP (Yang, 2009).

Figure 4-4 shows the initial configuration of the ice keel and the seabed soil in free field ice gouge testing of PIRAM JIP project (Yang, 2009). The FE model of this configuration was presented earlier in Figure 4-2. Two different tests (P06 and P07) with different sand relative densities (50.8% and 39.0%) and different ice moving velocities (0.11 m/s and 0.55 m/s) were selected for comparisons with the currents study. The ice keel was initialized to desired gouge depth to create a front mound for a faster achieving the steady state gouging condition.

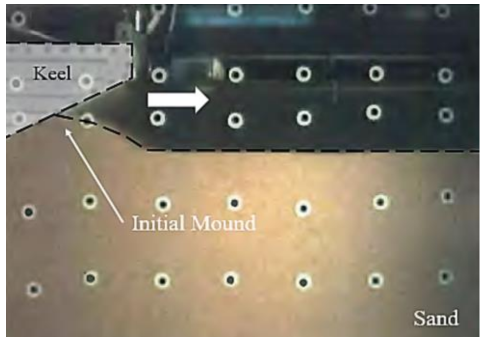


Figure 4-4. The centrifuge test of this paper (Yang, 2009)

The ice keel was horizontally displaced with a constant velocity for 300 mm. The subgouge soil deformations were recorded by placing displacement markers in the test bed and using a transparent observation window and digital cameras for particle image velocimetry (PIV) analysis. The PIRAM JIP project resulted in developing an effective stress constitutive soil model for sand which was later used by Eskandari, (2014) to simulate the conducted tests. The elastic modulus was considered as constant through the model (Eskandari, 2014; Konuk et al., 2007). The summery of tests parameters is provided in Table 4-2.

Table 4-2. PIRAM centrifuge test properties (Yang, 2009)

Parameters		Values	
		PIRAM P06	PIRAM P07
Gouge Depth (m)		2.3	2.4
Ice Velocity		0.11 m/s	0.55 m/s
D_r		% 50.8	%39
Ice Keel	Speed (m/s)	0.11	0.55
	Attack Angle	30°	
Young Modulus (MPa)		26	
Poisson's Ratio		0.32	
Density (Kg/m^3)		1455	1421

Eskandari, (2014) conducted a series of ice gouging analysis in the sand to simulate the PIRAM tests by developing and implementation of an improved version of the Norsand soil model to better capture the non-linear dilatancy effects (Yang, 2009). However, compared with the simplified methodology undertaken in the current study, an extensive amount of complicated coding is needed to be done by an advanced user to develop a user-defined material subroutine (i.e., VUMAT). Also, the model contains nine parameters that need to be properly calibrated through experimental studies. Table 4-3 presents the MC and MMC soil model parameters that were adopted in the current study to simulate the PIRAM tests conditions (P06 and P07). The densities used in MC and MMC models are similar to the centrifuge tests. However, the density adopted by Eskandari, (2014) in Norsand model is larger by about 400 Kg/m^3 (Eskandari, 2014). Moreover, a constant density index (I_R) of 0.97 and 0.6 were used in Norsand model for the test P06 and P07, respectively. For MMC model, as advised by Bolton (1986), the I_R values were varied by p' for the specific D_r of the centrifuge tests (I_R is about 0 to 4).

Table 4-3. MC and MMC parameters adopted in this study

<table>
<tr><th colspan="2" rowspan="2">Parameters</th><th colspan="2">Values</th></tr>
<tr><th>MC</th><th>MMC</th></tr>
<tr><td colspan="2">$\varphi'(°)$</td><td>$\varphi'_c = 35°$</td><td>Eqs. 1 to 11</td></tr>
<tr><td colspan="2">$\psi(°)$</td><td>6°</td><td>Eqs. 1 to 11</td></tr>
<tr><td colspan="2">Cohesion (kPa)</td><td colspan="2">2</td></tr>
<tr><td rowspan="6">Parameters of variation of φ' and ψ</td><td>A</td><td colspan="2">3</td></tr>
<tr><td>K</td><td colspan="2">0.5</td></tr>
<tr><td>φ_{in}</td><td colspan="2">29</td></tr>
<tr><td>C_1</td><td colspan="2">0.22</td></tr>
<tr><td>C_2</td><td colspan="2">0.11</td></tr>
<tr><td>m</td><td colspan="2">0.25</td></tr>
</table>

In this study, to mitigate the time and computational effort prior to achieving the steady state gouging process (Lele et al., 2011; Phillips and Barrett, 2011), the ice keel was gradually initialized to the desired initial gouge depth, while a front mound was created. Tracer particles were used in a 3D configuration and in a range of different distances from the initial ice keel position to capture the subgouge soil deformation. A set of tracer particles were used right in a place described by PIRAM for a better comparison against the test results.

4.3.1. Subgouge deformations and keel reaction forces

Figure 4-5 shows the comparison of the subgouge soil deformation and the ice keel reaction forces obtained from the current numerical study (MMC and MC models) with PIRAM centrifuge test results (tests P06 and P07, (Yang, 2009)) and the numerical study conducted by Eskandari, (2014) using the improved Norsand model. The horizontal and vertical keel reaction forces were shown by positive and negative values to facilitate observing the differences.

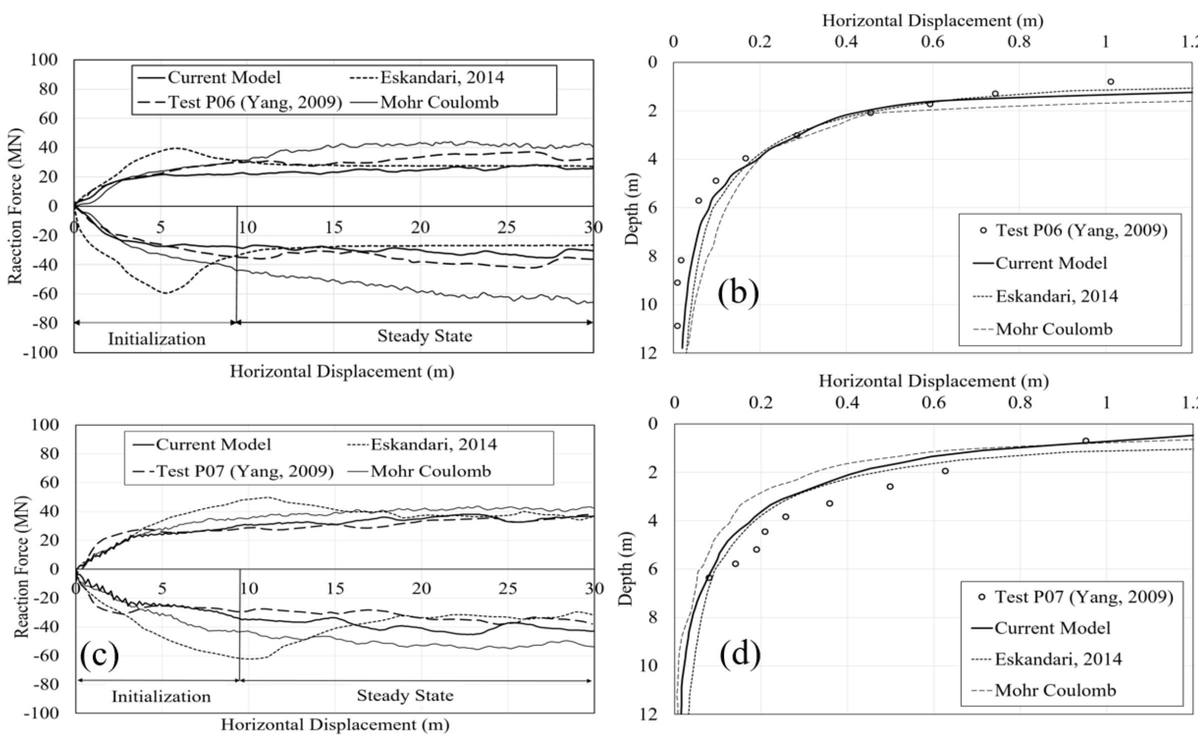


Figure 4-5. The comparison of subgouge deformations and reaction forces

The results obtained by the current MMC model are in good agreement with PIRAM test results. As expected, the adopted MMC model has well reduced the keel reaction forces compared with the classical MC model (Figure 4-5(a) and (c)). Compared with the numerical work conducted by Eskandari, (2014) (modified NorSand model), the classical MC model, and the PIRAM test results, much faster achieving the steady state scour condition was obtained by incorporation of the adopted MMC model. This resulted in a significant reduction of the initialization computational effort.

In addition, the MMC model has properly captured the cyclic oscillation of the reaction forces that have been observed in experimental studies (Eskandari, 2014). It seems, as the ice keel moves forward, the front berm is enlarged resulting in a slight increase of the reaction force. Then the berm is failed, and the material flows towards the sides of the ice keel resulting in reaction force relaxation. This is cyclically repeated resulting in oscillation of the reaction force. The oscillation amplitude is about 5 m and 10 m for simulation of P06 and P07 respectively, which are well correlating with the conducted test results. This cyclic oscillation that seems to be caused by cyclic pre-peak hardening and post-peak softening of dense sand that has not been captured in earlier numerical ice gouging studies but observed in experimental research works.

Figure 4-5(b) and (d) show a consistent agreement of the subgouge soil deformation predicted by the current MMC model and the test results. It was observed that the classical MC and modified NorSand models underestimated the subgouge soil deformation in P07 with a lower relative density (39%) and overestimated the results in P06 with a higher relative density (50.6%). A similar trend was observed in MMC predictions, but with the lower magnitude and a better prediction, closer to the test results. A better correlation was observed between the MMC model and the test results in P06 due to a higher range of relative density.

4.3.2. Front and side berm formation

Figure 4-6 shows the excessive dilation of the classical MC model relative to the current MMC model. The incorporation of the non-linear stress-strain behavior of dense sand that correlates the internal friction and dilation angles in progress shear bands in the base and front of the ice keel resulted in significant reduction in the front and side berms dimensions and consequently the mobilized reaction forces and subgouge deformations. Figure 4-6 shows that the front berm predicted by MC model in P06 is about 3.29 m higher than the adopted MMC model. This magnitude has been decreased by 10.6% in P07, for a 22.9% lower relative density.

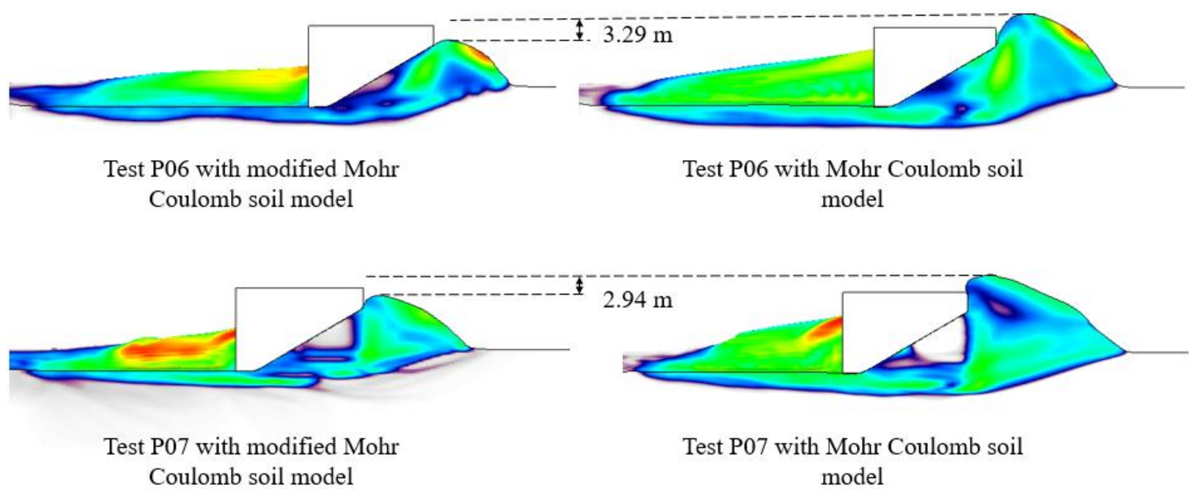


Figure 4-6. Visual comparison of front berm dimensions in MC and MMC models (The conturs show the maximum plastic shear strain which is not the foucus of this figure ;therefore, the legend was not provided.)

The influence of non-linear stress-strain response of dense sand on dimensions of side berm is illustrated in Figure 4-7. Compared with the MMC model, the side berm predicted by MC model is 1.1 m wider for P06 and 1.3 m wider for P07 (15.3% higher difference for 22.9% reduction in relative density). The effect of non-linear model features on side berm was found to be less than the front berm.

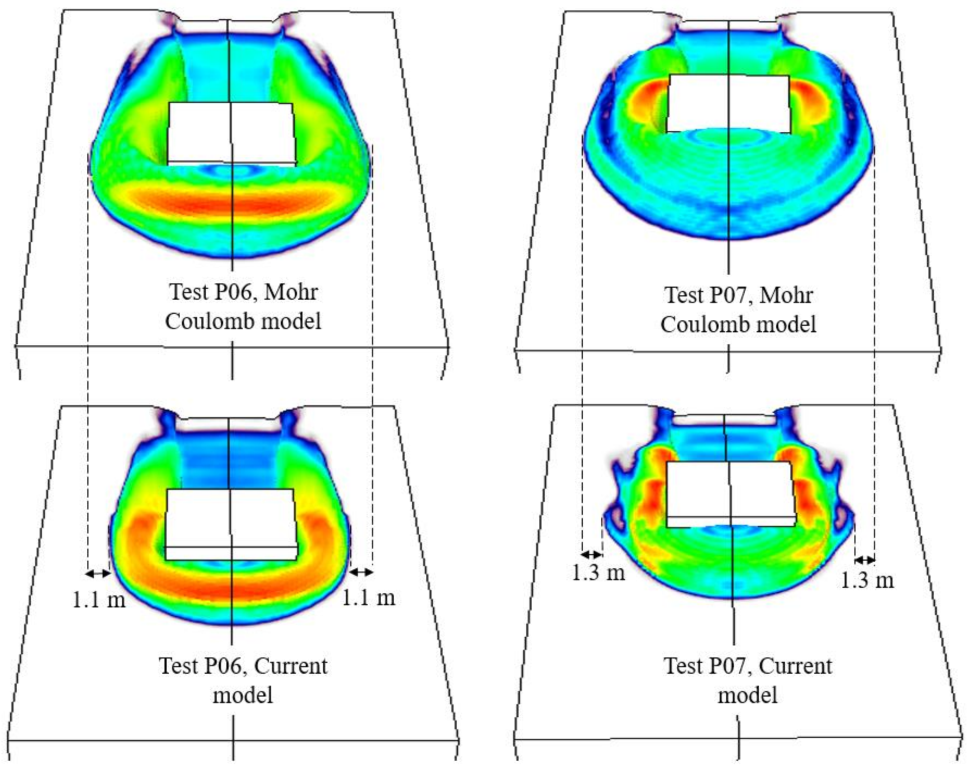


Figure 4-7. Visual comparison of side berm dimensions in MC and MMC models (The conturs show the maximum plastic shear strain which is not the foucus of this figure ;therefore, the legend was not provided)

4.3.3. Failure mechanisms and soil particles trajectories

The progressive failure mechanism of the seabed soil during the ice gouging process is illustrated in Figure 4-8. By initiating the scour process, the failure starts from the base of the ice keel. With a larger displacement of the ice keel, a basal shear band is horizontally developed underneath the ice keel and then deviated towards the seabed in a spiral curve.

The basal shear band ends up right at the edge of the created front soil berm. A dead wedge with almost no strain is formed right under the inclined part of the ice keel and moves forward as the keel proceeds with scouring the seabed. During this initialization process, the front berm is gradually developed. By approaching the steady state, gouging condition the soil in front berm flows towards the sides of the ice keel and the side berm is developed. As the gouging process continues, the front berm is cyclically mobilized and collapsed towards the ice keel sides, and this results in slightly oscillation of the keel reaction forces.

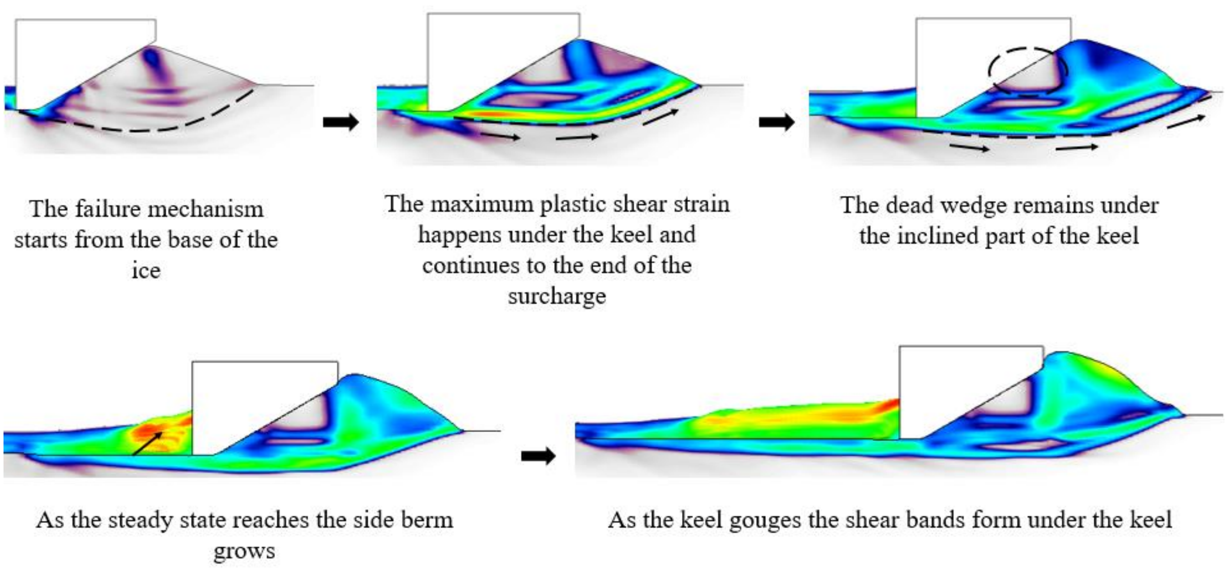


Figure 4-8. Failure mechanism of sand in Test P07 (The conturs show the maximum plastic shear strain which is not the foucus of this figure ;therefore, the legend was not provided)

This soil deformation process results in progressive variation of the plastic shear strain within the shear bands that is shown in Figure 4-9 for an instantaneous spot. The maximum plastic shear strain is developed in front and the side of the ice keel. Figure 4-9 shows that the test P06 with a higher magnitude of the relative density resulted in a greater plastic shear strain field.

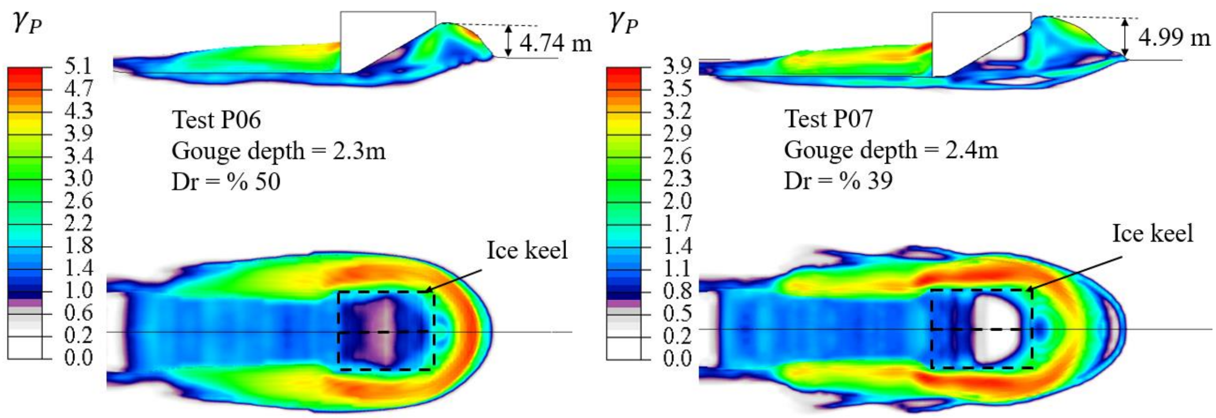


Figure 4-9. Progressive variation of the plastic shear strains

The plains of tracer particles located at different intervals showed the trajectory of the soil particles during the gouging process (see Figure 4-10). Also, the tracers well illustrate the subgouge soil deformation in different stages of the scouring process. Figure 4-10 shows that the soil particles in front of the ice keel moves forward and upward and then deviate towards the side of the ice keel. The soil particles right underneath the ice are moved forward and downward, while the particles in deeper depths almost move in a horizontal line.

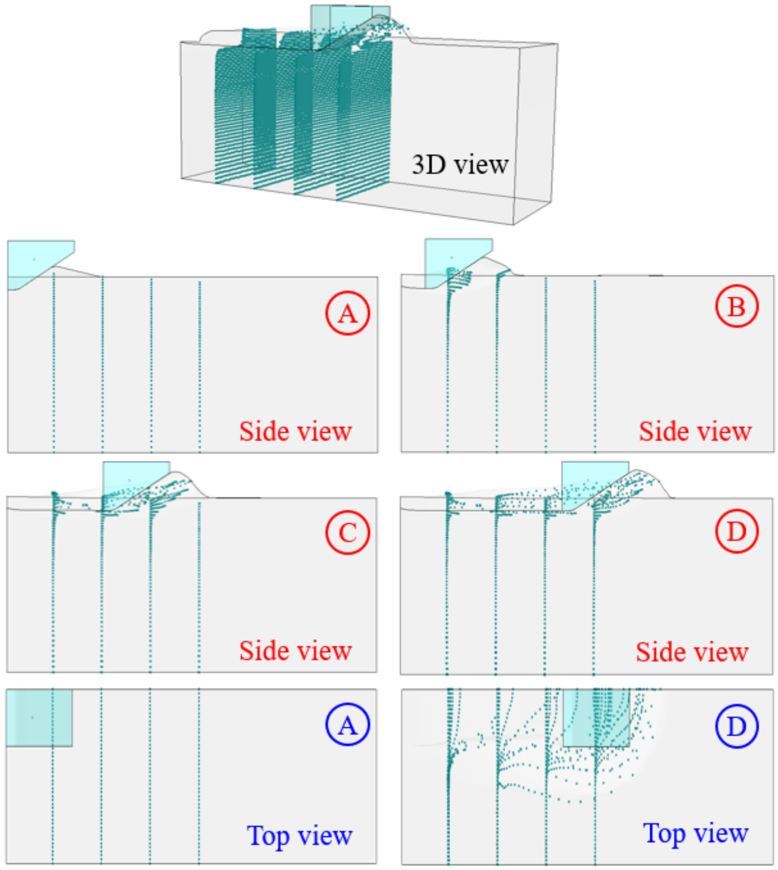


Figure 4-10. Soil particles trajectory during the gouging process.

4.4. Case Studies

In order to further investigate the influence of adopted non-linear stress-strain behavior of dense sand on ice scour process, a comprehensive parametric study was conducted using the developed numerical model with twenty-four different case studies (CS-1 to CS-24). Various key parameters from ice keel configuration and seabed soil properties were examined one at a time and the resultant subgouge deformations, keel reaction forces, and soil berm formations were compared with classical MC model predictions. Table 4-3. shows the summary of the conducted cases studies and the corresponding parameters. The cells surrounded with solid lines refer to the varied parameters.

Table 4-3. Sensitivities Studies Parameter

Case studies	Ice				Soil			
	Attack Angle (°)	Gouge Depth (m)	Keel Width (m)	Geometry of keel	Dr	K_ψ	A_ψ	γ (kN/m^3)
CS-1	15	1.5	10	Rectangular	80%	0.5	3.0	17.9
CS-2	30	1.5	10	Rectangular	80%	0.5	3.0	17.9
CS-3	45	1.5	10	Rectangular	80%	0.5	3.0	17.9
CS-4	30	0.5	10	Rectangular	80%	0.5	3.0	17.9
CS-5	30	1.5	10	Rectangular	80%	0.5	3.0	17.9
CS-6	30	2.5	10	Rectangular	80%	0.5	3.0	17.9
CS-7	30	1.5	2	Rectangular	80%	0.5	3.0	17.9
CS-8	30	1.5	5	Rectangular	80%	0.5	3.0	17.9
CS-9	30	1.5	10	Rectangular	80%	0.5	3.0	17.9
CS-10	30	1.5	2	Conical	80%	0.5	3.0	17.9
CS-11	30	1.5	5	Conical	80%	0.5	3.0	17.9
CS-12	30	1.5	10	Conical	80%	0.5	3.0	17.9
CS-13	30	1.5	10	Rectangular	90%	0.5	3.0	17.9
CS-14	30	1.5	10	Rectangular	80%	0.5	3.0	17.9
CS-15	30	1.5	10	Rectangular	70%	0.5	3.0	17.9
CS-16	30	1.5	10	Rectangular	80%	0.5	3.0	17.9
CS-17	30	1.5	10	Rectangular	80%	0.6	3.0	17.9
CS-18	30	1.5	10	Rectangular	80%	0.8	3.0	17.9
CS-19	30	1.5	10	Rectangular	80%	0.5	3.0	17.9
CS-20	30	1.5	10	Rectangular	80%	0.5	3.8	17.3
CS-21	30	1.5	10	Rectangular	80%	0.5	5.0	17.6
CS-22	30	1.5	10	Rectangular	80%	0.5	3.0	17.3
CS-23	30	1.5	10	Rectangular	80%	0.5	3.0	17.7
CS-24	30	1.5	10	Rectangular	80%	0.5	3.0	17.9

4.4.1. Ice keel configuration studies

In these series of case studies (CS-1 to CS-12) four key parameters of ice gouging configuration including keel attack angle, gouge depth, ice keel width, and ice keel geometry was studied. Figure 4-11 summarizes the effects of the gouging depth, keel width, and attack angle on the reaction forces and subgouge soil deformations. The keel speed was set to 1 m/s for all of the case studies. It was observed that the deeper gouge depths result in larger subgouge deformations, and produce larger reaction forces. For identical soil properties, the reaction forces and subgouge deformations showed a direct relationship with the keel width; the larger keel width, the greater reaction forces, and the larger subgouge deformations. The case studies showed that the more inclined attack angles cause larger reaction forces and subgouge deformations. All of the conducted studies consistently showed that the MMC model with non-linear stress-strain behavior resulted in limiting the excessive dilations commonly observed in the MC model and produced lower magnitudes of keel reaction force and subgouge deformations.

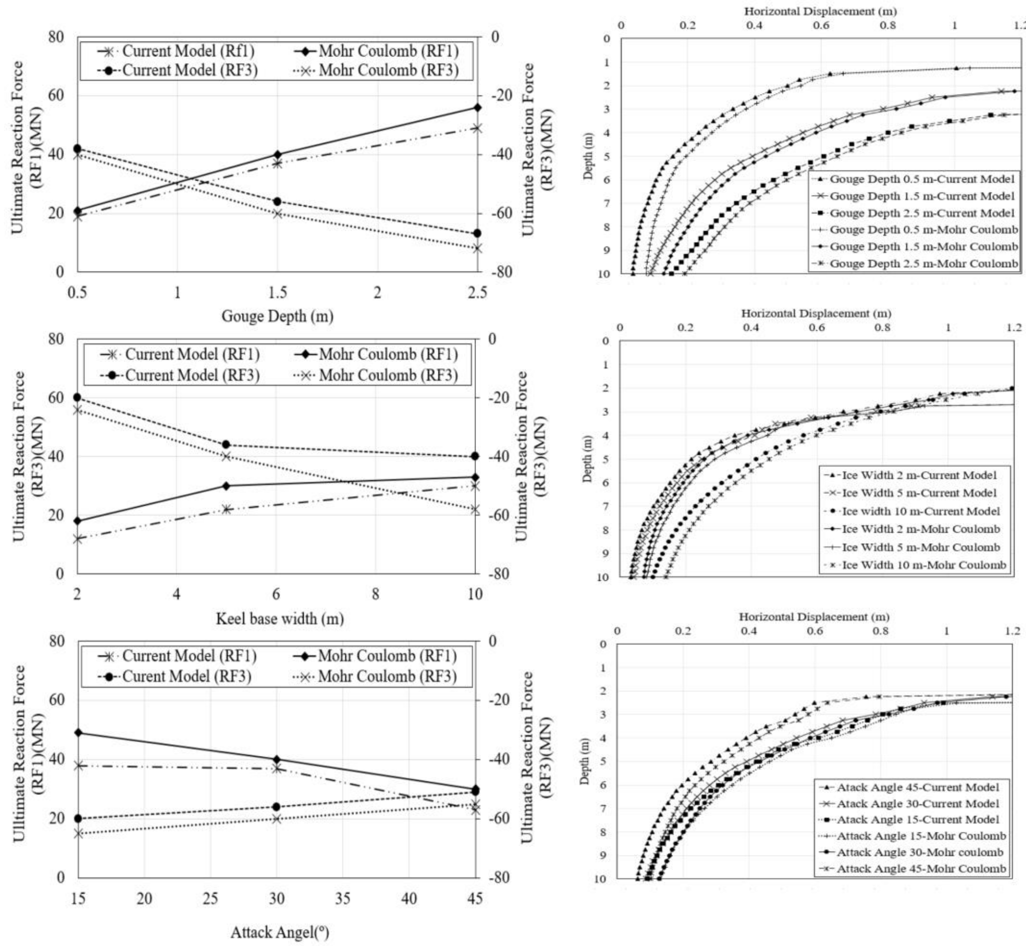


Figure 4-11. Effect of ice parameters on seabed response to ice gouging

Figure 4-12 compares the mound formations in front of the ice keel in different gouge depths, keel width, and attack angles. The front berm dimensions grow with the increased magnitude of the gouge depths and the keel width. However, the side berm height is not remarkably affected by these parameters. The results showed that the attack angle did not heavily affect the front berm height. However, the side berm size is decreased with increasing of the attack angles. Also, the case studies showed that the classical MC model overestimates the mound dimensions.

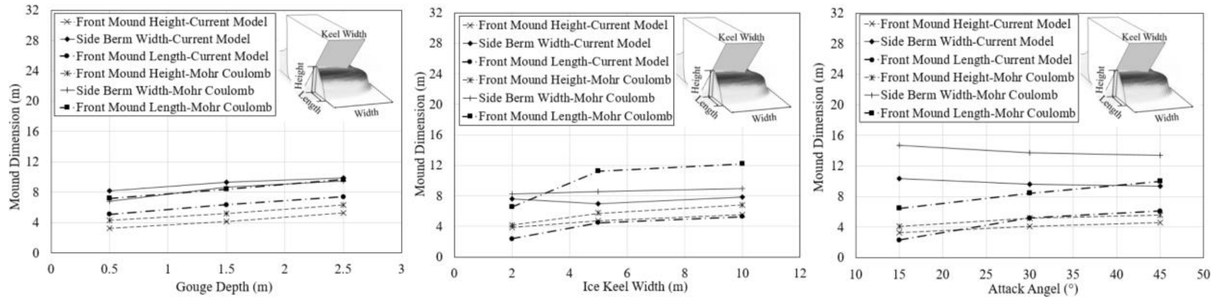


Figure 4-12. Effect of ice parameters on the formation of mound

The effect of different keel geometry is presented in Figure 4-13 and Table 4-5. The subgouge soil deformation did not show considerable sensitivity to the ice keel geometry, whilst the keel reaction force is affected by the ice keel geometry. The side berms created by rectangular ice keel are sharper than the conical ice. Therefore, the simplification of the ice keel to rectangular shape would overestimate the design loads.

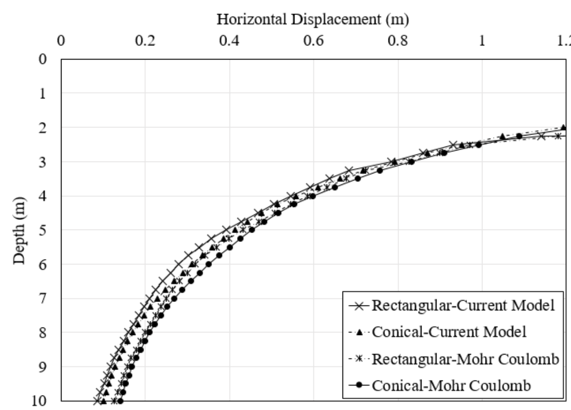
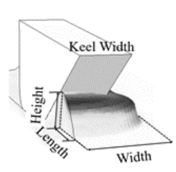


Figure 4-13. Comparison of the subgouge deformations of different geometry of keel

Table 4-5. The comparison of different geometries results

	MaximumRF1 (MN)	MaximumRF3 (MN)	Height (m)	Length (m)	Width (m)
Rectangular, MMC	30	-40	4.1	5.2	9.6
Conical, MMC	36	-56	5.5	5.3	7.9
Rectangular, MC	33	-58	5.2	8.4	13.7
Conical, MC	40	-60	6.8	12.2	9.0

4.4.2. Seabed soil property studies

The sensitivity of ice gouging event to soil properties was investigated by conducting twelve case studies (CS-13 to CS-24), where the key MMC model parameters were examined one at a time. The main results obtained from these series of case studies are summarized in Figure 4-14. The results show that the ultimate or average steady-state reaction forces are increased for the larger magnitude of relative densities. The subgouge soil deformation is decreased for lower magnitudes of relative density. However, the trend is getting inverse for the depths closer to the ice keel. This might be due to the effect of direct shear in the basal shear zone. The relative density showed a minor effect on berm dimensions. However, the general trend is slightly descending for the larger magnitudes of relative density.

Similar trends were observed for the effect of the other MMC model parameters, i.e., K, A, and γ_s. An ascending/descending trend was observed for the effect of A and K on the keel reaction forces that shows an absolute peak value in a moderate range of the parameters. Figure 4-14 shows that the high values of K (e.g., 0.8), which is mostly used for plain strain condition has resulted in the largest reaction forces. A low range of this parameter (e.g., 0.5), which is used for the triaxial condition is more critical and the moderate magnitude of K (e.g., 0.6), which is in between the plain strain and triaxial conditions resulted in the smallest reaction forces. A similar trend was observed in subgouge soil deformation, where the moderate magnitude of K produced a larger subgouge deformation near the surface. The front and side berm dimensions are not significantly affected by this parameter. The parameter A was varied between the 3.8 and

5 which is usually used for plain strain and triaxial conditions, respectively. Similarly, trends to the effect of K parameter were observed. Figure 4-14 shows that by increasing of γ , the reaction forces become higher and the subgouge deformation is increased. However, the more the particles are close to the surface, the bigger the subgouge deformation becomes. A larger subgouge deformation right underneath the ice keel and a lower deformation in deeper areas were observed for smaller magnitudes of γ (kN/m^3) have. The variation of parameter γ showed a minor effect on mound dimensions.

Overall, the case studies conducted on the effect of soil model parameters showed a significant influence on subgouge soil deformation and keel reaction forces and a minor effect on dimensions of soil berms in front and side of the ice keel. Further visualized results of the conducted case studies can be found in Appendix A.

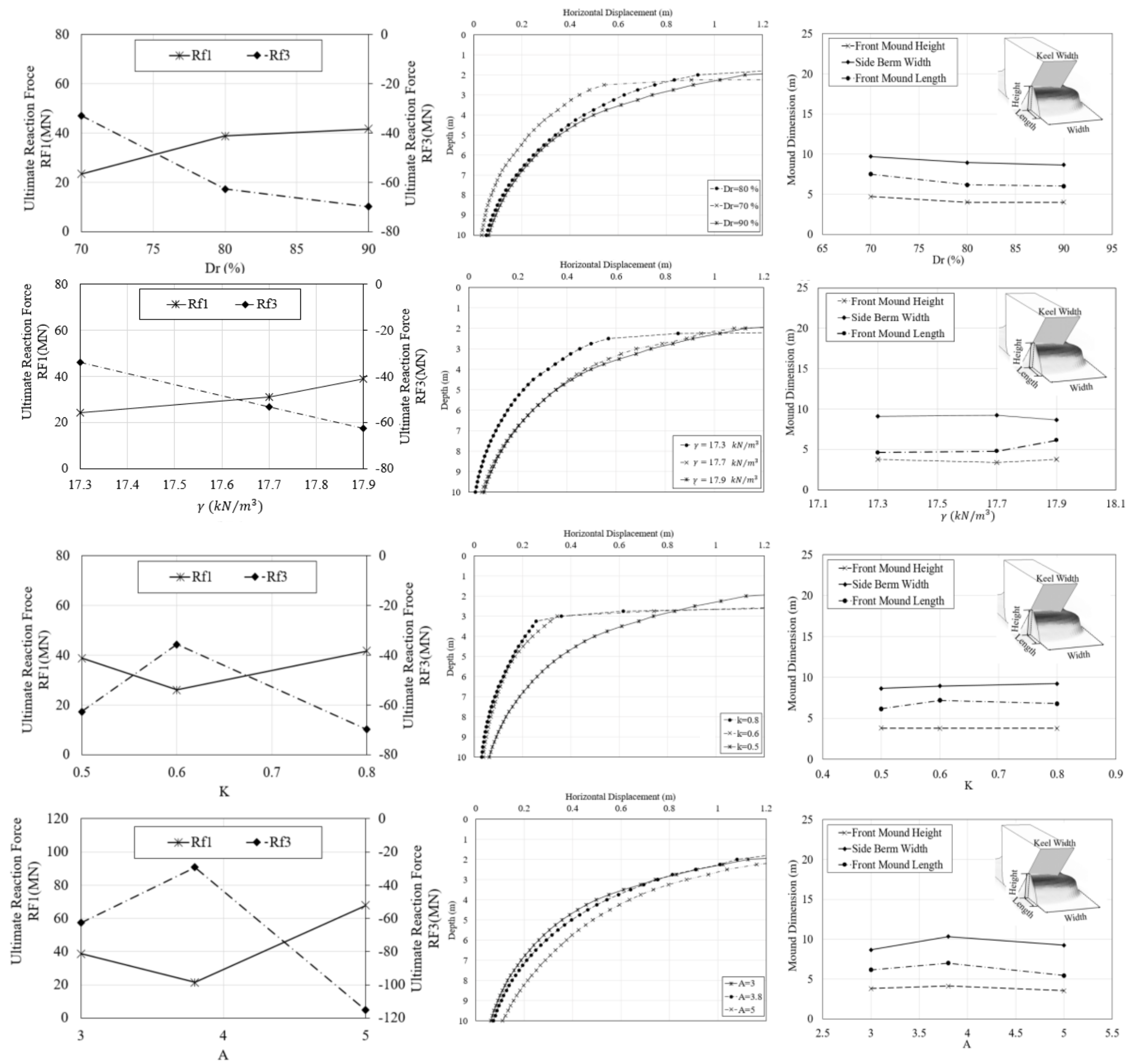


Figure 4-14. Effect of soil model parameters on seabed response to ice gouging

4.5. Conclusion

Various features of some the advanced constitutive soil model were combined and an MMC model was adopted to incorporate the non-linear stress-strain behavior of dense sand in ice gouging analysis. The adopted MMC model captured the influence of plastic shear strain, loading condition, density and confining pressure. Coupled Eulerian-Lagrangian (CEL) methodology was used in a series of dynamic ABAQUS/Explicit analysis. The

MMC soil model was coded in a user-subroutine (VUSDFLD). The subroutine was incorporated into the time-based incremental analysis in a simplified way to minimize the computational effort. The ice keel was initialized to the desired gouge depth and then horizontally moved with a constant velocity, while the vertical displacement was restrained. The adopted model prediction was validated against the published test results and compared with the performance of the classical MC model and published numerical studies using advanced constitutive soil models. A comprehensive parametric study was conducted by performing twenty-four different case studies, where the influence of ice keel configuration and soil model parameters on subgouge soil deformation, keel reaction forces, and soil berm development were investigated. Several important observation was made that are shortly summarized as follow:

- The classical MC model with constant magnitudes of friction and dilation angles overestimates the ice keel reaction forces, subgouge soil deformation, and soil mound formation in front and sides of the ice keel.
- The MMC model with incorporated non-linear features of stress-strain behavior resulted in more accurate predictions well correlating with conducted tests. The magnitude of ice keel reaction forces, subgouge deformations, and soil berm dimensions were found to be less than the MC model.
- The proposed MMC model well captured the cyclic oscillation of the ice keel reaction forces during the steady-state scour condition that has been reported in published experimental studies but not captured in earlier numerical simulations.

- The proposed methodology and the adopted MMC model was found to be a simple but strong tool to improve the accuracy of the numerical modeling of ice scour in dense sand while reducing the computation cost.
- The relative density and other MMC model parameters showed significant impact on keel reaction forces and subgouge deformations. Therefore, care should be taken in determining these parameters, and sufficient laboratory/field tests shall be conducted to ensure the accuracy of model parameters.

Acknowledgment

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Appendix A

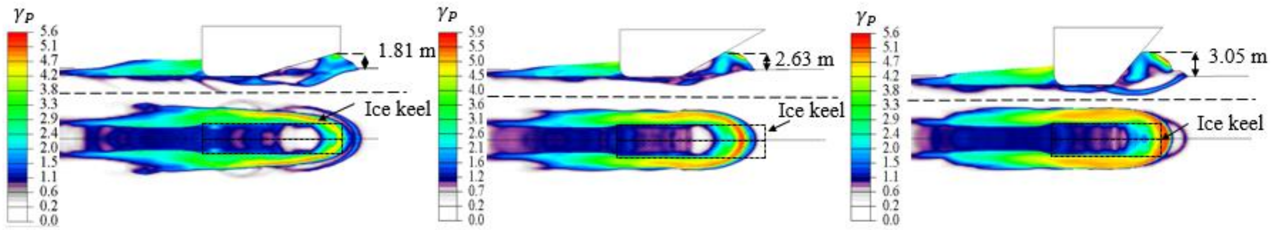

Figure 4-15. Ice keel with 15º, 30º and 45º attack angel

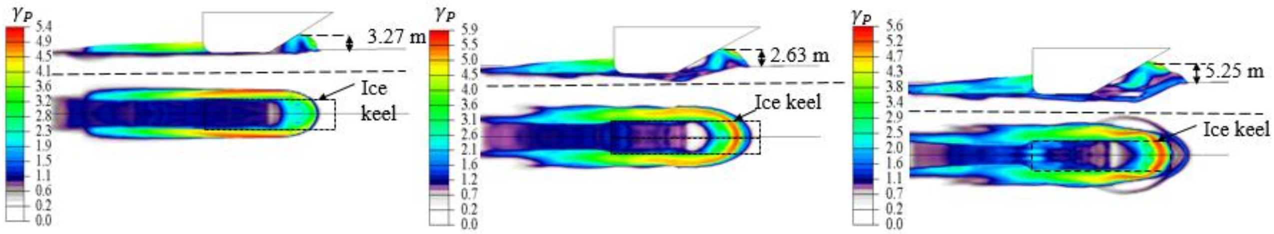

Figure 4-16.Ice keel with 0.5, 1.5 and 2.5 m gouge depth

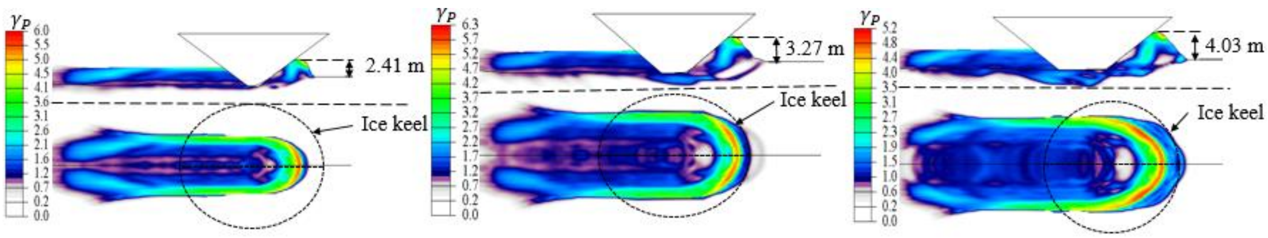

Figure 4-17. Ice keel with 2, 5 and 10 m keel base width

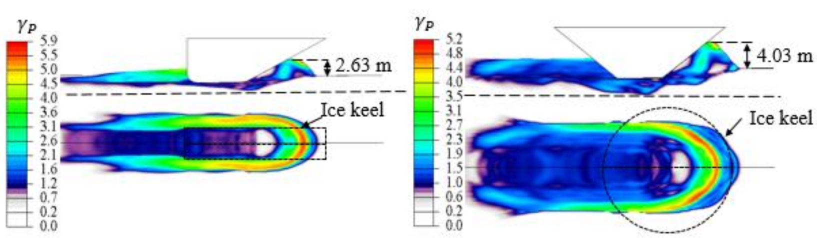

Figure 4-18. Rectangular and Conical keel shapes

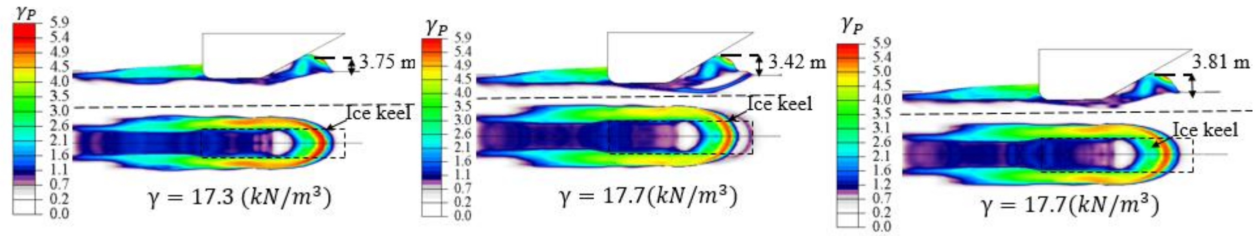

Figure 4-19. Soil with 17.3, 17.7 and 17.7 (kN/m^3)

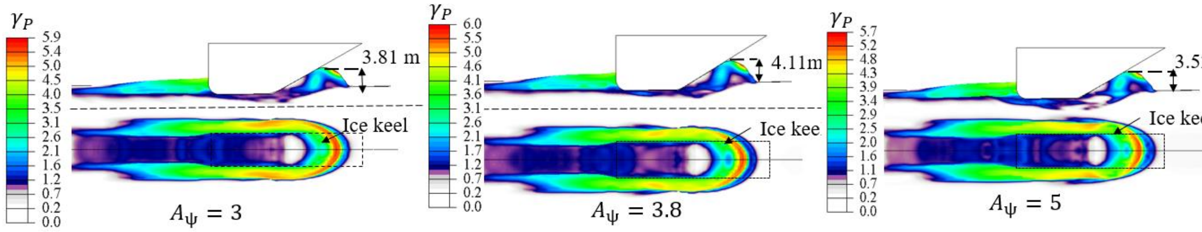

Figure 4-20. Soil with A_ψ = 3, 3.8 ,and 5

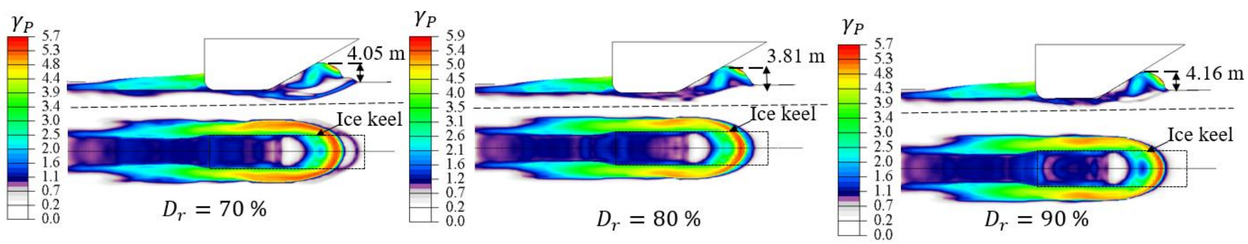

Figure 4-21. Soil with Dr = 70, 80 ,and 90 %

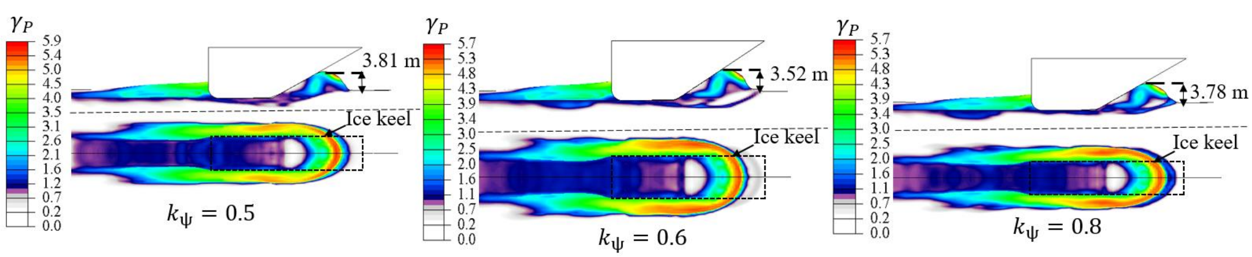

Figure 4-22. Soil with k_ψ = 0.5, 0.6 ,and 0.8

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Chapter 5

Conclusion

5.1. Results

The work outlined in this thesis was conducted to enhance the numerical analysis of sandy seabed response to ice gouging.

In this thesis, the Mohr-Coulomb model was improved to capture the different response of sand, using the density and stress level. These developments include the modification of plastic parameters in the model to minimize over dilation at lower stress level and using a softening and hardening laws using critical state theory. The result is a simple model that can accurately anticipate the strain-stress behavior of sands. This finite element model solves the excessive dilation angle problem which the tradition Mohr-Coulomb model suffers from. The variation of the friction and dilation angles based on the relative density, stress level, and plastic shear strain enables the model to simulate the strain softening behavior of the sand before and after the peak state. Also, the CEL model proposed in this study is shown to better simulate the interaction between the soil and ice than pervious approaches. The soil model was tailored in VUSDFLD subroutine, and the model was simulated in ABAQUS to capture the large strain behavior of sand during ice scouring events.

Two models similar to the centrifuge tests were developed to examine the validity of the finite element and soil models. The results showed good agreement with the physical experiments, and the cyclic response observed in the experimental results was also captured in the numerical predictions using model developed in this study.

A comprehensive sensitivity analysis was performed using the second model to investigate the effects of different parameters of ice on the soil reaction forces, subgouge deformations, and mound formation. In addition, the plastic strain of each parameter is presented, and the critical parts are illustrated visually as well.

A parametric study was conducted on various soil parameters to compare the influences of these soil parameters on the ice gouging events. This provided a better understanding of the effects of these key soil parameters.

The built-in Mohr-Coulomb model in ABAQUS has some limitations in the analyses of large deformation ice gouging events. By using the numerical analyses presented in this thesis, the accuracy of numerical analyses proven to be significantly influenced by the excessive dilation of the Mohr-Coulomb model and using constant friction angle. Despite the simplicity of the soil model, the modified Mohr-Coulomb model used in this study eliminates these shortcomings of the built-in model. This model was able to predict the sand behavior and subgouge deformation well.

Using the CEL and modified Mohr-Coulomb, some of the crucial factors in scouring mechanism are studied in this thesis. It is illustrated how basic soil properties affect the seabed behavior under a scouring process. Through the numerical analyses, it is demonstrated that:

- The classical MC model with constant magnitudes of friction and dilation angles overestimates the ice keel reaction forces, subgouge soil deformation, and soil mound formation in front and sides of the ice keel.
- The MMC model with incorporated non-linear features of stress-strain behavior resulted in more accurate predictions well correlating with conducted tests. The

magnitude of ice keel reaction forces, subgouge deformations, and soil berm dimensions were found to be less than the MC model.

- The proposed MMC model well captured the cyclic oscillation of the ice keel reaction forces during the steady-state scour condition that has been reported in published experimental studies but not captured in earlier numerical simulations.
- The proposed methodology and the adopted MMC model was found to be a simple but strong tool to improve the accuracy of the numerical modeling of ice scour in dense sand while reducing the computation cost.
- The relative density and other MMC model parameters showed significant impact on keel reaction forces and subgouge deformations. Therefore, care should be taken in determining these parameters, and sufficient laboratory/field tests shall be conducted to ensure the accuracy of model parameters.

5.2. Future study

Some of the subjects which can be a potentially interesting topic for the future of this research are discussed. Ice gouging is a complex event, and different aspect of this event more than the suggestions of this part can be explored.

- Improvement of the Numerical Models
  - This can include enhancing the strain hardening or softening equations, elasticity rate, considering crushing of the sand particles, etc.
- Undrained analyses of Ice gouging
  - A model for the undrained condition of soil under the scouring load can be opposed.
- Arbitrary Lagrangian Eulerian Analysis

- The developed VUSDFLD subroutine was tested in the CEL framework in this thesis. Implementation of this subroutine in the ALE framework in which the large deformation can be simulated very accurately for soil analysis.

- Ice/Soil/Pipe Interaction
    - By using the modified Mohr-Coulomb subroutine in the coupled ice/soil/pipe analyses, the current state of practice in pipeline design can be enhanced, and the mechanism of pipeline displacement under the ice scouring can result in deep understanding.

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APPENDICES

Appendix A: Large deformation analysis of ice scour process in dense sand

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This paper has been submitted for CMN 2019 and it is a summery of chapter 4 which compare two soil models in an ice gouging event.

Abstract

Ice-related subsea geohazard threatens the integrity of subsea pipelines in the Arctic regions. Burying the pipeline to provide physical protection against the ice loads is a common and cost-effective solution. Determining the minimum burial depth of the pipeline to minimize the construction cost is a challenging design aspect of Arctic offshore pipelines. This requires an in-depth understanding of the ice-soil-pipe interaction, which in turn is significantly affected by ice-soil interaction. The conventional approach for continuum modeling of dense sand is to use Mohr-Coulomb soil model adopting the constant friction and dilation angles. However, this approach neglects the pre-peak hardening and the post-peak softening behavior of dense sand. In this study, an advanced Coupled Eulerian-Lagrangian (CEL) free-field ice gouging analysis was conducted using ABAQUS/ Explicit scheme incorporating modified Mohr-Coulomb models that were coded into a user-defined subroutine. The strain dependency of the key model parameters was incorporated, and the sub gouge soil deformation and ice-soil contact pressure were extracted and compared with the results of the original Mohr-Coulomb model. The study showed the significance of incorporating the strain rate dependency of dense sand on seabed response to ice gouging. The methodology was found to be a strong but simple framework that can be used in daily engineering analyses. It was observed that the proposed model could significantly mitigate the subgouge soil deformation and the reaction forces leading to more economical design.

A.1. Introduction

The ice gouging event is the process of scouring the seabed by the floating ice as it reaches the shallow water. One of the main hazards to the subsea pipeline is ice gouging. The ice gouges the soil and penetrates it until it reaches a steady state condition with almost a constant gouge depth. The ice impact threatens the integrity of the pipeline and overcoming this challenging aspect is one of the key design aspects of the Arctic subsea pipelines.

One of the most common and economical solutions to this problem is to bury the pipeline under the seabed (Lanan et al., 1986; Palmer et al., 1990). However, the burial depth itself is a debatable subject. Since the burial process can have huge impacts on the cost of the projects, the optimized burial depth which maintains the safety of the pipeline under the ice attack needs to be identified for any specific project.

With the advancement of technologies and computers, simulation of the large deformation ice gouging process become more popular. This approach has facilitated applying different soil materials, boundary conditions and loading scenarios through the finite element analysis.

Several studies have been conducted on ice scouring process to find the optimized burial depth of the pipeline both in clay and sand (Banneyake et al., 2011; Barrette, 2011; Kenny et al., 2005; Phillips et al., 2005; Pike and Kenny, 2012). Dense sand is quite common in Arctic seabed sediments and need to be further investigated to obtain more efficient modeling approaches.

In the current ice gouging modeling studies, there are two common approaches to simulating this process. The first approach is the Winkler soil-spring structural models and the second one is the continuum models. The conventional beam-spring structural method exhibits some limitations such as superposition errors and directional load decoupling which has been discussed in detail in the previous studies (Eltaher, 2014; Konuk et al., 2006; Konuk et al., 2007; Lele et al., 2011). However, the industry traditionally accepted this approach for its simplicity and utilized it for designing the pipelines under the ice gouging loads. In continuum models, the decoupled method has been proven to be more robust than the other methods (Pike and Kenny, 2016). In the decoupled method, the ice gouging interaction with soil is modeled to find the subgouge deformations and keel reaction forces. The pipeline will then be added to the model with a sufficient burial depth to simulate the effects of ice gouging on the subsea pipelines (Been et al., 2013; Kenny et al., 2000; Nixon et al., 1996; Phillips and Barrett, 2012; Woodworth-Lynes et al., 1996).

During the ice scour event in the sand, the soil goes under large plastic strains and deformations within the shear bands resulting in variation of the internal friction and dilation angles. However, the conventional Mohr-Coulomb model simply uses constant values for these key parameters, which is considered a gross simplification from the geotechnical standpoint.

In this study, a modified Mohr-Coulomb model was coded into a user-defined subroutine that incrementally updates the magnitudes of strength parameters based on the plastic shear strain. The soil model was incorporated into Coupled Eulerian-Lagrangian analysis to simulate the large deformation of the seabed soil due to ice gouging event. The results of subgouge soil deformation and the keel contact pressure were obtained and compared with conventional Mohr-Coulomb model. It was observed that the variation of sand strength parameters with plastic shear strain could significantly reduce the soil deformation resulting in a design that is more economical.

A.2. Finite element modeling

The Lagrangian mesh cannot be efficiently used in large deformation problems due to the mesh distortion and convergence issues. The dependency of the mesh and material properties makes it much more challenging when one need to model the nonlinear responses. An alternative solution that is widely used today for large deformation analysis is the Coupled Eulerian-Lagrangian (CEL). The CEL applies fixed mesh whereby material can flow easily inside the mesh. Therefore, mesh distortion would no longer be a problem. The CEL analysis was adopted in this study for analysis of ice gouging event.

The model configuration was taken same as the study conducted by Yang, (2009). The ice was modeled as a Lagrangian rigid body, where all the boundaries, except the horizontal, constraints were fixed while the ice was horizontally moving inside the soil. The four nodes, three-dimensional discrete elements were used to mesh the ice. The sand domain was simulated by Eulerian mesh with EC3D8R elements which are eight nodes, reduced integration brick elements with hourglassing control. Different tracer particles were implemented inside the Eulerian mesh to follow the subgouge deformation of soil during the process, and the location of these tracers was adopted form the published studies (Yang, 2009). Figure A-1 shows the general configuration of the numerical model.

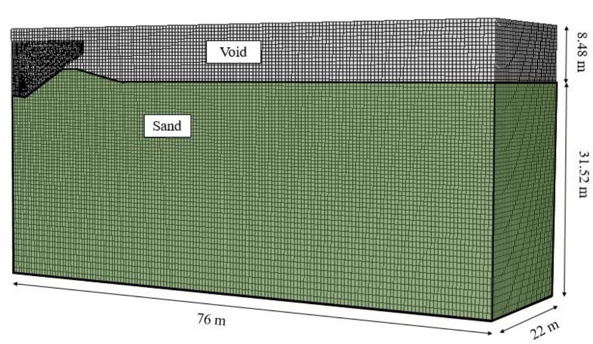


Figure A-1. The general geometry of the developed model

To avoid any instabilities, the ice corners were rounded, and the ice started to move gradually. An initial mound was added to expedite reaching the steady state condition and minimize the computational efforts. The geostatic stress and gravity were initially established by predefined field variables in ABAQUS. In the first step, and right after initialization, the ice keel started to move horizontally for 30 m.

The contact between the ice and soil was defined by the general contact method. The tangential contact was approached by penalty based contact with a friction coefficient of $\mu\ (\tan(\varphi_c)) = 0.7$ and the normal behavior of the ice was considered as hard pressure over-closure which controlled the penetration of ice into the soil.

A.3. Soil constitutive model

One influential factor in the success of an ice gouging simulation is the constitutive soil model. The key sand strength parameters that are defined as input parameters of the built-in conventional Mohr-Coulomb model in ABAQUS are the friction (φ') and dilation (ψ) angles. This Mohr-Coulomb model does not consider the pre peak hardening and the post peak softening behavior of the sand and its dependency on plastic strains. The magnitudes of the φ' and ψ decrease from a peak value with the plastic shear strain (Bolton, 1986). Therefore, to incorporate these effects into the analysis a combination of existing soil models were adopted (Bolton, 1986; Roy et al., 2015). These models have been original proposed for lateral response of the pipelines buried in the sand. These models consider the effect of some of the influential parameters including the density, confining pressure, and the plastic shear strain that are illustrated in Figure A-2.

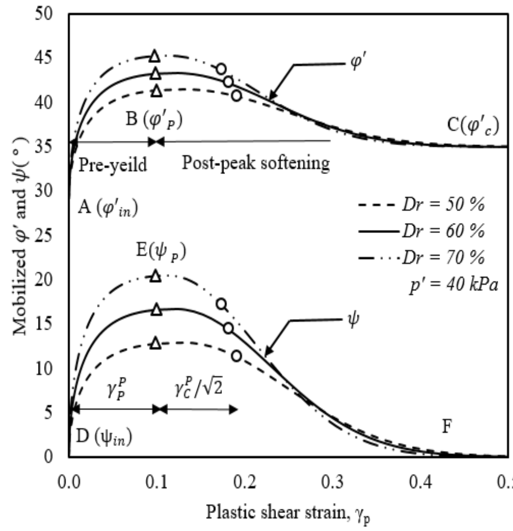


Figure A-2. Mobilized φ' and ψ (Roy et al., 2015)

Since there is no direct solution in ABAQUS to apply the nonlinear variation of the φ' and ψ with the plastic shear strain, mean effective stress, and density, a user-defined subroutine was developed to incorporate the soil model into the model constructed in ABAQUS. Table A-1 shows the soil parameters used for simulations of the current study.

Table A-1. Soil parameters for Mohr-Coulomb and developed model

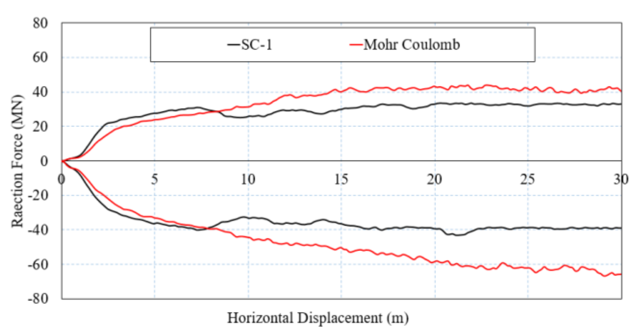
<table>
<tr><td colspan="2" rowspan="2">Parameters</td><td colspan="2">Values</td></tr>
<tr><td>Mohr-Coulomb</td><td>Modified Mohr-Coulomb</td></tr>
<tr><td colspan="2">φ′(°)in</td><td>φ'_c =35</td><td>(Roy et al., 2015)</td></tr>
<tr><td colspan="2">ψ(°)in</td><td>6</td><td>(Roy et al., 2015)</td></tr>
<tr><td colspan="2">Cohesion (kPa)</td><td colspan="2">2</td></tr>
<tr><td rowspan="6">Parameters of variation of φ' and ψ</td><td>A_ψ</td><td colspan="2">3 (Roy et al., 2015)</td></tr>
<tr><td>k_ψ</td><td colspan="2">0.5 (Roy et al., 2015)</td></tr>
<tr><td>φ_{in}</td><td colspan="2">29 (Roy et al., 2015)</td></tr>
<tr><td>C_1</td><td colspan="2">0.22 (Roy et al., 2015)</td></tr>
<tr><td>C_2</td><td colspan="2">0.11 (Roy et al., 2015)</td></tr>
<tr><td>m</td><td colspan="2">0.25 (Roy et al., 2015)</td></tr>
</table>

A.4. Simulation results and discussion

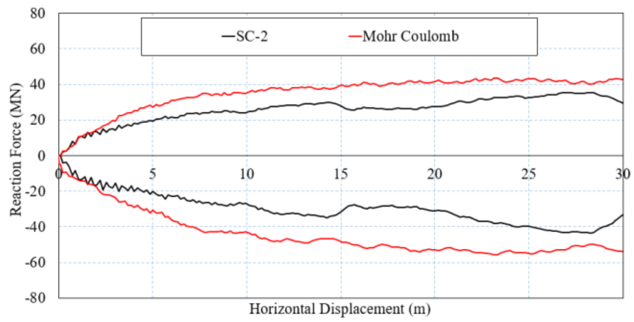
Two study cases were considered (SC-1 and SC-2). The subgouge soil deformation and keel reaction forces were obtained and compared between the conventional Mohr-Coulomb and modified Mohr-Coulomb models as the key output results commonly investigated in ice gouging events.

It was observed that the modified soil model resulted in less subgouge soil deformation and the keel contact pressure compared with conventional Mohr-Coulomb model, which is believed to overestimate the soil response (see Figure A-3). Therefore, the model could result in a more economical design. Also, the modified soil model was able to capture the cyclic steady state response that has been reported by experimental studies in the literature (Yang, 2009).

There are still other constitutive soil models for dense sand like Norsand model that provides better results in comparison with conventional Mohr-Coulomb model. However, the number of parameters and the technical methodology for implementation of the current model is much simpler and less time consuming than other constitutive soil models, which is considered as a key advantage.

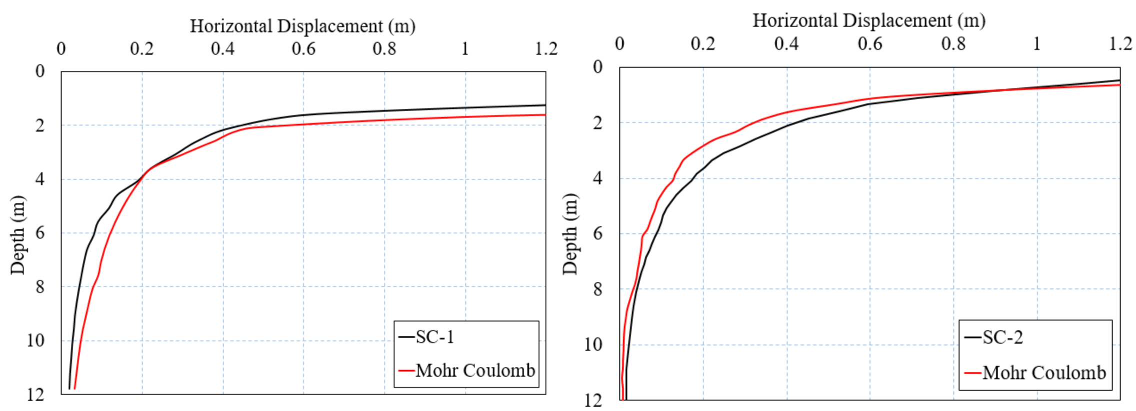


(a)



(b)

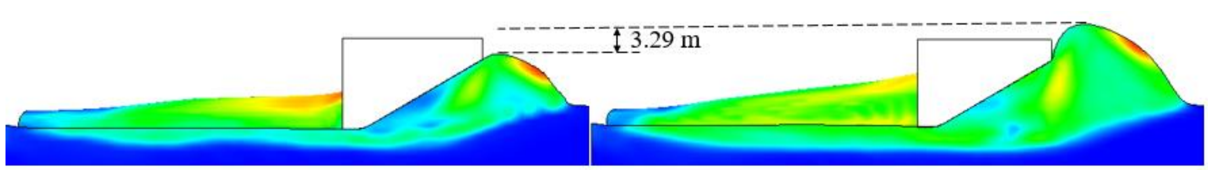
Figure A-3. The comparison of reaction forces in two case studies



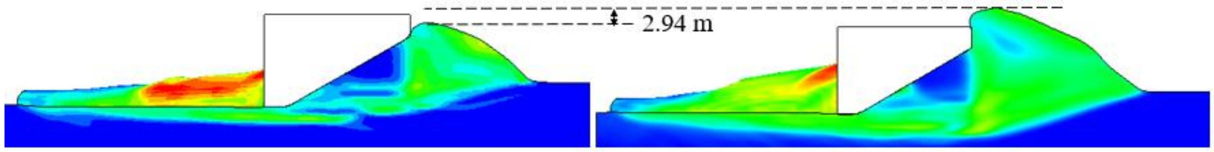
(a) (b)

Figure A-4. The comparison of subgouge deformations. a., SC-1, b., SC-2

Figure A-5 and Figure A-6 show the excessive dilations predicted by conventional Mohr-Coulomb model in comparison with the modified soil model. Also, the current model well predicts the local and basal shear bands where the plastic strain is largely developed and affects the magnitude of key strength parameters.



(a)



(b)

Figure A-5. The visual comparison of the Mohr-Coulomb model and developed model in two study cases.

The tracer particles, which were placed in the current model, are shown in Figure A-6. This particle well illustrate the trajectory of soil displacements in different stages of ice gouge displacements.

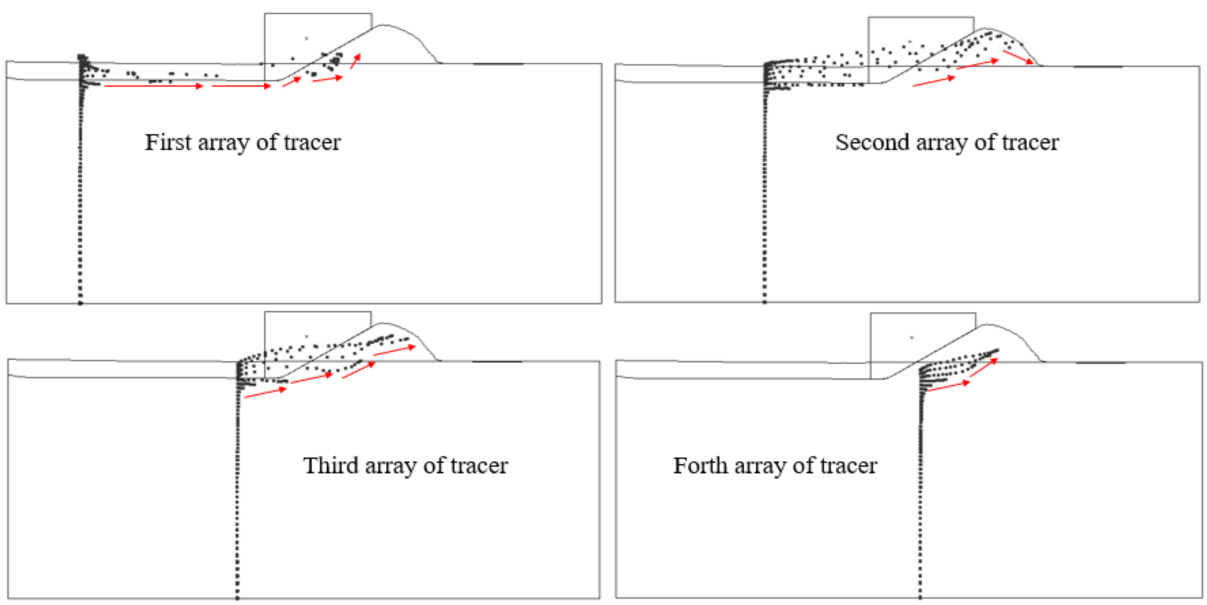


Figure A-6. Tracer particles inside the developed model of SC-1

A.5. Conclusion

A numerical study of the free-field ice-gouging event in dense sand was conducted. Coupled Eulerian-Lagrangian approach was used for large deformation analysis. A modified Mohr-Coulomb soil model was coded in a user-defined subroutine to incrementally update the shear strength parameters of sand with plastic strains. The model well captured the pre-peak hardening and the post-peak softening behavior of the dense sand within the basal and other shear bands. The cyclic steady state response of the ice gouging event was also captured. It was observed that the modified soil model resulted in much lower subgouge soil deformations and keel contact pressure magnitudes compared with conventional Mohr-Coulomb model. This can result in less excavation and trenching depth requirement and consequently a more economical design. Also, the adopted model was found to be an attractive framework for more accurate modeling of the sand shearing response through ice gouging process. The modified model prevented excessive dilation of the gouging heave in front and sides of the ice keel. Further investigation is still going on to investigate the performance of the model in coupled ice keel-pipe interaction and the resultant stresses and strains in the buried subsea pipelines.

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