Ice Scour and Gouging Effects with Respect to Pipeline and Wellhead

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Task 2 – Literature Review of Test Data

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Jorge L. Alba, Senior Consultant
Jorge.alba@woodgroupkenny.com
Tel: +1 281 646 4160

Wood Group Kenny
15115 Park Row
3rd Floor
Houston, TX 77084

Tel +1 281 675 1000
http://www.woodgroupkenny.com

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Executive Summary

Researchers use several approaches to generate information on scouring phenomena and to gain understanding of seabed response to ice gouging. These approaches can be divided into two categories: observations of real events and artificial simulations.

Observation of real events is done by performing extensive site surveys (seabed scanning), identifying gouging characteristics, and locating areas of high gouging occurrence rates. However, surveys have challenging technical and economical limitations, as was discussed in the first task of this study.

Artificial simulations can be useful tools to fill in the gaps and provide better understanding of the complexity of gouging processes. Their advantage over field observations is that they allow full control of the gouging test parameters. Artificial simulations are classified into two types:

- Physical testing
- Numerical simulation

The scope of this task is to perform a detailed literature review of the available physical testing data and evaluate the major parameters that influence physical testing. A literature review of numerical simulations will be performed in Interim Report 3.

Physical tests are conducted in the field or in laboratory settings using small- or large-scale instrumental setups. Physical testing can be performed under two different types of testing conditions.

The first type is ice gouge testing at normal gravity (1g), which can be performed indoors (laboratory) or outdoors (large scale), depending on the size of the keel being pushed into the soil bed to induce the gouge. Primary issues are associated with the range of confining stresses, uncertainty of scaling laws, contact mechanics, interface conditions, and strain localization.

The second type of testing condition is performed in a centrifuge facility. The centrifuge applies an increased ‘gravitational’ acceleration to physical models to produce identical self-weight stresses in the model and prototype. Centrifuge testing has practical limitations related to the level of acceleration that can be applied and the size of the scale model being used.

The advantage of simulations over field observations is that simulations allow full control of the test parameters that dictate the ice gouging response. These parameters include:

- Soil type.
- Keel width and depth.
- Attack angle.
- Ice keel properties.
- Subsea structure properties.

Physical tests are performed for both cohesive and cohesionless soils under dry and saturated conditions. Subgouge deformation profiles are sensitive to the type of soil used.

The effect of keel geometry (gouge width and depth) is usually investigated by using an idealized ice keel shape (steel or concrete) and varying its dimensions. The gouge depth may be constant or variant when buoyancy or heave is considered.

The influence of the keel attack angle is particularly important to the gouging process. The block-shape keel was used in most past experiments conducted for keel attack angles in the range of 40^{o} to 70^{o} and at 90^{o}.

The shear failure of the gouging ice feature itself could be the limiting mechanism for the gouge depth reached. However, only a limited number of physical test studies have used real ice keels.

Most of the physical tests performed so far have simulated free field conditions and focused on subgouge deformations and reaction forces acting on the keel. The load transfer to the subsea structure is directly related to these parameters, but the relative stiffness of the structure to the soil dictates a coupled response. Further experimental studies focusing on the coupled keel-structure interaction will aid in establishing arctic-specific design and operation methodologies for offshore structures in cold climates.

Findings and Recommendations

- Since 1972, 487 tests have been performed. Approximately 88% (427 tests) of the physical tests were performed under normal gravity conditions. Sixty tests were performed in centrifuge to represent realistic confinement stress conditions.
- A review of the available dataset with respect to the keel attack angle shows that no tests were performed for attack angles less than 10^o and between 30^o and 40^o. Most of the runs were performed for keel attack angles in the range of 40^o to 70^o and at 90^o.
- The percentage of experiments performed using real ice keel, which is approximately 3% of the total number of experiments, is low. Wood Group Kenny recommends to conduct additional experiments using ice keel.
- Tests were performed to simulate single-keel icebergs. According to the literature reviewed, soil failure under pressure load tests from multi-keel icebergs was not attained.
- Most of the physical tests that have been performed so far simulate free field conditions and focus on subgouge deformations and reaction forces acting on the keel. It would be beneficial to further investigate the coupled soil-pipe response by incorporating pipe elements into the simulations.
- The literature review identifies the scarcity of experiments that include wellheads in the analysis. Only one experimental study examines the response of a wellhead arrangement that is housed in a caisson for protection against an ice gouge scenario. This is an important gap that should be bridged with further experiments.

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1.0 Introduction

1.1 General

This interim report has been written as part of the requirements included in the Statement of Work in Contract No. E14PC00011 between the Bureau of Safety and Environmental Enforcement (BSEE) and Wood Group Kenny (WGK). The project is entitled "Ice Scour and Gouging Effects with Respect to Pipeline and Wellhead Placement and Design."

The research work produced as part of this contract is a result of a proposal submitted in response to Broad Agency Announcement (BAA) E14PS00019 "Arctic Safety of Oil and Gas Operations in the U.S. Outer Continental Shelf."

1.2 Project Objectives

The objective of the project is to identify the knowledge gaps in ice scour and gouging effects with respect to pipeline and wellhead placement and design in arctic environments.

The deliverables for Tasks 1, 2, and 3 of this project are three interim reports. The findings of Tasks 1 to 3 will be provided in the Final Report, which BSEE will publish. Task 2, which is presented in this report, includes a comprehensive literature review of test data. WGK has performed the following tasks:

- Task 1 – Literature Review of Field Data
- Task 2 – Literature Review of Test Data
- Task 3 – Literature Review of Numerical Modeling
- Task 4 – Final Report is a compilation of the first three tasks.

1.3 Scope of the Report

This study is a comprehensive literature review that examines available physical testing datasets. In addition, modeling aspects such as test setup, procedure, soil types, soil-failure mechanisms, and testing-range parameters are discussed. The data sources include small- and large-scale physical experiments as well as reduced-scale centrifuge tests.

WGK will also perform a gap analysis to identify deficiencies in the current datasets and will make valuable recommendations for future work.

1.4 Abbreviations

Below is a list of abbreviations that are used throughout this report.

Table 1.1: List of Abbreviations

APOA	Arctic Petroleum Operator's Association
BAA	Broad Agency Announcement
BSEE	Bureau of Safety and Environmental Enforcement
C-CORE	Centre for Cold Ocean Resources Engineering
FE	Finite Element
LSD	Limit State Design
MCSK	Marine Computation Services Kenny
MMS	Minerals Management Service
PRISE	Pressure Ridge Ice Scour Experiment
USGS	United States Geological Survey
WGK	Wood Group Kenny

2.0 Seabed Response to Ice Gouging

2.1 Overview

Researches use several approaches to generate information on scouring phenomena and gain understanding of seabed response to ice gouging. These approaches can be divided into two categories: observations of real events and artificial simulations. Figure 2.1 presents a diagram prepared by Barrette et al., 2012 [8] that describes the current approaches used to study ice gouging.

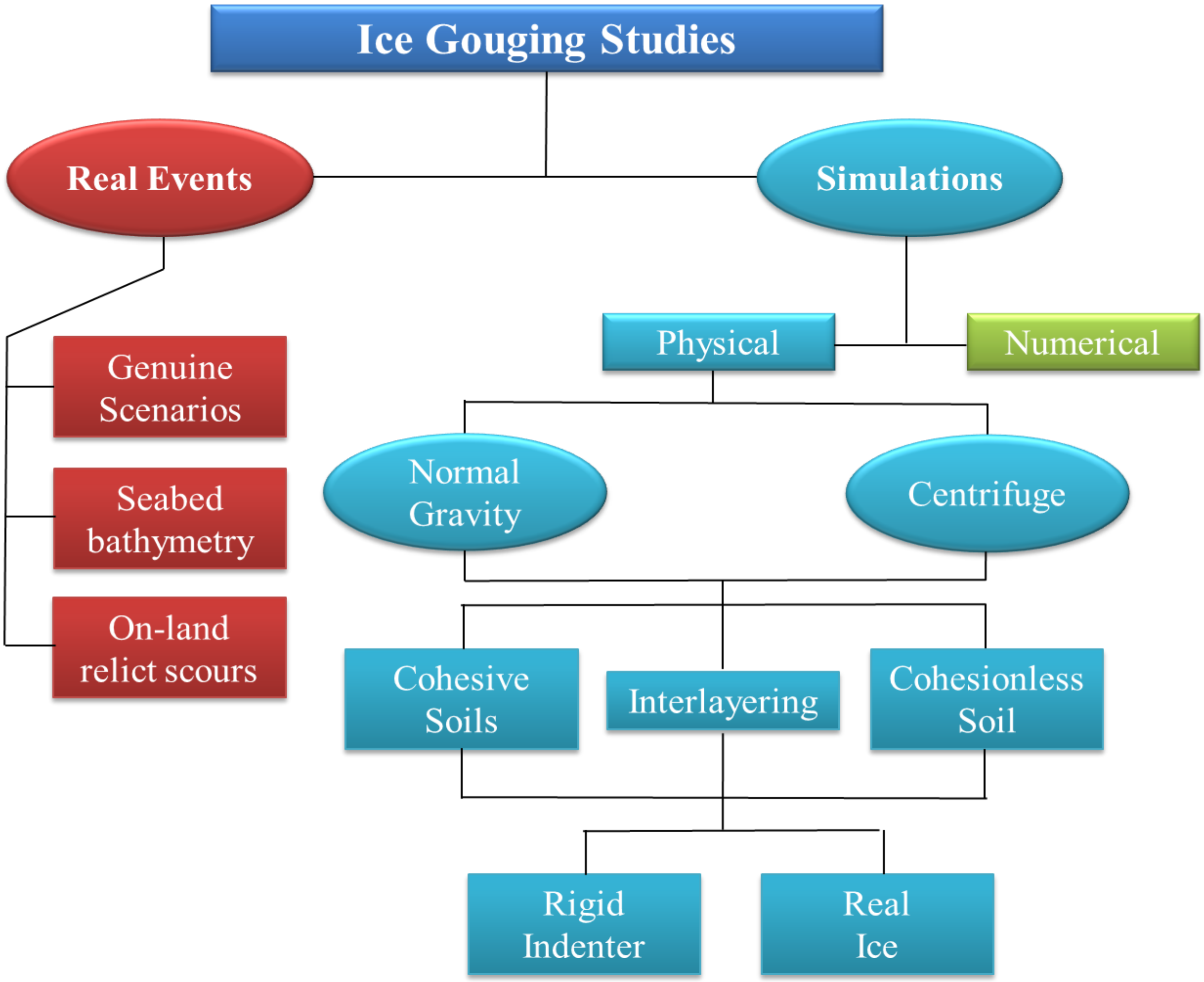

Figure 2.1: Current Knowledge Base on Scouring (Barrette et al., 2012 [8])

In the early 1960s, field surveys in the Arctic region focused on collecting gouge information at identified sites of interest. Seabed mapping allows for a better understanding of real-scale scouring activity.

Repetitive mapping of the same seabed is a method that is used to:

- Distinguish recent scours from old ones.
- Collect information on scour depth, width, length, orientation, and density.
- Determine scouring frequency.

Developing accurate models that correlate all of the above factors requires a thorough review of a large database of gouge records and statistical analyses. Surveys provide the data to calibrate the models used to predict the minimum required burial depth. Thus, these models critically affect the design in terms of cost and safety. However valuable their output is, the models have some technical and economical limitations.

Data collection must be performed in a recurring fashion to establish scouring frequency; however, it is time consuming, with an average time period of 5 years between surveys. Furthermore, the observations are site dependent and cannot be generalized for other locations. Another limitation is that surveys cannot offer any information on keel geometry. This limitation has proven to have a significant effect on subgouge deformations.

Simulations of ice gouging can be an alternative approach to provide better understanding of the complexity of the gouging processes. The advantage of physical testing over seabed surveys is that physical testing allows full control of the gouging test parameters. All the aspects involved in ice gouging (e.g., soil failure, contact mechanics, ice-structure interaction) can be broken down into separate processes and monitored closely. Likewise, the influence of each parameter can be investigated thoroughly and independently by using tailored experimental setups. For example, the influence of an ice keel attack angle on a specific soil type can be accurately investigated using indenters of varying cutting face angles. Another advantage of using simulations is the integration of the structure of interest (pipe/wellhead), enabling a better understanding of the keel-structure interaction. Simulations can be performed through numerical (computational) or physical tests.

For the last three decades, researchers have adopted physical testing to study ice gouging events. (A detailed literature review of physical testing is provided in Section 4.0 of this report.) The sub-sections that follow briefly describe each approach (real event, numerical, and physical) and provide a comparison of the approaches and a discussion of the advantages and disadvantages of each approach.

In their efforts to establish guidance that addresses the inherent uncertainty in ice gouge design, researchers have conducted extensive site surveys (seabed scanning) that identify gouging characteristics and areas with high rates of gouging occurrence. The pipeline design philosophy is based on the development of strain-based criteria that may be structured within a Limit State Design (LSD) basis. For this reason, predicting the maximum possible gouge depth as well as soil deformation is essential to determining the optimum burial depth and ensuring integrity. A detailed review of the current practices for site surveys and survey datasets is presented in Interim Report 1. The report concludes that surveys offer valuable inputs, yet they suffer from certain limitations such as site-dependency and insufficient information regarding ice keel characteristics.

2.2 Simulation of Ice Gouging

Simulations can complement field observations of ice gouging processes and can bridge the gaps. The main advantage of simulations is that they enable full control of the gouging parameters, such as keel characteristics, soil parameters, and pipe parameters. For example, unlike field surveying, the parameters for keel geometry can be pre-specified. Using simulation can improve the pace of knowledge development on ice gouging by isolating and quantifying the influence of each input parameter independently.

The inputs and outputs of typical ice gouging simulation are presented in Figure 2.2.

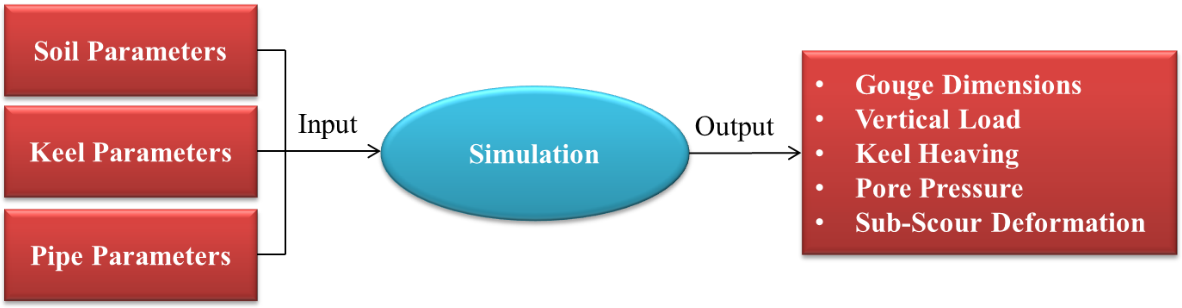

Figure 2.2: Inputs and Outputs of Simulation Test

2.2.1 Numerical Simulations

Numerical (computational) simulation is an approach used to study a wide range of engineering problems, including ice gouging. With the increasing computational capacity of processors and enhancements in commercial software, ice gouging simulation is now possible. Numerical simulations, which use finite elements, provide useful information about the seabed response to gouging such as deformation profiles and stress distribution of the seabed as well as local stresses and strain demands in the structure (pipe/wellhead). However, like any approach, numerical simulations have limitations. Computational time and the shortcomings of in-built constitutive models to simulate multi-phase materials of time-dependent stress-strain behavior are some of the areas where further advancement is required. A literature review on the numerical modeling of ice gouging is provided in Interim Report 3.

2.2.2 Physical Testing

Physical tests can be conducted in the field or in laboratory settings, indoors or outdoors, using small- or large-scale instrumental setups. Physical testing can be performed under two different types of testing conditions.

Normal Gravity

The first type of testing condition is ice gouge testing at normal gravity (1g). Normal gravity facilities mimic real gouging events. Geotechnical materials have non-linear mechanical properties that depend on the effective confining stress and stress history. Soils are tested under the normal confinement stress that results from the soils' self-weight. Depending on the size of the facility and the experimental setup, this implies that soil failure can be observed inside or outside the range of confinement stresses that exist in reality.

The primary issues with ice gouge testing at normal gravity are associated with the range of confining stresses, uncertainty of scaling laws, contact mechanics, interface conditions, and strain localization. For example, there are technical difficulties extrapolating the results from 1g physical models to full-scale models for extreme ice gouge events (e.g., 10 ft. deep and 30 ft. wide) with respect to bearing pressure, interface behavior, strain localization, and soil behavior, particularly in dense, cohesionless seabeds. It is preferable to perform full-scale tests that don't require full-scale verification; however, whether the tests are conducted in a purpose-built facility or in the field, the tests are costly and have technical constraints. For this reason, most of the ice gouging studies have been performed at normal gravity in indoor facilities. The typical configuration of a normal gravity experimental facility is shown in Figure 2.3.

Centrifuge Facility

The second type of testing is performed in a centrifuge facility. To produce identical self-weight stresses in the model and the prototype, the centrifuge applies an increased 'gravitational' acceleration to the physical models. The one-to-one scaling of stress enhances the similarity of geotechnical models and makes it possible to obtain accurate data to help solve complex problems. During centrifuge testing, the vertical stress in the soil is equal to the self-weight factored by the 'g-level' (g is the gravity acceleration) under which the test is conducted. For example, if the centrifuge test is performed under 10g vertical stresses in soils, the increase is ten times the vertical stress in normal gravity tests. Therefore, soils can be tested under higher (simulated) vertical stresses.

Centrifuge testing has practical limitations related to the level of acceleration that can be applied and the size of the scaled model used. The typical configuration of a centrifuge testing facility is presented in Figure 2.4.

The dimensions of the testing tank vary as a function of the study objectives. A sketch of a typical tank prepared by Green et al. [22] is shown in Figure 2.5.

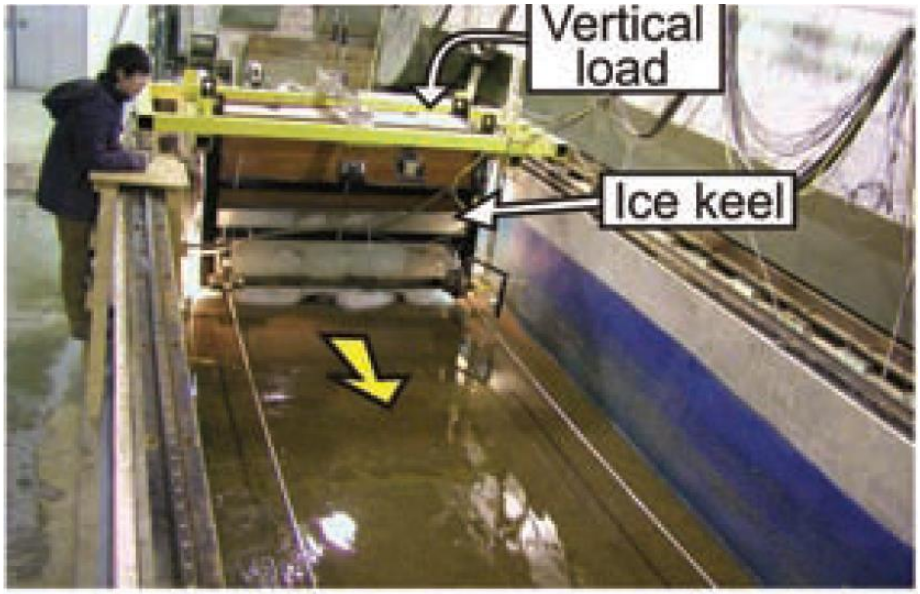

Figure 2.3: Typical Normal Gravity Testing Facility (Barrette et al., 2012 [8])

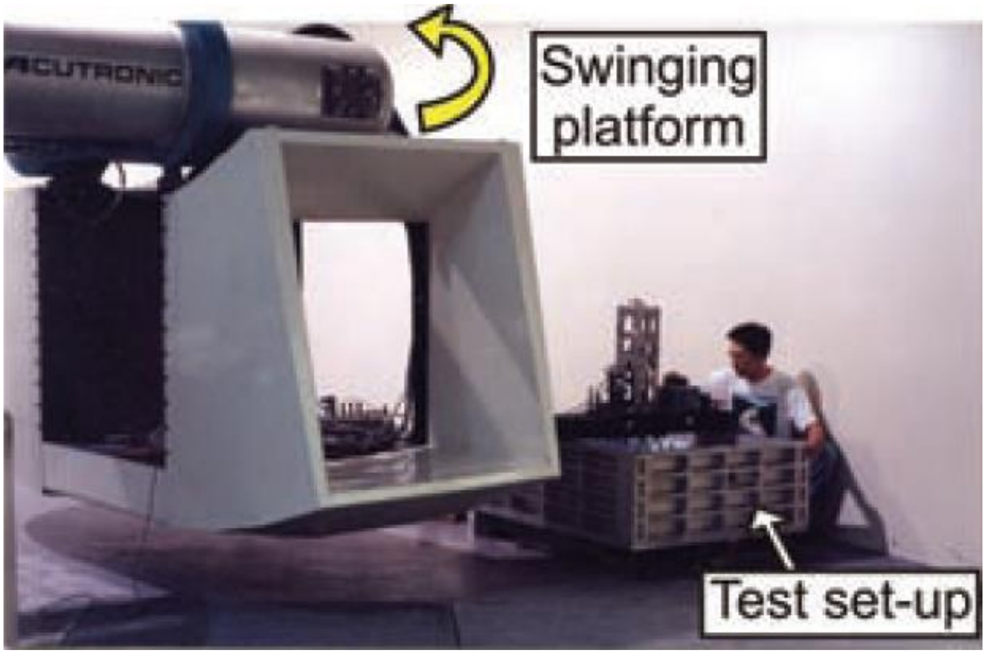

Figure 2.4: Typical Normal Centrifuge Testing Facility (Barrette et al., 2012 [8])

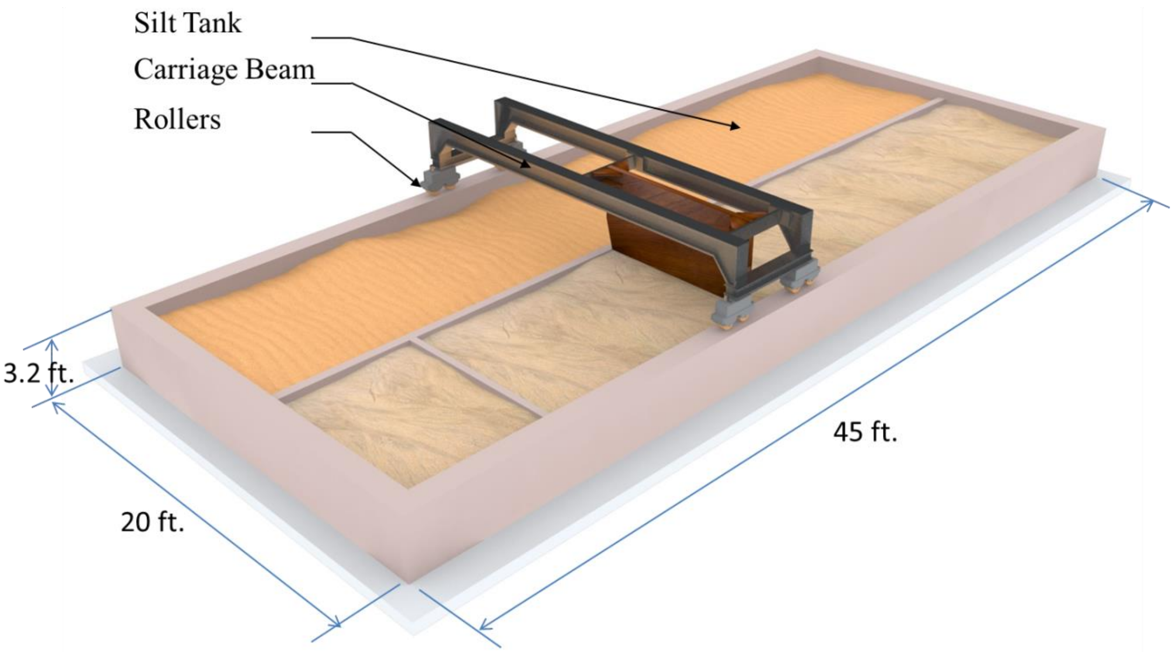

Figure 2.5: Schematic of Typical Ice Gouging Tank (Green, 1983 [22])

Physical testing may be conducted for different types of soil under dry or saturated soil conditions. For the latter case, sensors called piezometers can measure pore water pressure and monitor changes in the pore pressure that are generated by the gouging event. Reaction loads (vertical and horizontal), stress distributions, and displacements can be monitored and recorded with the appropriate sensors and data acquisition system.

Because of difficulties associated with the use of real ice, the keel is predominantly modeled using a steel or concrete mass. Ice ridges of loose and more compacted structures, simulating first-year ridges and multi-year icebergs, respectively, were used in only a limited number of experiments. In reality, keels are strongly heterogeneous masses that come in a wide range of shapes. In physical tests, the keel shape is a block-shaped mass. Several shapes are assumed for the keel face, most of which have a flat, smooth surface, with some exceptions where roughened surfaces are used. Contact between the keel and soil can occur along a rounded or rectangular keel face. The most influential parameter of the keel shape is the attack angle, which is defined as the angle between the keel face and the contacting soil surface. Several studies have investigated the effect of the attack angle on the applied pressure to the soil surface and the induced subgouge deformations.

According to Barrette et al. [8], physical testing parameters can be classified into five categories. Four of the categories, which represent the inputs for the test, are:

- Soil parameters
- Keel parameters
- Pipeline
- Test conditions

The fifth category represents the testing results (e.g., pressure, horizontal and vertical load, pore water pressure). .

Table 2.1 presents a summary of the five testing parameters proposed by Barrette et al.

Table 2.1: Summary of Database Parameters (Barrette et al., 2012 [8])

Categories	Parameters
Information on the soil (sediment) bed	• Bathymetry (level or slope) • Soil type (cohesionless, cohesive, other) • Soil density, strength, and other mechanical properties • State: Over-consolidated, saturated • Pipeline trench backfill properties
Information on the keel	• Keel type (rigid indenter vs real ice) • Keel dimensions • Attack angle • Degrees of freedom allowed (e.g., heave, pitch) • Keel surface roughness • Ice type, strength (for keel made from real ice)
Information on the buried pipeline (if applicable)	• Pipe outer diameter and wall thickness • Material properties • Crown depth (below seabed) • Constraints (free to move or anchored) • Instrumentation

Categories	Parameters
Test conditions	• Acceleration (n) level for tests in centrifuge • Normal gravity (1g) vs. centrifuge (ng) • Vertical load on keel (depending on test setup) • Pre-set depth (depending on test setup) • Keel displacement rate • Scour length (i.e., travel distance) • Instrumentation
Test results	• Horizontal load • Vertical load • Assessment of steady-state • Keel heaving (depending on test setup) • Pore pressure • Post-test bathymetry (scour depth, width, side berms, front mound) • Subscour deformation

2.3 Comparison of Ice Gouging Study Approaches

A comparison of the available approaches to study ice gouging is presented in Table 2.2. Each approach has both advantages and limitations.

Table 2.2: Comparison of Ice Gouging Study Approaches

Source(s)	Real Event	Physical Testing	Numerical
Soil	Site Dependent	Cohesive and cohesionless	Cohesive and cohesionless
Saturation	Saturated Only	Saturated or Dry	Dry Only
Keel Information	Not Available	Available	Available
Pipeline	Not applicable	Applicable	Applicable
Site	Site dependent	Not site dependent	Not site dependent

Source(s)	Real Event	Physical Testing	Numerical
Study output	Gouging location, prediction of gouge dimensions	Gouge dimensions, forces acting on keel, force acting on pipe, pore pressure	Gouge dimensions, forces acting on keel, force acting on pipe, pore pressure

The key advantage for physical testing is that it allows full control of the test parameters. In addition, the test can be performed on all soil types, under saturated or dry conditions.

Large-scale testing is preferred, but it is challenging to establish a full-scale test facility that accounts for the processes and physics during the gouge event, such as:

- Ice keel kinematics (e.g., vertical stiffness, heave, pitch, or rotation).
- Pull or tow forces (i.e., to overcome the seabed reaction forces).
- Preparation of the test bed (e.g., consolidation of cohesive seabed, placement of cohesionless seabed, saturation).
- Measurements during the test (e.g., real time monitoring, subgouge soil deformations, pipe strain, pore pressures).

Centrifuge experiments can be less complicated, but the cost of the appropriate instrumentation that can provide real time measurements (vertical/horizontal reaction loads, stress distributions and displacements) can be prohibitive. The size of the test may not be representative of a real ice gouging event, particularly with centrifuge models in which dense, cohesionless soil and over-consolidated clay test beds require full-scale verification.

2.4 Test Setup

During a physical test, the keel is moved horizontally to scour the soil surface. Contact between the keel and the soil causes disturbances to the soil surface and mobilizes the soil's passive resistance and bearing capacity. As a result, vertical and horizontal reaction forces act on the keel. In real situations, the ice keel may rupture because of the high-contact loads. The keel may also heave, reducing the contact pressure with the soil.

Physical testing can be conducted using two testing setups to investigate the forces acting on the keel. The first testing setup prevents the keel from heaving and is schematically presented in Figure 2.6. A load cell mounted on top of the keel can measure the vertical loads acting on the load cell. The measured load is indicative of the level of pressure applied to the soil surface. This kind of setup is used with a pre-set depth.

The second test setup is presented in Figure 2.7. Keel heaving is allowed for this test setup, and the gouge depth is not pre-set. Resistance to keel motion is caused by the friction between the keel surface and the seabed. A dead load is used to stabilize the keel during contact with the soil.

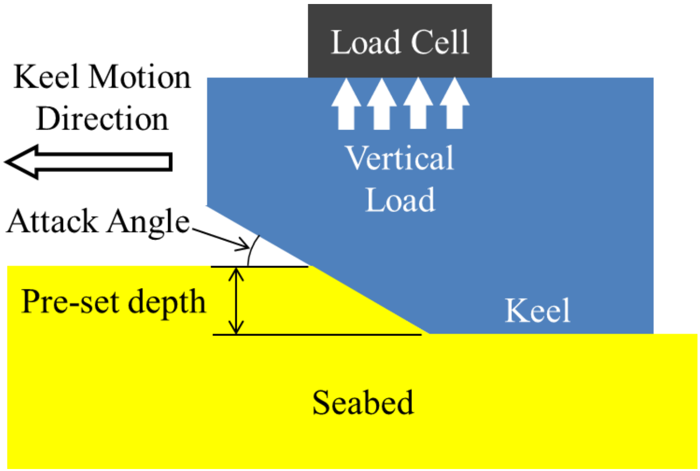

Figure 2.6: Test Setup 1 (Barrette et al., 2012 [8])

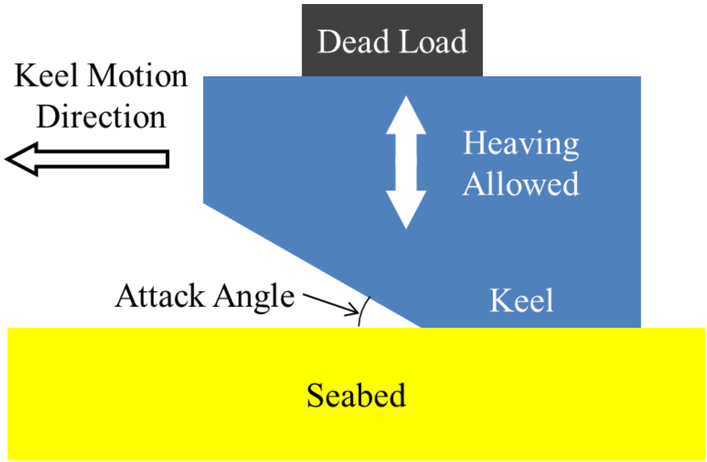

Figure 2.7: Test Setup 2 (Barrette et al., 2012 [8])

3.0 Soil Failure Mechanisms

3.1 General

The testing parameter of interest in the ice gouging process is the displacement of soil mass during gouging. The extent of soil deformation (deformation profile) is important because when the structure lies within a zone of large soil displacement, load transfer is likely to damage the pipe or wellhead. A buried pipeline is generally considered a flexible structure and, unless the soil is very soft (related to the pipe stiffness), the pipeline will be carried along with the soil. In this case, the soil flows around the pipeline. Unlike pipelines, wellheads are vertical structures that extend several meters above the seabed. This fact makes them more sensitive to lateral soil movements. For these reasons, integrity assessment of subsea structures in ice gouge events call for an understanding of the mechanism of soil failure and the associated soil displacement.

3.2 Movement of the Keel

After it makes contact with the seabed, the ice keel continues to scour until the initial kinetic energy and the work done by the driving forces are expended or until soil resistance exceeds the strength of the ice keel (ice fracture). Depending on the characteristics of the ice feature and the seabed, the ice mass may rotate, tilt, or lift during the scouring process. The ice keel itself may be subject to breakage and abrasion.

Movement of the keel is predominantly horizontal, and it is controlled almost entirely by the iceberg. The ploughing face may have a very low angle to the horizontal, generally less than 30°. Ice keel widths are generally large, compared to the keel depth. As the keel progresses, vertical forces exerted by the seabed onto the ice keel increase, which forces the ice feature to move upward. Ice rotation may occur because of the unbalanced moments.

The uplift resistance depends on the forces generated between the ice ridge and the seabed, and between the ice ridge and the surrounding ice sheets.

As the ice gouge process continues, different scenarios related to vertical movement may occur:

- If the vertical movements of the ice keel are small, the ridge will deflect without breaking or failing.
- If the ice uplift is significantly high, larger vertical forces will be generated.
- As the ice ridge is forced upward, it induces a bearing failure in the surrounding ice sheets, similar to the seabed bearing failure. Depending on the bond between the ice ridge and the surrounding ice sheets, the ice ridge moves downward to restore vertical equilibrium. The vertical load decreases rapidly; consequently, the vertical movements become smaller.
- The ice ridge will separate from the surrounding ice sheets if the uplift forces are high enough to generate failure at the keel. As a result, the scour depth will be significantly reduced because of the marked reduction in uplift resistance.

3.3 Soil Failure Mechanisms

3.3.1 Palmer et al. (1989)

The study by Palmer et al. (1989) [30] proposed an analytical approach using the upper bound theorem of plasticity and generating velocity field solutions. The approach was based on the work presented in two different papers by James and Bransby in 1970 [25] and by Chen and Rosenfarb in 1973 [18].

In Palmer’s study, it was assumed that the rupture planes produced by a feature moving horizontally did not extend below the edge of the moving feature. The validity of this assumption was also proved experimentally. Only in non-homogeneous soils, when soil strength decreased with depth, did the feature move from stiffer to softer material (e.g., trench), or when there was a significant component of vertical movement of the ice. There was some evidence of the rupture surface dipping down below the cutting plane. It was also observed that quasi-dead zones of soil are generally formed within the failure zone.

The soil deformations beneath the gouge were inconsistent between analytical and experimental observations. Experimental observations showed that the depth of the zone below the indenter, where significant soil displacements occurred, was greater in loose sands and soft clays than in dense sands and stiff clays. Inversely, the analyses presented by Palmer et al. suggested that the denser, more dilatant sands should exhibit a greater tendency to disturbance below scour depth. This inconsistency was later attributed to the shear dragging mechanism.

3.3.2 Been et al. (1990)

The Been et al. 1990 [9] study was among the first to recognize the potential for subgouge disturbance associated with the shearing mechanism. The dominant scour mechanism is illustrated in Figure 3.1. A zone of soil with small or negligible relative movement with respect to the ice keel (wedge) forms within the failure zone in front of the ice keel and is carried along as scouring advances. Soil wedges of this type are commonly observed in cutting soil experiments, and their effect is to increase the cutting angle. It is assumed that friction between the ice feature and the soil mass is fully mobilized. As the ice keel advances, soil is pushed up and out in front of the scour.

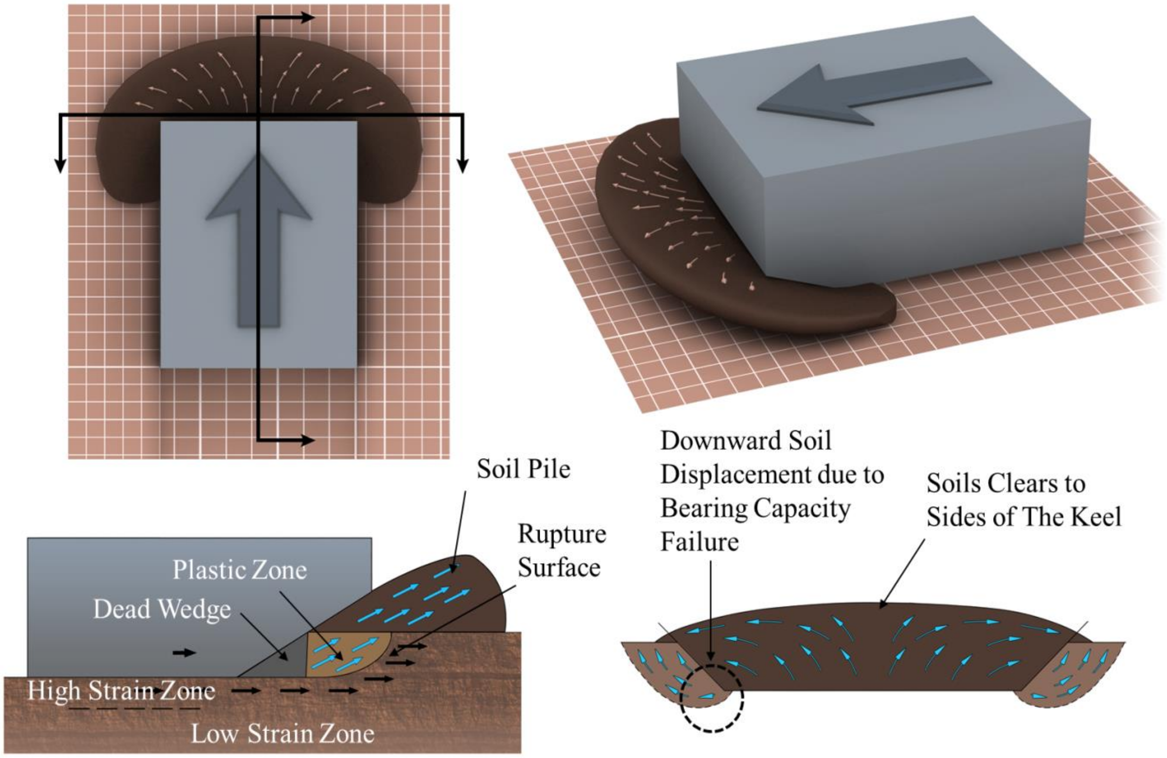

Figure 3.1: Gouge Mechanism Diagrams for Horizontally Moving Ice (Been et al., 1990 [9])

An amount of soil is displaced in front of the keel and, as scouring continues, it reaches a stable configuration (steady state). Additional soil feeds in from the failure zone. Soil is progressively cleared from the path of ice, forming berms on both sides of the scour. At the edges of the ice keel, greater lateral movements are possible. The dead wedge becomes unstable and may erode as soil is pushed sideways because of transverse forces. These edge effects, combined with the ploughing motion in front of the dead wedge in the central portion of the keel, form a spoon-shaped failure zone, as illustrated in Figure 3.1.

Been et al., 1990 [9] explained the following two failure mechanisms:

- Bearing capacity and passive earth pressure failure – The synergy of these mechanisms develops a rupture surface, where soil undergoes large strains. A schematic of bearing capacity and passive pressure failure mechanisms is presented in Figure 3.2.
- Shear dragging – The soil adjacent to the rupture surface is dragged along in the direction of shearing because of the ice scour, as presented in Figure 3.3.

The development and propagation of rupture surfaces is not fully explained by bearing capacity and passive pressure solutions. The motion of the object is a special case of a more general problem involving an inclined plate moving into a soil mass in a direction that is not perpendicular to the plate.

Been et al. concluded that subgouge displacements are associated with a shear dragging mechanism outside the rupture surface, rather than subgouge rupture surfaces. Soil that is adjacent to a rupture surface or a rigid body which is sliding is dragged along in the direction of the shearing. A zone of dragging shear is formed below the scour. The depth of this zone is controlled by the stress strain behavior of the soils. A strain-hardening soil (e.g., loose sands and soft clays) develops a thicker band of dragging disturbance as the soil close to the scour surface strain hardens. Stresses through the hardened material are transmitted to the softer soil below. At the other end, a strain-softening soil (e.g., dense sands and stiff clays), which is close to the scour surface, fails and a weaker sheared material forms.

Further shearing remains concentrated in the shear dragging zone because it is weaker than the surrounding soil. This type of shear band localization can be shown using the theory of plasticity and bifurcation (Drescher and Vardoulakis, 1982 [19]).

A solution to the scour's general mechanism, as described by Been et al. [9], is based on the characteristics and finite differences outlined by Sokolovski, 1965 [41]. The solution calculates the size and orientation of the dead wedge in a way that is similar to the method presented by Hettiarachi and Reece, 1975 [24]. An alternative analytical approach is to use the upper-bound theorem of plasticity and generate velocity field solutions as described by Palmer et al., 1989 [30]; James and Bransby, 1971 [25]; Chen and Rosenfarb, 1973 [18]; and Golder Associates, 1989 [20]. A schematic of the typical rupture surface and dead zone is presented in Figure 3.4 and Figure 3.5.

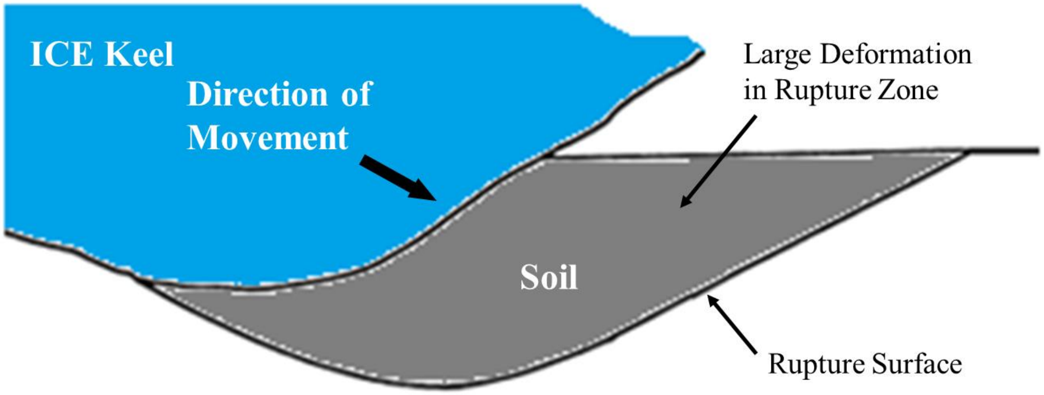

Figure 3.2: Rupture Surface Caused by Passive or Bearing Capacity Failure (Been et al., 1990 [9])

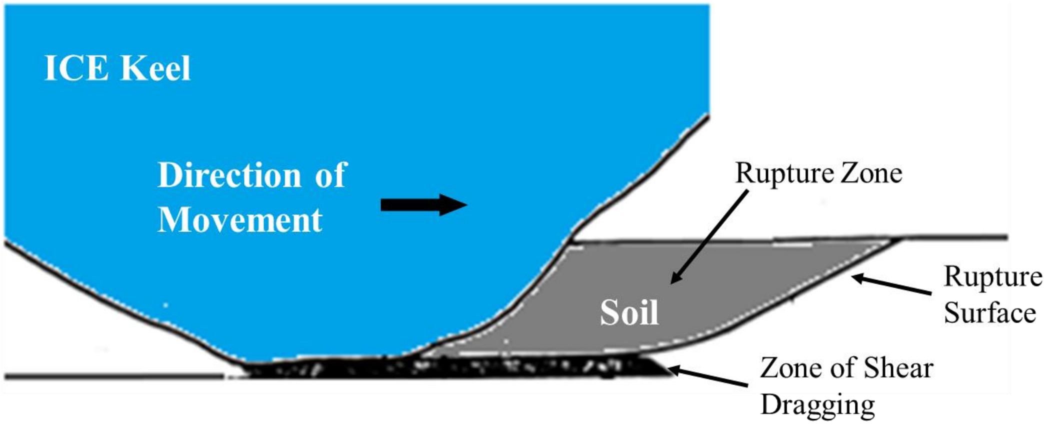

Figure 3.3: Shear Dragging Adjacent to Ice or Rupture Surface (Been et al., 1990 [9])

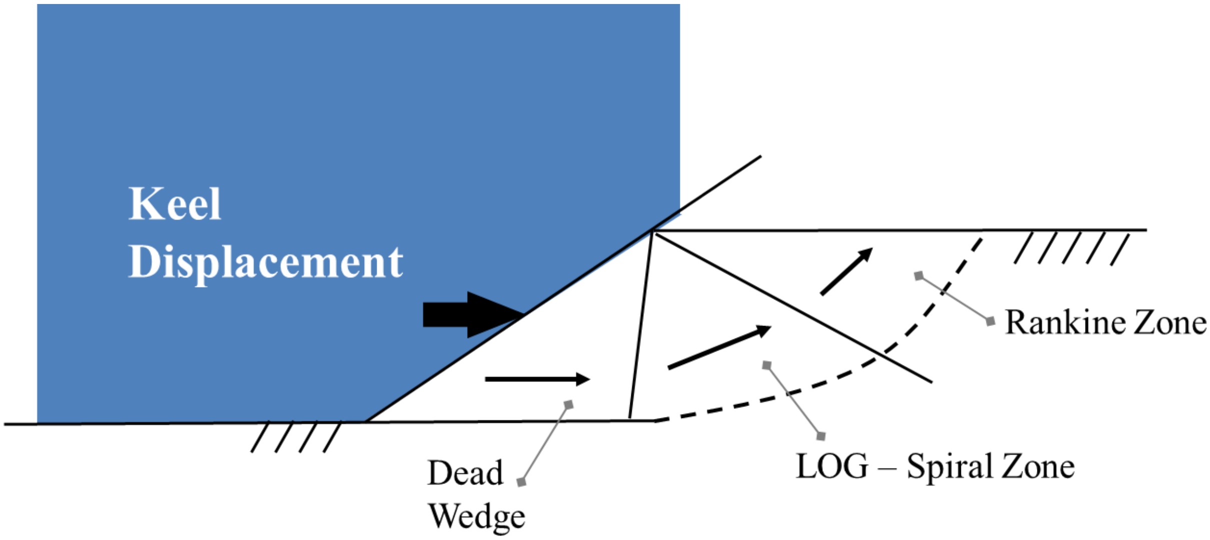

Figure 3.4: Typical Rupture Surface and Dead Zone in Dense Sands (Been et al., 1990 [9])

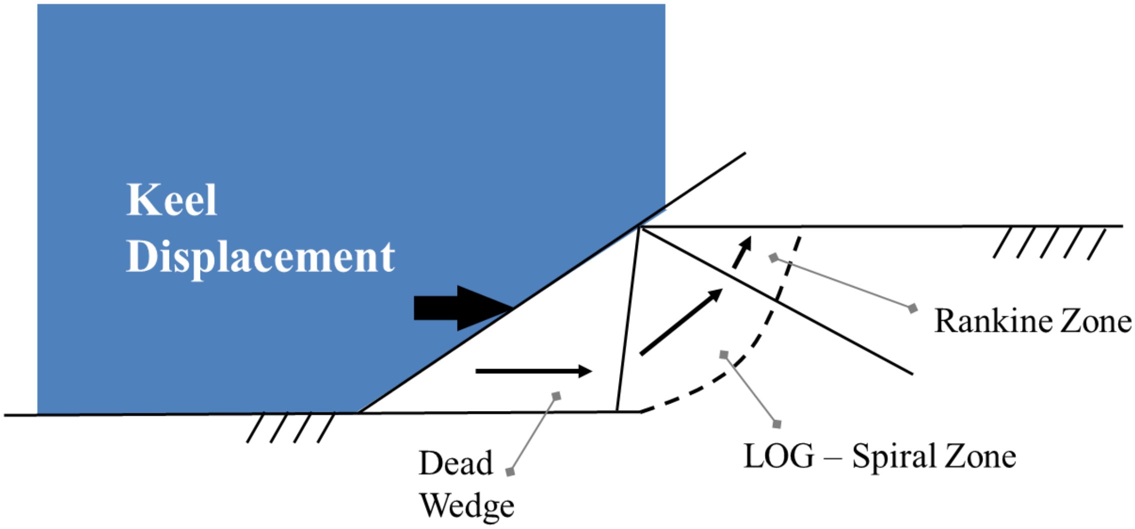

Figure 3.5: Typical Rupture Surface and Dead Zone in Clays (Been et al., 1990 [9])

3.3.3 Palmer (1990)

Palmer et al. [31] reported that buried pipes are subjected to damage even if they are buried below the maximum expected gouge depth. Gouging introduces high levels of strain to soil layers that may penetrate deeper than the expected burial depth. Pressure loads are transferred through the soil to the pipe. Therefore, soil deformation, as well as the pressure transferred to the pipe, must be investigated.

Based on Palmer's observations, the seabed floor during a gouging event can be split into three zones.

- Zone 1: The uppermost seabed that sustains very large strains and soil deformation as the ice keel passes through the seabed. It is reasonable to assume that the integrity of the pipeline in this zone will be compromised. Often, this zone is delineated at the basal plane of the ice keel, as presented in Figure 3.6. However, not all the soil above the basal plane moves upward.
- Zone 2: This soil is below the ice keel, and it is subjected to substantial disturbance. It is likely that the pipeline would deform plastically within this intermediate zone. The spatial extent and magnitude of soil deformation in this zone is still debatable and uncertain.
- Zone 3: The soil extending beneath Zone 2 is subjected to much less disturbance. It is likely that the pipeline will only deform elastically.

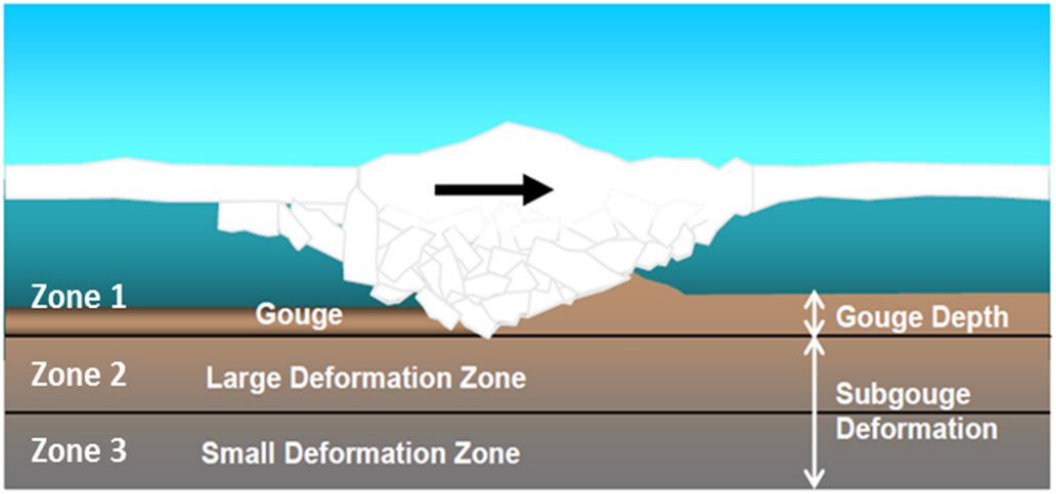

Figure 3.6: Seabed Gouging Schematic (Palmer, 1990 [31]) – Modified by WGK

4.0 Literature Review

4.1 Overview

Physical testing can be conducted under normal gravity and centrifuge gravity conditions. Normal gravity tests can be performed indoors or outdoors, depending on the size of the keel. The keel is pushed into the soil bed to induce gouge under its self-weight.

Normal gravity facilities intend to mimic real gouging events. However, soil mechanical properties are governed by the effective confining stress and stress history. Soils tested under normal gravity experience confinement stress because of self-weight. Depending on the size of the facility and the experimental setup, a soil failure can be tested inside or outside the range of confinement stresses that it is actually subjected to in situ. An issue related to the selection of the appropriate confining stress range is the uncertainty of the scaling laws.

For example, results from 1-g physical models have to be extrapolated to full scale for extreme ice gouge events. There are technical challenges to simulating the bearing pressure, interface behavior, strain localization, and soil deformations—particularly in dense, cohesionless seabeds.

To produce identical self-weight stresses in the model and prototype, the centrifuge applies an increased ‘gravitational’ acceleration to the physical models. The one-to-one scaling of stress enhances the similarity of geotechnical models and makes it possible to obtain accurate data to help solve complex problems. In simple terms, soil can be tested under higher confinement stresses (at the same magnitude as in the field).

This section of the report presents a literature review of the physical tests performed at normal gravity and centrifuge gravity. The test procedures, innovations, and further contributions to knowledge on ice gouging are discussed in the following sub-sections.

4.2 Literature Review on Testing Under Normal Gravity (1-g)

4.2.1 Harrison (1962, 1972)

One of the earliest studies relevant to ice scouring is attributed to Harrison, 1972 [23]. The experimental work observed soil failure on an inclined plane delimiting the edge of a passive soil wedge, using ‘plate grousers’ up to 1.6 ft. (0.5 m) in width. This study was conducted in a glass-sided flume using three types of soil conditions: dry sand, saturated clay, and intermediate loam. The researcher's objective was to verify the conventional theory of soil failure using slip line fields.

4.2.2 Chari (1975, 1979, 1980, 1981, 1982)

Chari [13] [14] [15] [16] [17] was the first researcher to analyze the gouging processes from a detailed geotechnical point of view. The researcher took into account the bearing and passive resistance failure mechanisms. The idealized keel shape is presented in Figure 4.1. This figure explains the mechanism of shear plane development as presented by Chari. Keel movement produces horizontal passive pressure (P) on the soil surface. As a result, shear stress (S) develops at an inclined plane (X1). Soil failure occurs when the shear stress component exceeds the shear strength of the tested soil.

Tests were designed to observe the mechanics of scouring and to illustrate the complexity of the keel/soil interaction model. The experimental program focused on measuring the pressures and forces on the model during scouring and monitoring soil displacements in the vicinity of the keel.

During the experiment, the model was driven into the sloping testbed while towing forces and pressures were being recorded. The primary resistances to the model's motion were identified as passive soil resistance in front of the model and soil movement in front of and below the model, which occurred during the scour formation. A pattern of failure surfaces originating at the keel toe was explained by Chari. The soil failed at an angle of 25° to 30° with respect to the testbed surface (horizontal plane).

The results showed that soil mobilization in the testbed took place far ahead of the models in both sand and clay. The results describe failure surfaces that begin or extend below the maximum scour depth. Unfortunately, the researchers did not provide the magnitude of the displacements.

Soil failure along successive shear planes in front of an earthmoving machine is presented in Figure 4.2.

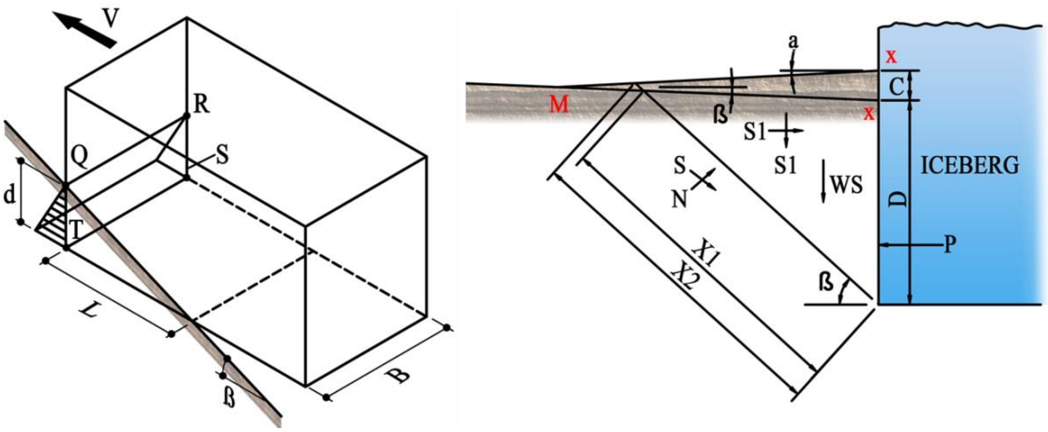

Figure 4.1: Assumed Type of Soil Failure in Front of Idealized Iceberg (Chari et al., 1982 [17])

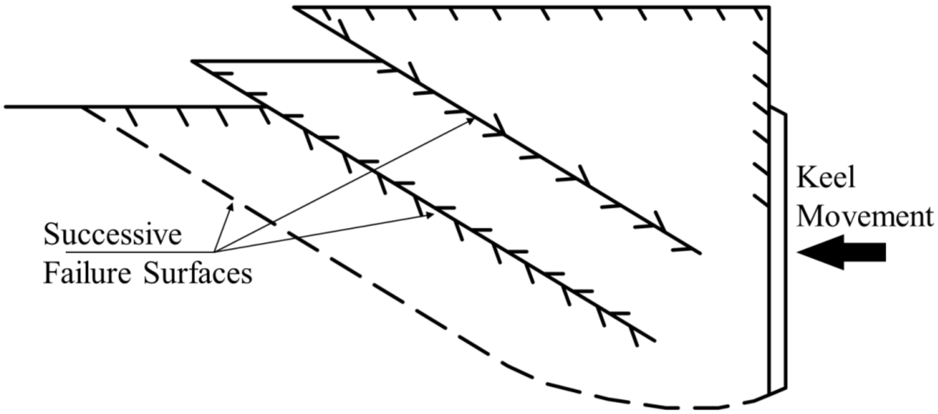

Figure 4.2: Soil Failure Along Successive Shear Planes in Front of Earth Moving Machines (Chari, 1982 [17])

4.2.3 Abdelnour (1981, 1984)

Abdelnour [1] [2] conducted extensive testing to understand the soil resistance to keel motion during an ice gouging event. To investigate the influence each testing parameter has on the measured pressures, the parameters were changed independently for each test setup. A range of modeling parameters such as soil types, model keel shapes, model scale, scour cut depth, and towing velocities was used in the testing. Two model shapes were used in the study. The first model was an inverted pyramid shape with a 63° angle (measured with the horizontal plane). The second model was a rectangular prismatic shape with 90° faces. The two model widths were 0.85 ft. (26 cm) and 2.7 ft. (82 cm). A total of 110 runs were conducted during this program, which was funded by the Arctic Petroleum Operator’s Association (APOA).

To measure the soil resistance to keel motion, pressure transducers were placed on the face of the model to measure the applied pressure on the soil surface and the force acting on the keel mounting frame. Information regarding the gouge geometry was listed for each experiment.

Abdelnour used the findings of the test program to develop dimensional and non-dimensional semi-empirical relationships. The analysis was extensive and provided deep understanding of the influence of each testing parameter on the resulting contact pressure. However, as Paulin, 1991 [32] reported, information regarding subscour was not included in the study.

4.2.4 Green et al. (1981,1983)

Green [21] [22] conducted physical tests using Chari’s model, in which the keel was driven into the sloping testbed while recording towing forces and pressures. Tests were limited to cohesionless sand. The purpose of these experiments was to study the gouging process in dry sand. Pressures and forces were measured on the keel as well as on an instrumented model pipeline buried in the testbed. The effects of several modeling parameters were investigated using different sized models and keel shapes.

The tests were conducted in a concrete tank at Memorial University, Newfoundland, Canada. Six different iceberg models of varying sizes and shapes were used. Pressure cells and load cells were used to measure horizontal force. A plexiglass model pipeline, which was instrumented with pressure transducers, was rigidly mounted in the testbed at predetermined distances and locations below the scouring model.

The primary resistance on the model was attributed to passive earth pressure. During the test, failure planes were developed in front of the ice model. Soil resistance measured during the model tests was directly related to the width of the iceberg model, but a change in shape from a vertical front face to a sloping front face increased soil resistance by as much as 35%. The speed of the model test had no effect on the forces measured during testing.

The model pipeline was designed to be very rigid relative to the soil. The tests could not provide clear information on the pipeline displacements relative to the surrounding soil. Green’s experiment was a continuation of Chari’s work, focusing on the measurement of resistance pressures and forces and the effects of varying keel shapes and sizes.

4.2.5 Prasad (1985)

Prasad [36] performed a series of tests to study the effects of the keel shapes on soil resistance and pressures during a gouging event. The tests included observing the failure plains associated with each shape.

Six model shapes were selected. Each model had a common base of 3.3 ft. (1 m.) in length, 1.64 ft. (0.5 m) in width, and approximately 2 ft. (0.6 m) in height. The length of the keel face varied, depending on the shape of the keel face. Two angles were selected to model a tapered keel: 30° and 60°. The tip of the keel was modeled as a sharp corner in all cases. Prasad investigated gouging events for a keel with a rounded edge in which keel pressure was introduced to the soil surface over a larger area. In addition, a semi-cylindrical-shaped keel front was tested. Finally, an extreme case of soil penetration was modeled using a front-angled keel shape. All shapes and dimensions used in the study are presented in Figure 4.3

Prasad correlated the measured front face resistance for each model with the computed values using theoretical methods. It was shown that the influence of keel shape on the estimated scour depth is within an acceptable range of variation, and the experimental results were extrapolated to the scour model with confidence. The pressure measurements on the faces of the models varied from model to model, but the scouring profiles did not. A progression of failures toward the surface was observed and attested by the plot of horizontal load. Prasad related the increased face inclination to the increase of soil resistance, but he did not discuss pressure and displacement measurements in his study.

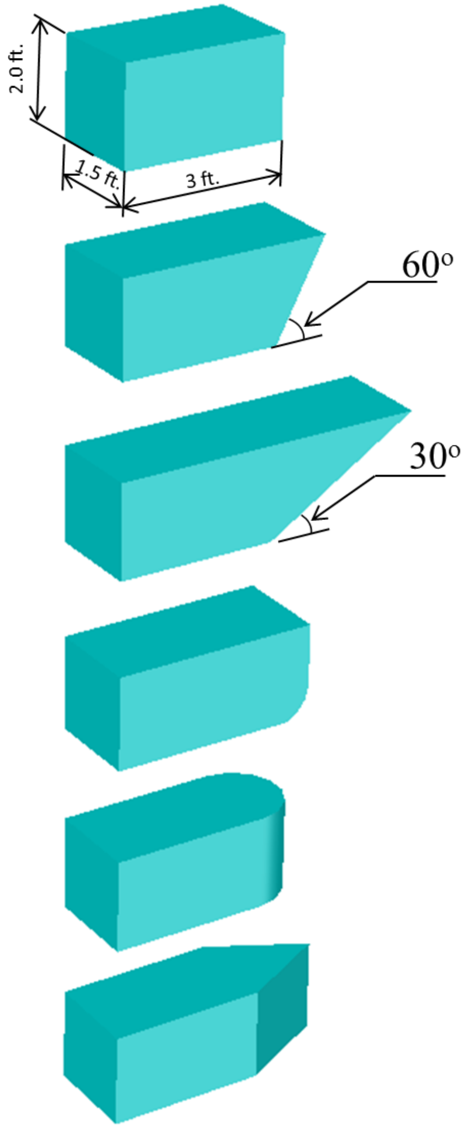

Figure 4.3: Model Shapes used (Prasad, 1985 [36]) – Modified by WGK

4.2.6 Golder Associates Ltd. (1989)

Golder Associates Ltd. [20] investigated soil movement below the scour. A small indenter was used to conduct 45 tests. Rigid indenters, which varied in width and attack angle, were driven into sand and clay testbeds. The displacements and forces on the indenters were measured during testing.

The patterns and loads of the failure planes that were observed for the models tested in sands were presented. The tests were repeatable, and they measured pressures and loads that were in agreement with the calculated values. Dead wedges of material, which were placed in front of the sloping indenters, were observed. These tests showed subgouge displacements below the indenter in the small-scale tests. In medium and dense sands, subgouge disturbance extended to only about 0.8 inches (2 cm) below the indenter, while in loose sand, disturbances were observed to a depth of 2.75 inches (7 cm). These observations were linked to critical state aspects. For example, below the indenter, dilation and strain softening took place in dense soil, while contraction and shear strains took place in loose soil. Clay soils behaved similarly to loose sands, although subgouge disturbances were found to be minimal.

This experimental work contributed to identifying the mechanisms involved in soil failure during scouring. The Been et al., 1990 [9] study attributed the movements below the scour in the Golder Associates' tests to shear dragging, which proved to be the missing link in understanding the patterns of subgouge deformations. Been's study highlighted, for the first time, the importance of determining the thickness of the shear dragging zone to ensure the safety of the pipeline.

4.2.7 Poorooshasb et al. (1989)

Poorooshasb et al., 1989 [35] reviewed C-CORE's work using small-scale modeling of an ice scour in saturated silt and dry sand. The Poorooshasb study conducted a series of four scour model tests at the Memorial University sand tank to investigate the size and nature of the deformation zone below a scouring iceberg. In addition, Poorooshasb et al. investigated the effect of width and attack angle on subgouge deformation. A force vector was calculated at specific time points during driving. A sample of total force vectors is presented in Figure 4.4.

Two factors that significantly affect the magnitude of subgouge deformation were identified. The first factor was soil density. In denser soils, the zone in which deformation occurs is restricted to an area immediately below the iceberg scour, while in looser soils, this zone is much larger.

The second factor that Pooroshasb highlighted was the attack angle. The two attack angles (15° and 30°) showed significantly different results. The 15° attack angle produced very little disturbance and was limited to a shallow zone under the iceberg.

The study indicated that soil deformations are larger in loose soils. Also, reducing the attack angle from 30° to 15° increases the force required for scouring as well as the subgouge deformation. On the other hand, in low strength, fine materials (clays and silts), small surface deformations may coincide with significant subgouge deformation and mobilizing shear stresses up to a depth of seven times the scour depth. Soil deformations in sandy soils decreased with decreasing attack angles. Similarly, decreased deformations were observed for soils with higher soil densities. The study emphasized the limitations when extrapolating small-scale test results to full-scale models and the lack of a correct self-weight stress.

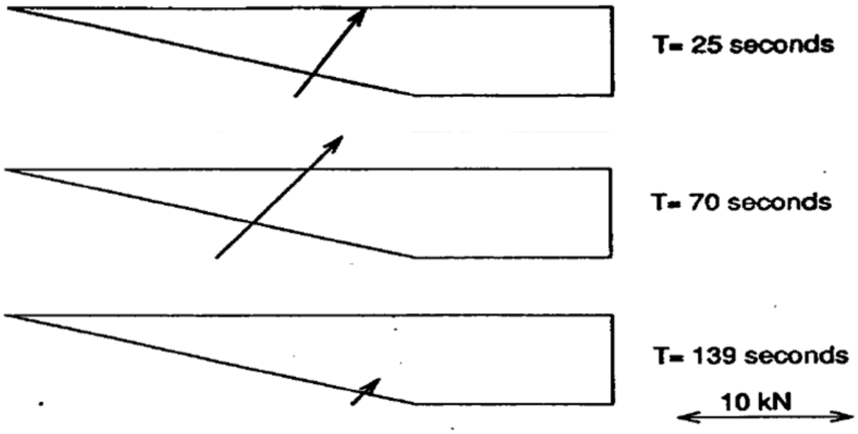

Figure 4.4: Total Force Vectors Acting on Keel during Driving – (Poorooshasb et al., 1989 [35])

4.2.8 Barker and Timco (2002, 2003)

Barker and Timco [4] [5] implemented a laboratory testing program to measure the loads and seabed response to the gouging event using an ice block. The authors performed 14 tests representing 35 configurations with a variety of seabed types. The study focused on the oil discovery areas within the Jeanne d’ Arc Basin area of the northeastern Grand Banks. A schematic of the experimental setup is presented in Figure 4.5.

The study was performed using two testing setups. In the first test setup, an ice block was mounted on a carriage that travelled along the length of the tank. In the second testing setup, the model was towed along an ice tank and was free to move throughout the water column. The scouring loads, displacement, angular movements, and resulting trenches were measured.

Testing results showed that the scour profiles were generally very uniform along each section of the test channels. The ice did not fail in shear, but general erosion was observed. Ice blocks moved in such a manner that the overall scouring forces on it were reduced, leading to sliding along the seabed. The loss of buoyancy, which was caused by sliding, also resulted in significant additional vertical loading on the seabed. The bearing capacity may have played a more significant role than was previously thought.

The scour depths measured in the gravel seabed were insignificant. The resistance forces were estimated from empirical relationships that were developed using regression analysis. The results achieved a satisfactory match between the measured and predicted forces.

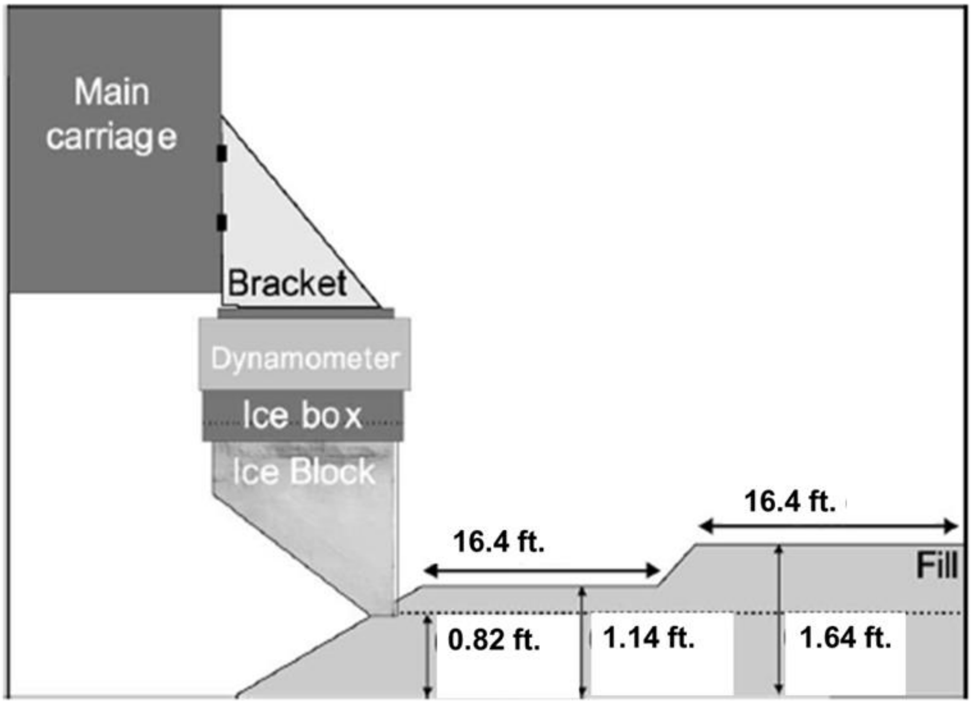

Figure 4.5: Schematic of Experimental Setup (Barker and Timco, 2002 [4])

4.2.9 Liferov et al. (2002), Liferov and Høyland (2004)

Liferov et al. [28] conducted an in situ program in the Van Mijen in Spitsbergen, Norway, to study keel destruction, investigate the process of scouring, and observe ice ridges throughout their lifetimes. During pulling, the keel of the ice ridge was sheared off by the sidewall of the trench. Figure 4.6 presents the in situ field condition observed by Liferov et al. A cross-section representing the testing setup is illustrated in Figure 4.7.

Two ice scour tests and one shear-off test (measuring the pulling force, displacements, failure of the keel, and the resulting plough) were performed during the testing program. The observed magnitude of the keel destruction was in the order of the scour depth and the heave of the ridge. The researchers observed a progressive failure of the keel as the ice ridge moved forward. The ice ridge followed the mode of the least resistance while scouring the seabed. The collected data was used for verification and justification of existing ice ridge gouge models as well as for the development of an improved ice ridge scour model.

Figure 4.6: In-situ Test Setup (Liferov and Høyland, 2004 [29])

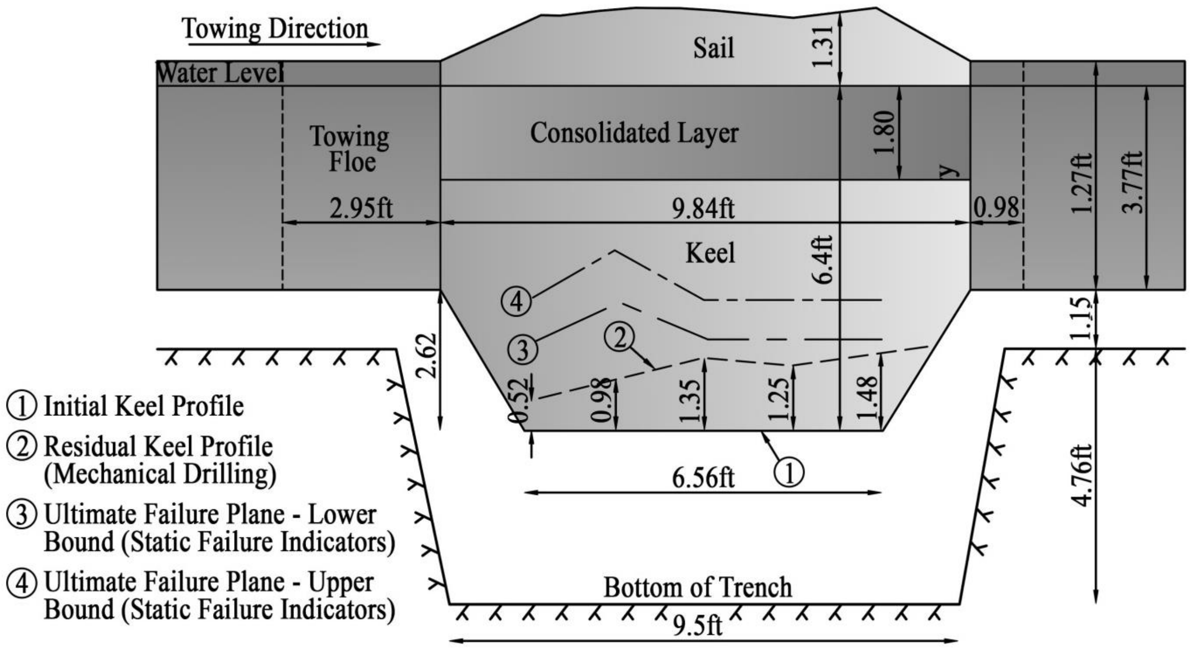

Figure 4.7: Cross-Section of Ice Ridge Along Centerline (Liferov and Høyland, 2004 [29])

4.2.10 Vikse et al. (2007)

The Vikse et al. [42] study performed small-scale laboratory tests to investigate the pressure distribution and soil deformation around a buried pipe segment. The test was performed using sand and sandy silt in the testbed. Vickse et al. discussed the dependence of subgouge soil deformations on several gouge-related parameters. The model setup was rather simplistic. A steel plate was used to limit keel motion only in the horizontal plane.

The authors observed that the buried pipe segments experienced cyclic movements, being first dragged forward and downward as the model keel approached the pipeline and then re-bounding when the keel passed over them. The maximum pipe displacement decreased exponentially with the pipe burial depth. The naturally formed soil mound in front of the keel influenced vertical pipeline displacement. Furthermore, horizontal pipe movements were larger at the lower attack angles of the ice keel.

4.2.11 Barrette et al. (2008, 2009)

The purpose of the testing program of Barrette et al. [6] [7] was to investigate the sliding resistance of ground-level ice and rubble on sand and clay in a laboratory environment simulating full-scale stress conditions. A 19.7 ft. (6 m) long flume was used to conduct the experiment. The researchers used measurement instruments to monitor stress distribution in the sediments during scouring while acquiring deformation profiles of the sediment column. Some of the instruments used were a displacement transducer to measure the vertical motion of the ice, a pore pressure transducer, and a few cameras to study keel dynamics.

Blasco et al. 1998 [10] documented the field observations recorded during the test to support the three-stage scouring project. In stage 1, the ice penetrated the seabed to a given depth. During stage 2, the ice went through a transition stage, and during stage 3, the ice scour became parallel to the seabed. The test results described in Blasco's paper coincide with stabilization of the horizontal load, which suggests a steady-state behavior during scouring.

Barrette et al., 2009 [7] reported that friction between the ice and the sediment controls the sliding resistance. Their analysis showed that the sliding resistance is a function of the effective shear response on the clay. Freezing was observed for sand seabeds around the keel, but it was not observed for clay seabeds.

The clay's undrained shear strength, which was measured with a vane (shear testing device), was consistently higher than the sliding resistance of the ice in all tests. A methodology was proposed to estimate sliding resistance by determining the effective internal friction angle of the clay, monitoring pore water pressure, and determining effective normal stresses. Using ice rubble instead of level ice provided an indication that ice rubble can promote clay consolidation (attributed to shorter drainage paths for pore pressure dissipation), yielding a potentially significant gain in shear resistance over the operational lifespan.

4.2.12 Sancio et al. (2011)

Sancio et al. [38] performed a testing program consisting of 17 large-scale ice gouging events. During each test, a composite steel and concrete indenter was pushed through an engineered soil bed of compacted clay or sand (a test 'basin'). The test was performed outdoors in saturated soils. The keel was pulled for several feet. The test incorporated a buried pipe that was 40 ft. (12.2 m) long, 0.55 ft. (0.168 m) in diameter, and 0.43 inch (11 mm) thick. The pipe was outfitted with 60 strain gages that were installed at four diametrically opposite places. Figure 4.8 shows the pipeline in the trench before the test was conducted.

The keel was pulled the entire length of the basin while measuring several parameters. The position of the keel was measured with a potentiometer, and the force required to pull the keel was measured using a dynamometer. The pitch and roll of the keel was measured with a biaxial tiltmeter that was installed on the keel. An inclinometer on the pull cable was used to measure the inclination. In addition, the researchers measured the displacements in the soil, the strains on a pipe segment, and pore water pressure response in the sand. The shape of the gouge after the test is shown in Figure 4.9. For sands, the subgouge displacements measured in this test program did not exhibit a direct relationship with the gouge depth, width, and soil density. In clay tests, subgouge displacements did not exhibit a direct relationship with undrained shear strength. Four piezometers were used to measure the induced pore water pressures during testing (see Figure 4.10). The magnitude of the induced pore water pressure was not included in the plot.

Figure 4.8: View of the Pipe (Sancio et al., 2011 [38])

Figure 4.9: Typical Gouge Produced in Sand Test (Sancio et al., 2011 [38])

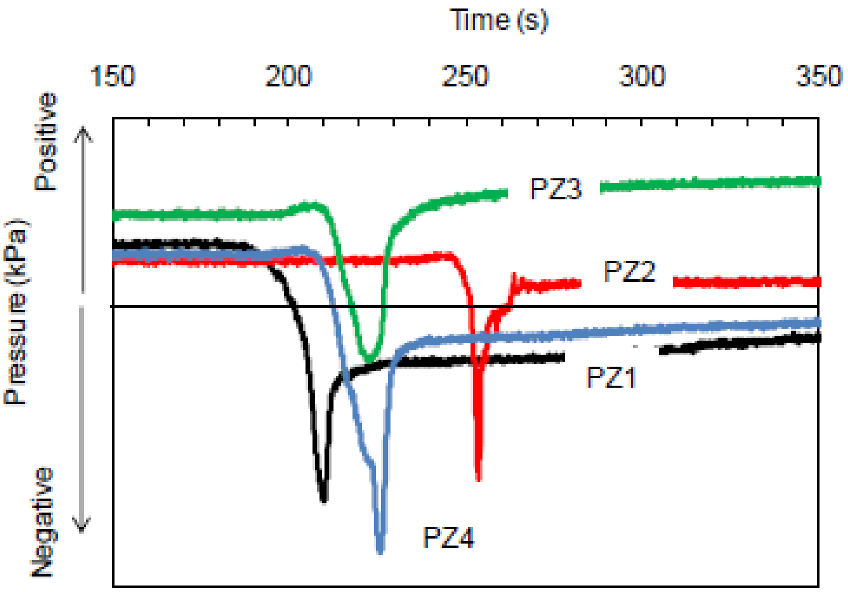

Figure 4.10: Pore Water Pressure Response in the Piezometers Installed in Saturated Sand Test (Sancio et al., 2011 [38])

4.3 Literature Review on Testing under Centrifuge Gravity

4.3.1 Paulin et al. (1991,1992), C-CORE (1995,1997)

In the 1990s, the Pressure Ridge Ice Scour Experiment (PRISE), a joint industry program led by C-CORE [11][12] (with input from Paulin et al.[32] [33]), highlighted the importance of subgouge soil deformations (see Figure 4.11) on buried offshore pipelines in ice gouge regions (Woodworth-Lynas et al., 1996 [43]). The C-CORE test program included a series of small-scale physical model ice gouging tests. The objective of the small-scale tests, which were conducted in a geotechnical centrifuge, was to enhance the understanding of soil deformations and ice loads produced during ice gouging events. Experimental procedures were divided into two physical studies with a total of 29 simulations performed.

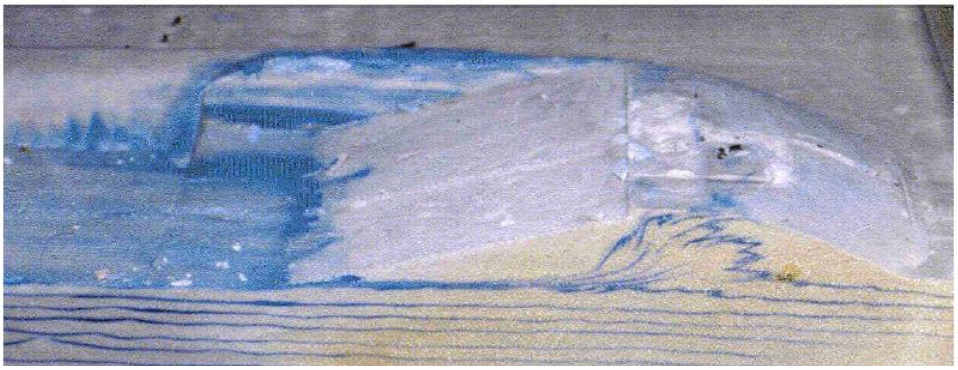

Figure 4.11: Typical Subgouge Failure Mechanism in Sand (C-CORE, 1995 [11])

The first study involved eight model tests that were conducted at 1-g in dry, partially saturated and submerged sands. The sand conditions, the model iceberg dimensions, and the scour cut depth were varied in these tests. The main objectives of the tests were to:

- Measure forces and pressures on the iceberg model during scouring.
- Monitor pore water pressures and total stresses in the sand.
- Measure the resultant force and subscour deformation.

The tests confirmed that deformations were greater in sand with a relative low density. They also confirmed that a change in attack angle from 15° to 30° degrees reduced the amount of subscour deformation and changed the dominant force acting on the model iceberg from vertical to horizontal.

In general, the scour process was similar in both the dry and the submerged tests. In both cases, spoil material built up in front of the models, and failure surfaces appeared on the sides and front of the models. However, a greater amount of infill and smaller berms were noted in the submerged tests, while the presence of water substantially reduced the horizontal and vertical forces required to create scour.

The second study involved two model tests that were performed on the centrifuge at an acceleration of 100-g in saturated, submerged clay samples of two different soil stress histories. Soil deformations below the scour were evident in both tests. Interestingly, in soft soil, soil movements that were opposite to the direction of travel were noted. It was concluded that the centrifuge tests closely simulated a full-scale prototype.

PRISE was the first extensive proprietary program designed to develop the engineering framework to allow pipeline installation in arctic regions. In a nutshell, it led to the development of a semi-empirical equation for horizontal subgouge soil deformations in clay soils, commonly referred to as the PRISE equation. The PRISE program provided the stimulus and a knowledge basis for the development and validation of numerical simulations.

4.3.2 Lach (1996) and Lach and Clark (1996)

Lach [26] and Lach and Clark [27] performed nine centrifuge model tests at a level of 100-g gravity at the University of Cambridge, England. The test objective was to investigate the effect of model variations in initial stress conditions (stress history), the model attack angle (15° to 25°), width, and vertical stiffness. The specified model width of 16.4 ft. (5.0 m) and speed of 0.23 ft./s (0.07 m/s) were fixed. Allowing an increased freedom of motion of the model (partially buoyant and free to lift and rotate) provided a more realistic representation of field events, but it reduced control over the input parameters. The data acquired from the experiments was compared to numerical data. The scientist observed a reasonable match between testing data and numerical data. Many later researchers have referred to Lach’s experiments and have compared their results of numerical simulations with his results.

4.3.3 Allersma and Schoonbeek (2005), Schoonbeek et al. (2006 a,b)

The Allersma and Schoonbeek [3] [39] [40] tests were conducted in a geotechnical centrifuge at the University of Delft in the Netherlands. Their focal point was to determine how measurable soil parameters, such as undrained shear strength (Su), influence subgouge deformation. Other test parameters measured were scouring speed, scouring depth, keel angle, and roughness of the keel surface. Additionally, the scale effects were examined by performing one test at 150-g instead of 100-g. During this testing program, some preliminary tests were performed on multiple scouring sites. The program also performed testing on layered soil to examine the effect of a seabed where a softer soil overlies an over-consolidated layer. During the tests, the horizontal and vertical loads and the soil deformation that was measured using image processing were also determined. The observed shear planes and visualization of soil deformation are presented in Figure 4.12. Horizontal movements extended up to four times the gouge depth in softer clay and up to two times the gouge depth in over-consolidated clay with a higher undrained shear strength. Vertical movements were smaller, but they extended deeper. Deep cracks, as well as large shear bands, could be observed.

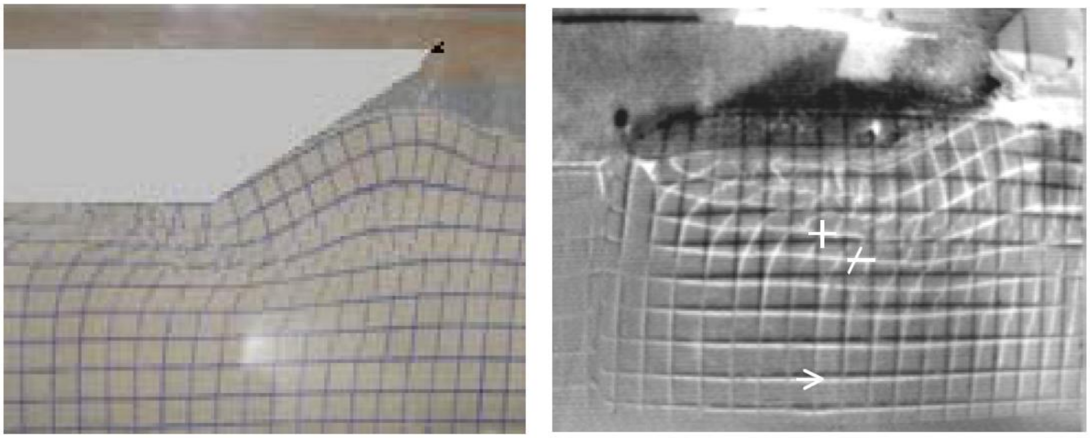

Figure 4.12: Shear Planes Observed in Test (left) and Visualization of Soil Deformation by Subtraction of Images (right) (Allersma and Schoonbeek, 2005 [3])

The deformation mechanism seemed to be sensitive for changes in deformation rate, keel angle, and roughness. It was particularly sensitive to the undrained shear strength of clay soils. The researchers defined an empirical formula to predict subgouge deformation from the undrained shear strength and the density of the soil (parameters that are measured in standard soil investigation for pipeline trenching).

The added value from those experiments is the use of remolded soil, as no other research focused on the effect of multiple scouring. In addition, the program investigated the scale effects and sensitivity of subgouge deformation in relation to the accuracy of soil strength estimates.

4.3.4 Phillips et al. (2005)

Phillips et al., 2005 [34] summarized the PRISE experimental program, the results of which became publicly available in 2004. The centrifuge tests were performed with an instrumented rough-faced rigid rectangular indenter at a fixed elevation, which could only travel horizontally. The seabed that was used for the tests was sand. Gouge forces and local bearing pressures on the indenter were monitored. Vertical to horizontal force ratio was equal to unity. An increase in scour depth with keel bearing pressure was shown, which, for gouge depths representative of the Canadian Beaufort Sea, implies prototype keel bearing pressure of 14.50 psi to 29.01 psi (100 kPa to 200 kPa). Basal shear, as opposed to passive resistance and side shear, was thought to be the main contributor to horizontal resistance. The vertical extent of subscour deformation varied as a function of sand state (i.e., dilatancy). The seabed failure mechanisms, assuming drained shear response, included the formation of a triangular dead wedge below the inclined keel surface, with passive failure ahead of it.

4.3.5 Ralph et al. 2011)

Ralph et al., 2011 [37] conducted a series of physical model tests using C-CORE’s geotechnical centrifuge facility to assess the feasibility of protecting multiple wellhead systems against gouging iceberg keels by housing them in a buried caisson. The physical tests simulated keel-soil-structure interactions representative of the design gouge features and soil conditions typically encountered in the Grand Banks. The objectives were to observe and study the global response of the protection structure in terms of stresses and deformations. Figure 4.13 illustrates the experimental setup. Various interaction scenarios were tested, and the results used to calibrate a numerical Finite Element (FE) model.

The relative position of the caisson's top to the base of the keel played a major role in the magnitudes of the stresses generated as well as the mechanism by which the dead wedge interacted with the caisson and ultimately flowed over it. The tests and the simulations investigated the wedge interaction with the cover and its effect. Apart from the cover's primary function to prevent debris from entering the box, the tests proved that the caisson affects the interaction of the keel-soil-structure and the transfer of forces/stresses to the structure.

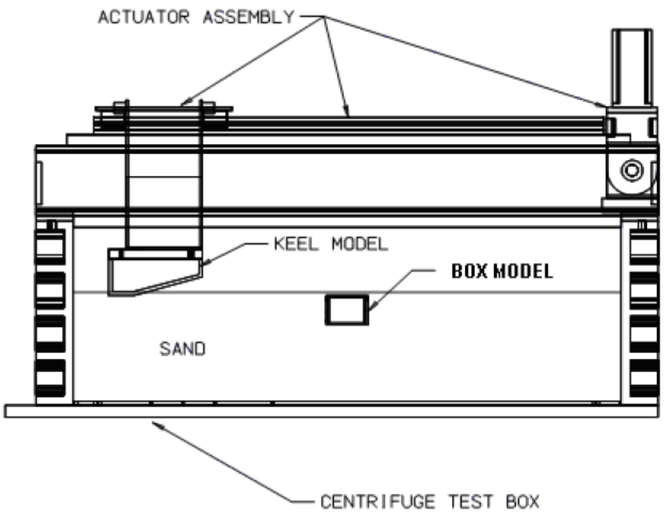

Figure 4.13: Illustration of Centrifuge Test Setup (Ralph et al., 2011 [37])

5.0 Gap Analysis

5.1 Overview

Several parameters control physical testing of ice gouging (i.e., soil type, friction contact between keel and soil, and keel characteristics). Soil presents different responses to scour events because of the complex interaction between a number of aspects (i.e., keel geometry, soil strength, and gouge characteristics). As discussed in previous sections, the influence of each parameter on gouge characteristics can be isolated and independently investigated in tailored experimental setups and under controlled conditions. Further complexity is introduced when the structure of interest (pipe or wellhead) is integrated into the model. At the same time, some simplification and idealization of testing parameters and/or conditions are essential to produce physically sound and repeatable test results.

5.2 Gap Analysis

5.2.1 Soil

The area of greatest model uncertainty is related to the characterization of soil response, commonly described as a soil constitutive model. Soil is a complex material that shows nonlinear, time-dependent, and often anisotropic behavior when loaded. This behavior can be generally contributed to non-constant soil stiffness, irreversible deformations, and changes in soil strength as a result of the loading history and pore pressure build-up under loading.

Physical tests were performed for cohesive and cohesionless soils under dry and saturated conditions. In most of the physical tests (427 of 487 tests), approximately 91% were performed under normal gravity conditions. Sixty tests were performed in centrifuges to represent conditions under higher soil confinement stresses. The highest gravity test recorded was 100 g. The typical soil layer thickness used in the laboratory tests was 3.3 ft. (1.0 m).

During testing, the soil layer was assumed to be a homogenous layer of soil with thickness that varied significantly between tests. The typical soil layer thickness filling the test tank was 3.2 ft. (1.0 m).

5.2.2 Keel

The keel was usually made of a steel or concrete mass that varied in shape and size, depending on the purpose of the test. The shape of the iceberg keel was usually irregular. However, during experiments, the keel was idealized to common shapes. Investigations of the keel shapes on the pressures imposed on the surface of soils were presented in several testing programs.

5.2.3 Attack Angle

The Barrette et al., 2012 [8] study summarized the number of simulation tests for each keel attack angle. This information is presented in Figure 5.1.

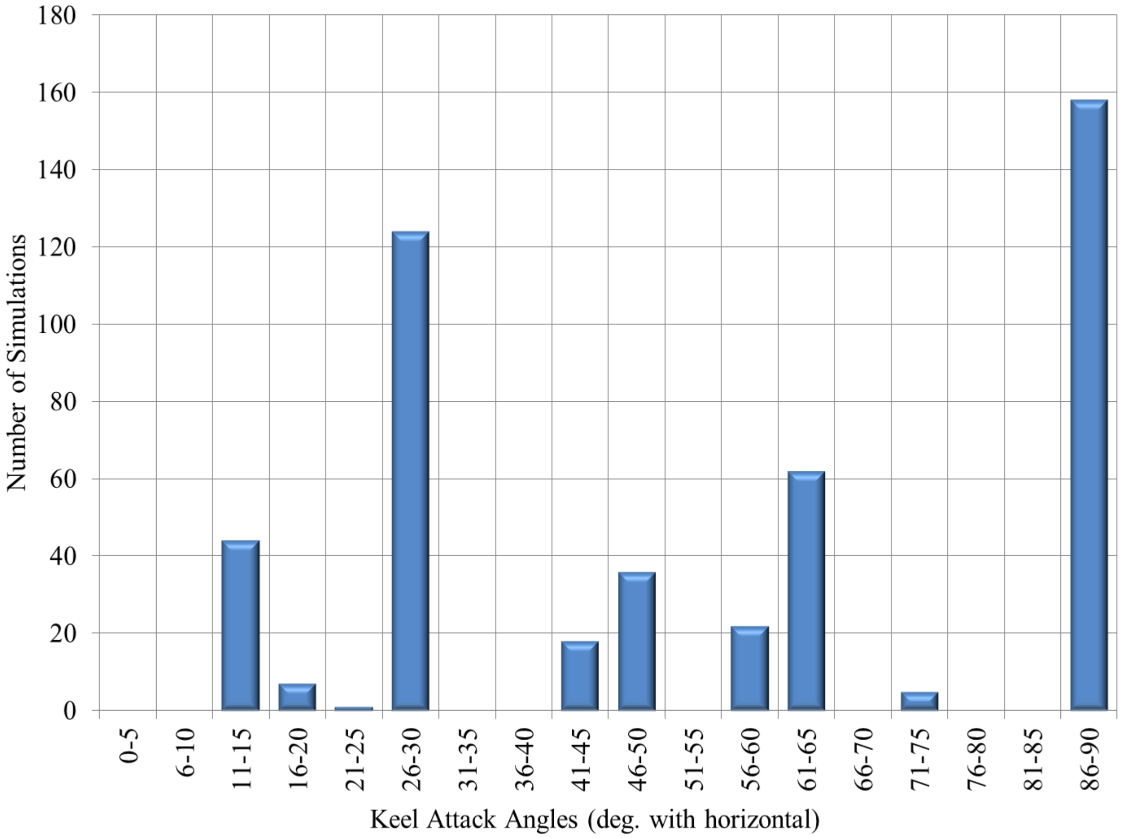

Figure 5.1: Number of Simulations (Barrette et al., 2012 [8])

The attack angle was measured between the keel face and the soil surface. The block-shaped keel was used in most of the experiments conducted in the past using an attack angle between 86° and 90°. No experiments were conducted for angles between 0° and 10°, 31° and 40°, and 76° and 85°. A large percentage of the experiments were tested at an attack angle between 26° and 60° and between 86° and 90°.

5.2.4 Ice Keel Properties

A limited number of studies used ‘ice’ keels for physical testing. The work done by Liferov et al., 2002 [28] and Barrette and Timco, 2003 [5] and 2008 [6], included only 18 tests. The percentage of experiments performed using ice keel is approximately 3% of the total number of experiments, a relatively low number of tests to draw any meaningful conclusion. Liferov’s 2004 [29] work restated that the failure of the gouging ice feature itself could be the limiting mechanism. In addition, using an ice keel may induce freezing in cohesive soils during gouging. The recommendation is to conduct more experiments using ice keel.

5.2.5 Pipe

A very limited number of tests using pipe have been conducted. Soil deformation around the pipe, as well as the pressure induced on the pipe, are important parameters when investigating displacement and the local buckling effect of the pipe. To estimate the minimum required burial depth, additional research on ice gouging, including pipe segments, is essential.

5.2.6 Wellhead

Only one experimental study (Ralph et al., 2011 [37]) examined the response of a wellhead arrangement housed in a caisson for protection against an ice gouge scenario. Further analyses are required to achieve a better understanding of the wellhead-ice keel interaction.

6.0 Summary and Recommendations

6.1 Summary

Several field and laboratory-based approaches were adopted to study the seabed response to possible gouging events in the early 1960s. Seabed surveying was a successful approach, but it had technical challenges and economical limitations. In contrast, the physical testing approach was adopted as the preferred method during the last three decades. Physical testing was given special attention because it allows full control of most gouging test parameters and allows an improvement in the gouging knowledge base process at a low cost and in a time-effective manner.

This report presents the following:

- A comprehensive literature review examining available physical testing datasets of ice gouging.
- A review of testing setups.
- An analysis of the technical advantages and challenges of physical testing programs performed by others.

The simulation of an ice gouging event is complicated because several parameters define the experiment. Soil types, ice keel, and subsea characteristics must be considered. Pressures acting on a buried pipe also have to be investigated through physical testing.

The soil failure mechanism during gouging events is the focal point in Section 3.0. The pressure imposed on soil surfaces causes a large disturbance of the soil. Failure of soil occurs under bearing capacity and passive earth pressure failure. Also, the soil surface may be dragged along in the direction of shearing, which is known as shear dragging failure.

Researchers are particularly interested in subgouge deformation and the loads transferred to a buried pipe during a gouging event. The influence of several parameters (e.g., soil strength, attack angle) on the subgouge deformation is essential to estimating the appropriate burial depth for a pipeline.

6.2 Findings and Recommendations

- In general, the technical literature provided extensive information regarding testing setups and instrumentations. Testing procedures were clearly stated in the literature.
- A total of 487 tests have been performed since 1972. Most of the simulations, 427 tests, were conducted under normal gravity conditions.
- Tests were performed for cohesive and cohesionless soils in both dry and saturated conditions. Most tests were performed for keel attack angles in the range of 40° to 70° and at 90°. No tests for attach angles below 10° and between 30° and 40° were reported in the literature.
- Tests simulating single-keel icebergs were conducted. Information about soil failure under pressure loads from multi-keel icebergs was not available in the literature.
- A limited number of experiments (approximately 3% of the total number of tests since 1972) were conducted using ice keel. It has been difficult to overcome the technical difficulties associated with using ice keel during the tests. If these difficulties can be overcome, using ice keels in the tests is recommended.
- Most of the tests focused on estimating the induced subgouge deformations and reaction forces acting on the keel during gouging. The load transfer to the pipeline is directly related to these parameters, but the relative stiffness of the pipe to the soil dictates the pipe response. It would be beneficial to further investigate the coupled soil-pipe response by incorporating pipe elements in the simulations.
- With proper instrumentation, the distribution of stresses and strains in the pipeline can be obtained. This would help establish an arctic pipeline-specific design and operation methodology for offshore pipelines in cold climates, and the methodology would account for the expected loading conditions and compliance with the Limit State Design (LSD) approach.

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