WOOD GROUP KENNY

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Ice Scour and Gouging Effects with Respect to Pipeline and Wellhead

Agenda

- Safety Moment
- Introductions
- Objectives of the study
- Background
- Review of Field Data
- Review of Test Data
- Review of Numerical Modelling
- Findings and Recommendations

SAFETY MOMENT

DID YOU KNOW

SAFETY IS NOT ONLY ABOUT TAKING PRECAUTIONS, IT'S ALSO ABOUT TAKING RESPONSIBILITY.

"See it. Own it." That phrase is particularly applicable to safety.

If you see an unsafe situation, or even a potentially unsafe situation, don't just walk away. Take responsibility for getting it corrected.

Whether it's in the office, while you're traveling, or at the work site, wherever you see something that you believe is unsafe, or could lead to an adverse incident, speak up. If it's unsafe to actually do something about it yourself, keep others out of the unsafe zone and contact your supervisor.

Think how you'd feel if you did nothing, then heard later that someone was injured.

INTRODUCTIONS

Safety & Assurance | Relationships | Social Responsibility | People | Innovation | Financial Responsibility | Integrity

Acknowledgment

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OBJECTIVES OF THE STUDY

Objectives Of the Study

The objective of this project was to identify the knowledge gaps in ice scour and gouging effects with respect to pipeline and wellhead design and placement in the US Artic region.

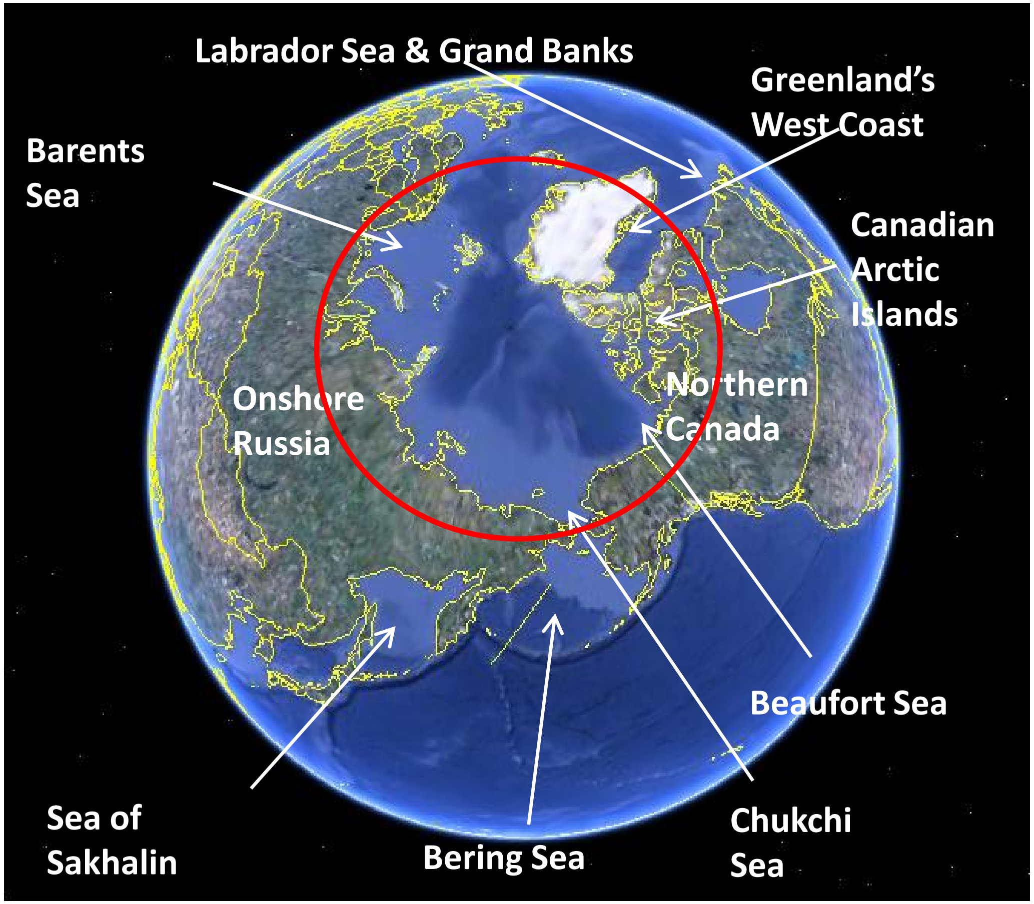
The project included a review of:

- Collected field data.
- Physical test data.
- Numerical modeling techniques that have been developed.

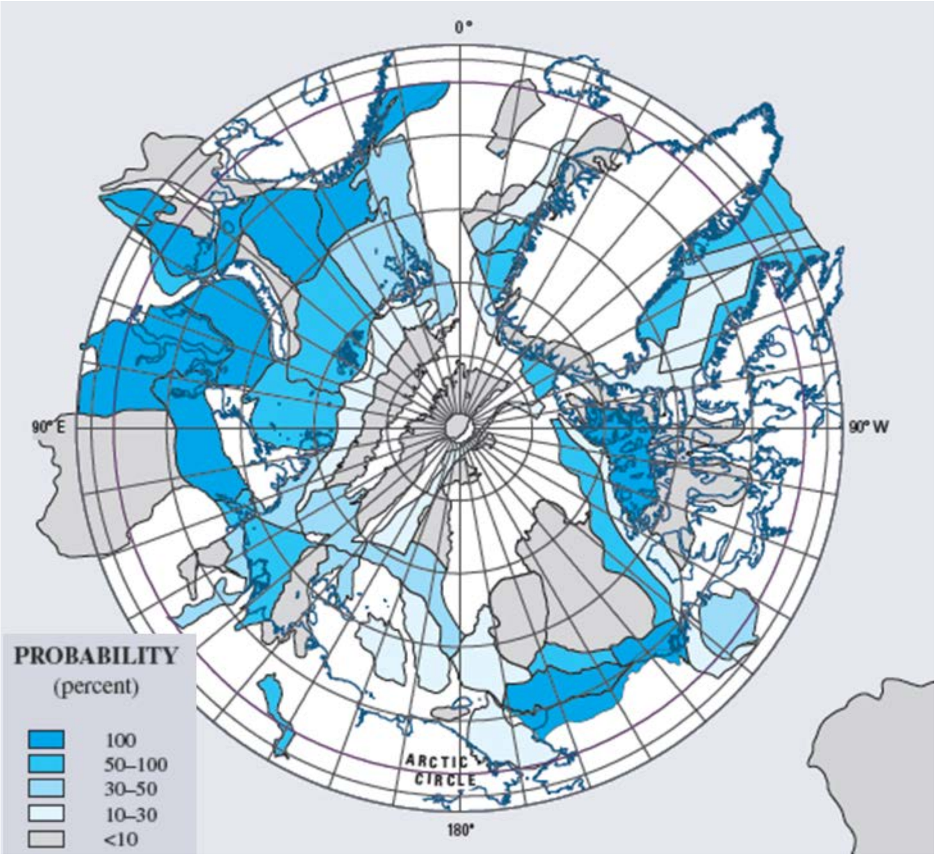
BACKGROUND

Why Pursue The Arctic?

- Increasing oil & gas consumption worldwide
- Decrease of production in several of the world's biggest fields
- Demand for new opportunities



Why Pursue The Arctic?



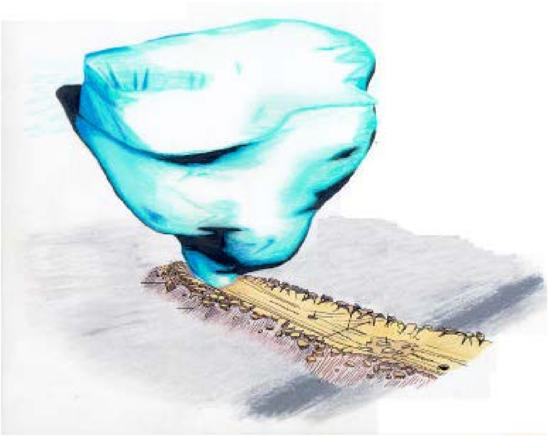
Isothermal Mean July temp of 57 ºF

5% of the earth's surface (USGS, 2008)

Circum-Arctic Resource Appraisal: Estimated Undiscovered Oil and Gas North of the Arctic Circle

indicates that 90 billion barrels of oil, 1,669 trillion cubic feet of natural gas, and 44 billion barrels of natural gas liquids may remain to be found in the Arctic, of which approximately 84 percent is expected to occur in offshore areas.

Arctic Challenges - General



- **General Arctic Challenges**
  - Location Related
  - Climate Related
  - Nature of Arctic
  - Environment Related

Arctic Challenges (1 of 4)

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Geographic Location
(Remoteness and Darkness)

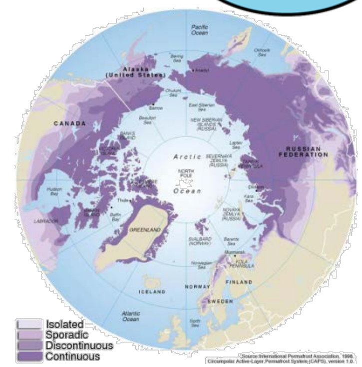
- Human Safety
- Working Conditions
- Communications
- Emergency Response
- Logistics
- Equipment Reliability
- Limited Time for Construction Activities

Arctic Challenges (2 of 4)

Climate Conditions & Ice Coverage

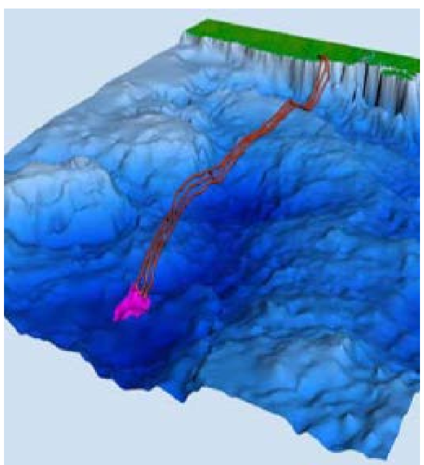
- Extreme Low Winter Temp
- Ice Gouging
- Strudel Scour
- Permafrost thaw

- Construction and Installation
- Operation and Maintenance
- Leak Detection
- Flow Assurance



http://www.fedre.org/

Arctic Challenges (3 of 4)



Nature of Arctic

- Large Fields
- Ultra Long Distances
- Complex Control Systems
- Efficient Power Transmission
- High Reliability
- Subsea Pumping
- Low Maintenance
- Shore Approach Facilities

Arctic Challenges (4 of 4)

Environmental Conditions

- Extremely Sensitive Ecosystem
- Slow Recovery
- Stringent Environmental Standards
- Zero Discharge / Zero Emission

Arctic Design Challenges

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Challenges in designing pipelines and wellhead placement in the Arctic:

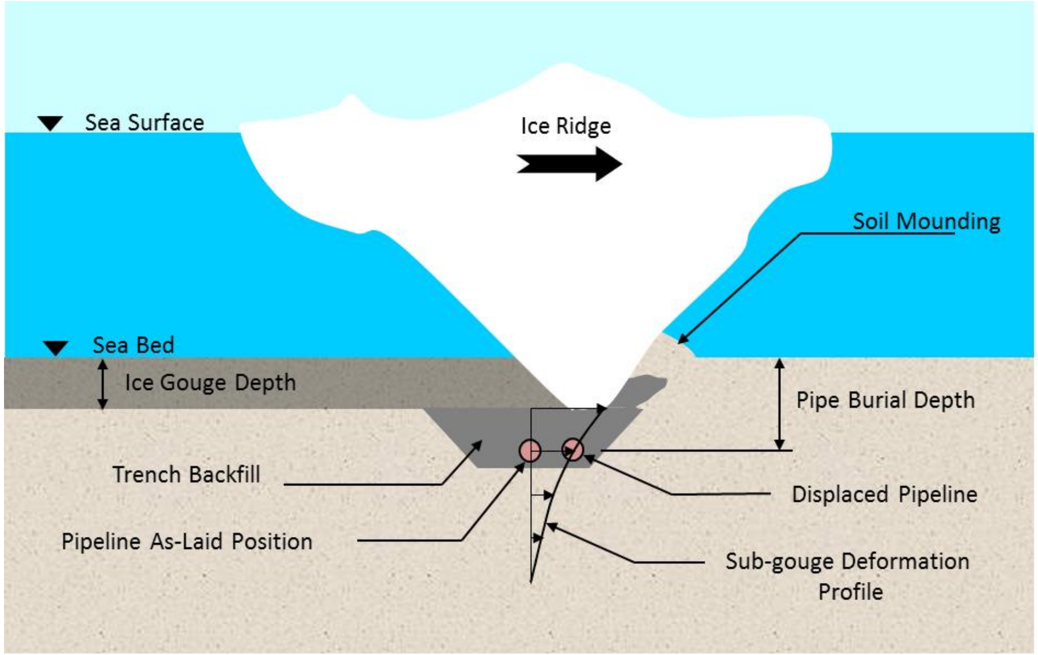
- Geographic location
- Climate conditions (ice coverage)
- Construction/Installation
- Transportation
- **Ice Gouging**
- Strudel Scour
- Permafrost

Ice Gouge Definition

Wind and current forces pile up sea ice into ice ridges.

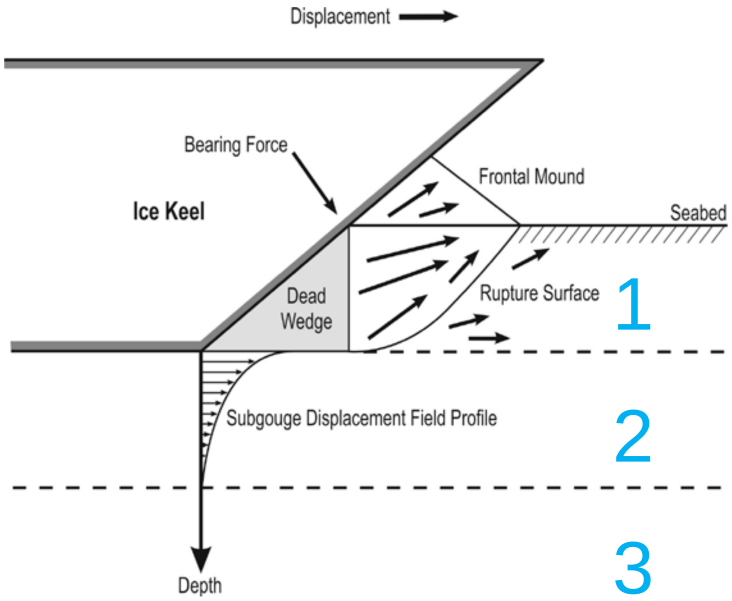
Ice ridges have a keel that extends below the water surface.

When pushed towards shallower water, ice keels cut deep gouges into the seabed.



Subgouge Deformations

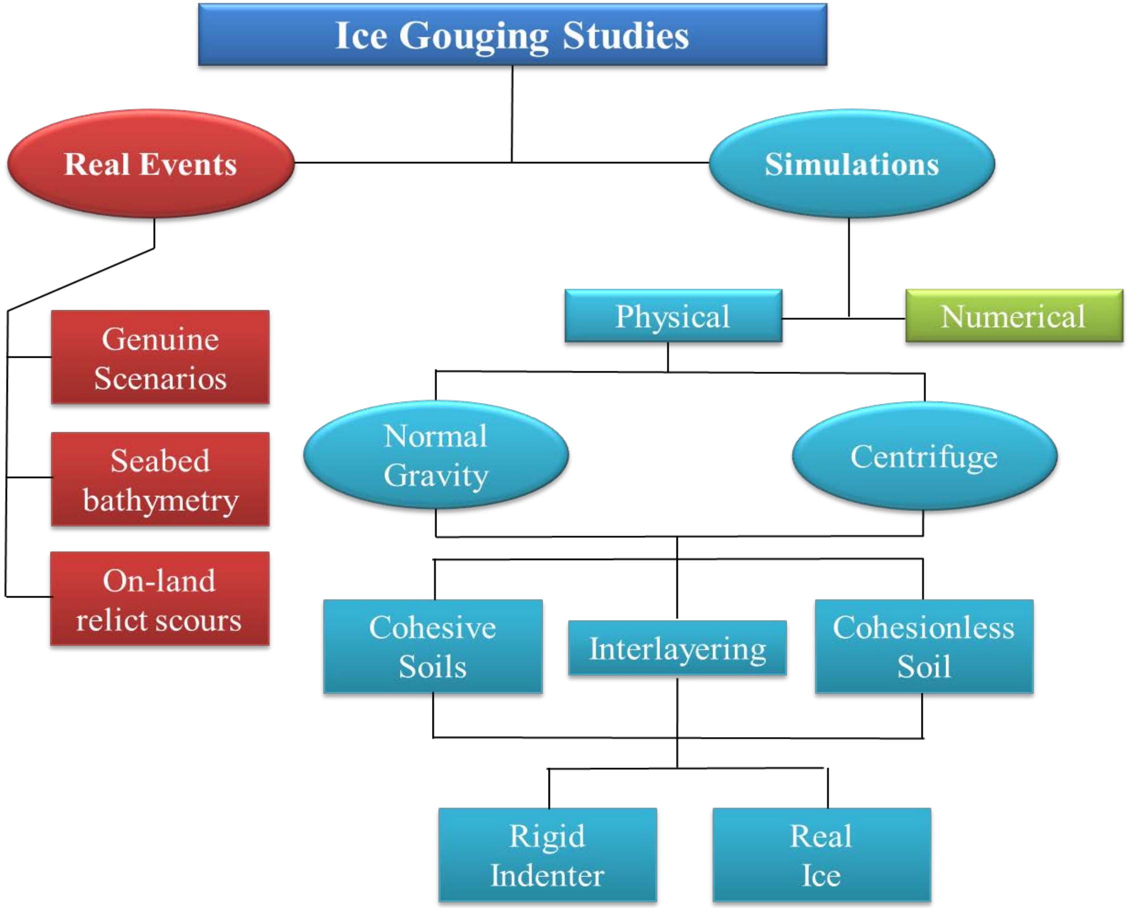
- Three zones have been observed during the scour process.
  - Zone 1 is the depth of soil gouged from the seabed and deposited in berms along the gouge track.
  - Zone 2 is the depth of soil plastically deformed.
  - Zone 3 is where the soil elastically deforms below Zone 2.
- Horizontal soil movements extend two or more gouge depths below the gouge base.



Design Against Ice Gouging

- Subsea infrastructures and pipelines must be designed and engineered to account for ice gouging.
- The burial depth, especially for pipelines, is determined by the maximum depth of expected gouges in the field.
- Special engineering techniques have to be implemented to avoid interaction of pipelines and wellheads with gouging or near gouging keels.
- Ice gouging is investigated through intensive field surveys, testing or numerical simulations.

Ice Gouging Studies



Current Knowledge Base on Scouring (Barrette and Sudom, 2012)

LITERATURE REVIEW OF FIELD DATA

Literature Review of Field Data

- Researchers used 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:
  - Observation of real events which involve performing extensive site surveys (seabed scanning), identifying gouging characteristics, and locating areas with high gouging occurrence rates.
  - Artificial simulations that can bridge the knowledge gaps and provide better understanding of the complexity of gouging process.

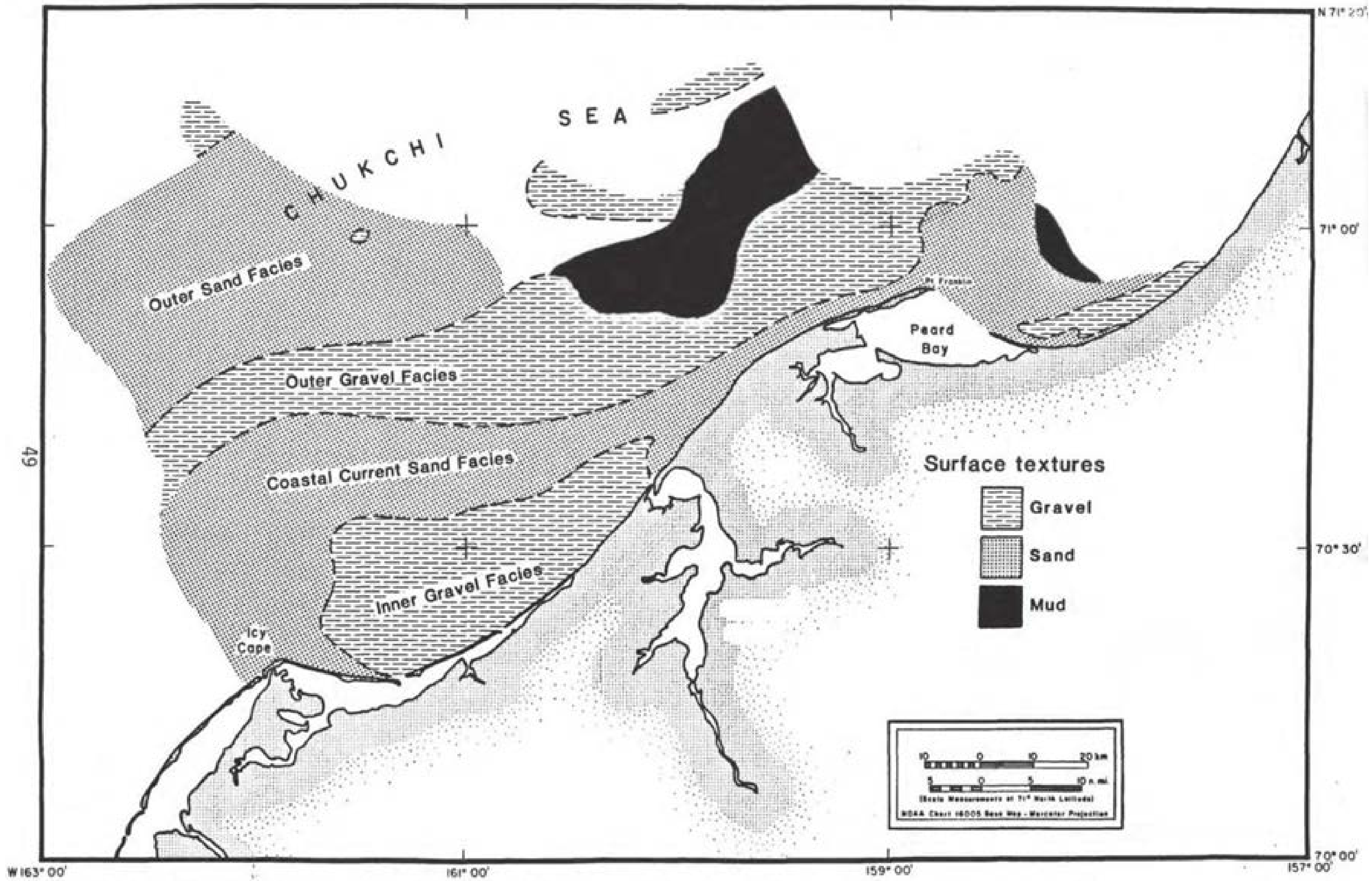
Literature Review of Field Data

Literature Review of Field Data

Geotechnical Characteristics of the Beaufort and Chukchi Seabeds:

- Ice gouging and geotechnical investigations surveys in both the Chukchi and Beaufort Seas were performed mostly during the 1970's and 1980's.
- Surficial sediments of the Beaufort Sea consist predominantly of clayey to silty soils. Near the barrier islands and along the shelf break there are coarsely grained soils of sedimentary origin. Seabed is predominantly very soft (5.0 psi).
- Surficial Sediment for the Chukchi Sea are predominately silts, sands and gravel across the Shelf. On the inner shelf range sediments range from muddy sand to gravelly sand. Surficial layers has a low shear strength of 3.0 psi

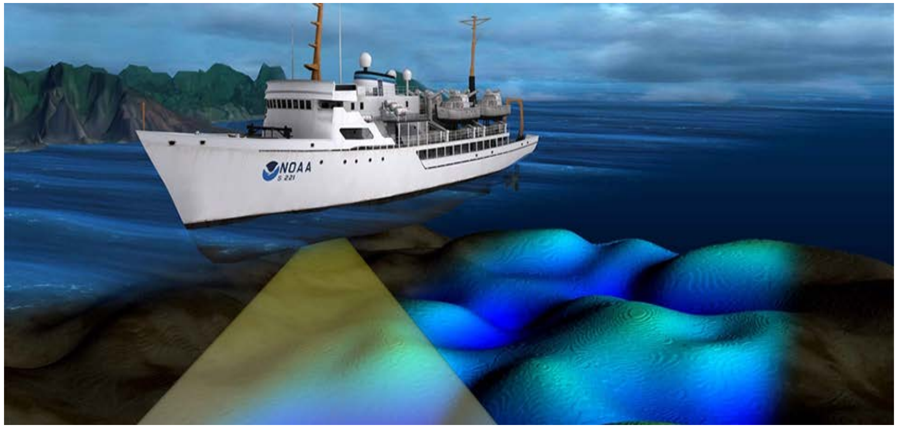
Sediment for the Chukchi Sea



Literature Review of Field Data

Seabed mapping

- Geophysical surveying of the seabed is performed using:
    - Single- or multiple-beam echo sounders
    - Side-scans sonars
    - Sub-bottom profilers.
- Information obtained includes:
    - Gouge depth, width and length
    - Orientation and density
- Repetitive mapping helps to distinguish young gauges from old ones to determine gouging frequency.



Literature Review of Field Data

Analysis of Data and Models

- USGS collected a significant amount of ice gouge data.
- Data was categorized according to water depth and locations
- Probability distribution was fitted for each of the interest parameters (depth, width, density, frequency).
- Analysis approach is used to generate exceedance probability plots and estimate the extreme design parameters at a certain level of risk.
- When analyzing the data sets researchers draw some general correlations between gouge features, seabed type and bathymetry:
    - Gouge depths increase with water depth.
    - Frequency of ice gouges increase with increasing latitude but decrease with water depth.

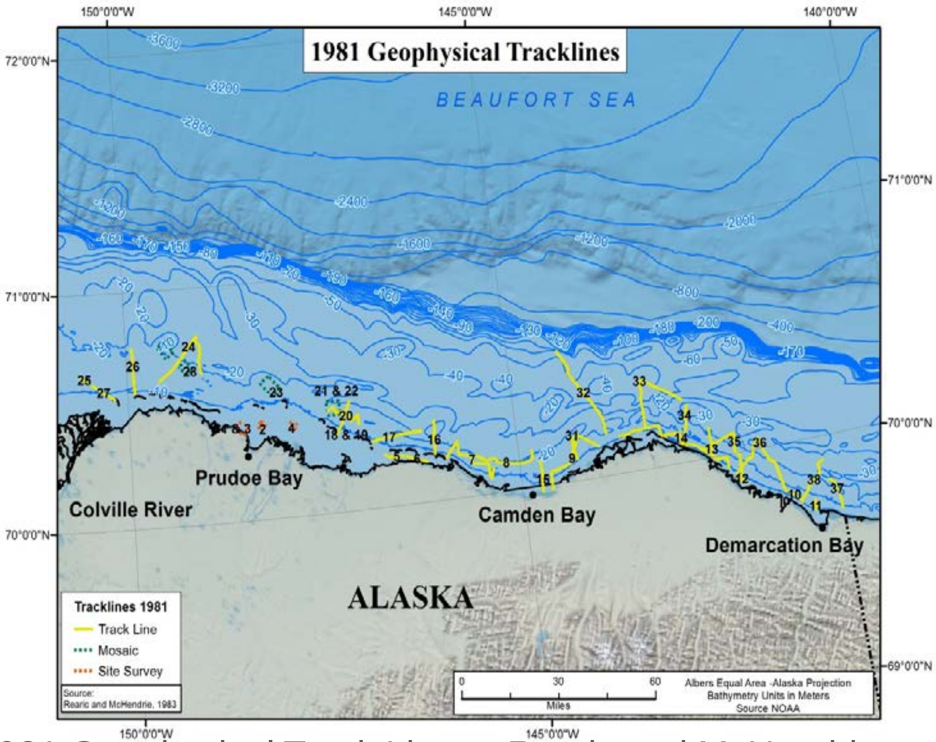
Literature Review of Field Data

- Approach for Ice Gouging Field Studies:
  - Surveying has challenging technical and economical limitations.
  - Repetitive surveys were conducted along track lines to characterize the ice gouges (gouge length, location, depth, width).
  - Statistical analysis was preformed to estimate the probability of iceberg crossing.
  - Accuracy (fitness) of the data to probabilistic function is sensitive to the size of the dataset; the larger number of records the better.
  - Surveys were limited to areas of interest.

Literature Review of Field Data

Surveys and Studies of Beaufort Sea

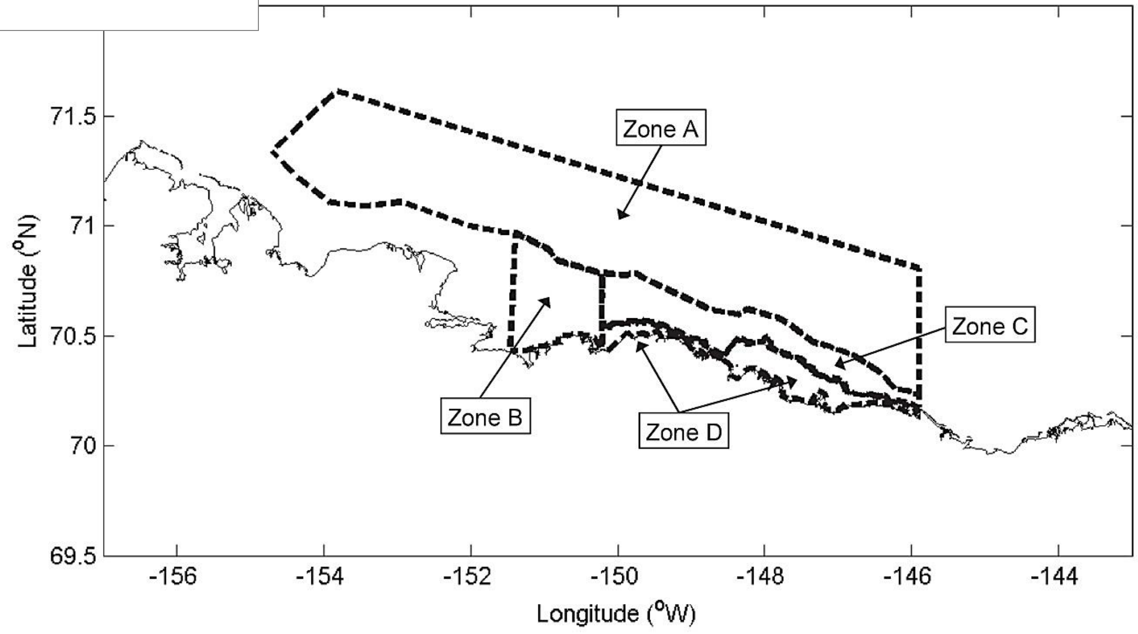
- Several studies were conducted to develop ice gouging rate prediction models.
  - **Rearic and McHendrie (1983)**
  - **Weber et al. (1989)**
  - **Nessim and Hong (1992)**
  - **Myers et al. (1996)**
  - **MMS (2002, 2008)**



1981 Geophysical Track Lines - Rearic and McHendrie (1983)

Literature Review of Field Data

Zone	Soil Type	Ice Gouging Frequency
A	Soft to stiff clay 2.90 to 14.50 psi (20 to 100 kPa)	High
B	Soft clay 1.45 to 4.35 psi (10 to 30 kPa)	Low to Medium
C	Dense sand and gravel 40° to 45° (friction angle)	Low to Medium
D	Soft to stiff clay 2.90 to 14.50 psi (20 to 100 kPa)	Low



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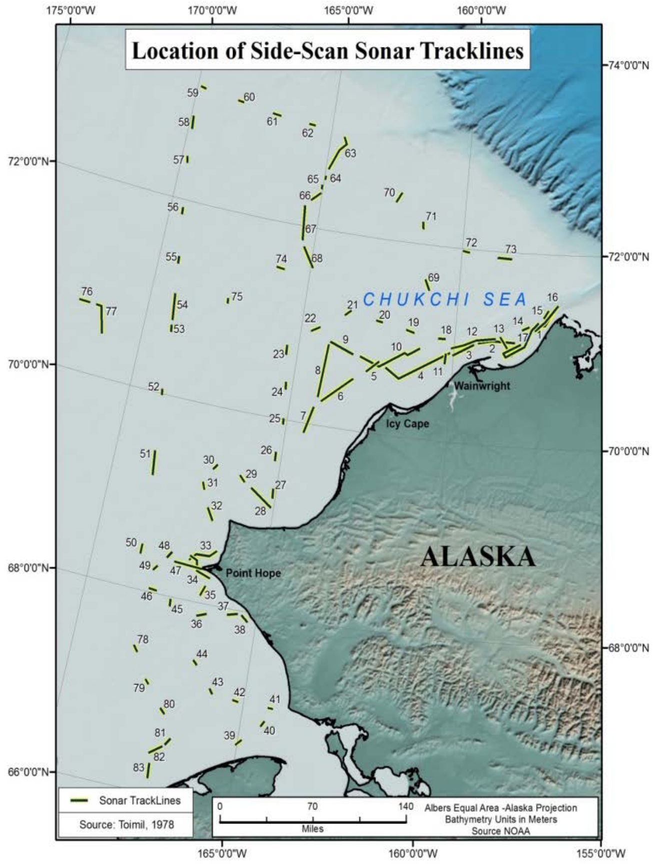
Literature Review of Field Data

<u>Surveys in the Chukchi Sea</u>

- Field survey conducted in 1974 by members of the Office of Marine Geology of the U.S. Geological Survey
- Since this survey, no repetitive mapping has been performed.
- The ages of the gouges were not identified, and the study was limited to the general trend of gouging in the Chukchi Sea



Location of Side-Scan Sonar Tracklines as Determined by Satellite – Toimil

Findings and Recommendations

- The maximum depths for single and multiple gouges were observed at water depths from 72 to 473 ft.
- The maximum number of gouges occurs in the water depth intervals between 82 and 131 ft.
- The highest calculated crossing density is 91 gouges per mile, which has been observed within the 66 to 82 ft. water depth interval.
- At the eastern Chukchi Sea, an estimated 10,200 individual gouges were identified in the water depths interval between 60 and 210 ft.
- The maximum noticed incision depth is equal to 15 ft. in the 115 to 130 ft. water depth interval.
- Gouges wider than 300 ft. occurred at 118 to 131 ft. water depths.

Findings and Recommendations

- The maximum occurrence of wide gouges occurs in the water depths interval of 101 to 148 ft.
- Investigators recommended the single–parameter exponential distribution as an effective and conservative probabilistic ice gouge model.
- Later efforts suggest that the Weibull distribution provides the better fit for the Canadian Beaufort Sea ice gouge depth data across the full range of available water depths.
- The two–parameter exponential and three–parameter gamma distributions tended to under–predict the amount of shallow gouge depth data.

Findings and Recommendations

- For the Chukchi Sea, log–normal distribution models have been produced, but the lack of sufficient gouge depth and widths data has resulted in limited confidence.
- The available dataset provided extensive information regarding gouge dimensions, location and frequency in the Chukchi and Beaufort Seas. Surveys covered large areas in both seas and were performed for a wide range of water depths.
- Some data obtained differentiated between the single and multiple keel gouges.

Findings and Recommendations

- Comparisons of the available datasets showed discrepancies and inconsistencies among surveys. Single and multiple gouges must be differentiated, and all observed gouge widths must be listed in the surveys.
- A consistent surveying approach must be instituted
- Statistical analysis of the available datasets showed that the data may not be enough to provide a reliable probabilistic distribution in some regions.
- The available data did not included all keel characteristics (mass, keel draft, keel geometry and near gouging keel distributions).

Findings and Recommendations

- Keel characteristic data listed above needs to be collected for both gouging keels and near gouging keels.
- There is not enough data available to recommend a design approach for wellhead placement (i.e., preventive or protective).
- It is highly recommended to perform additional surveys in the Chukchi and Beaufort Seas. Repetitive mapping must be performed periodically to record new ice gouges and changes to existing gouges.
- It is important to determine the age of gouges since this is a necessary parameter used to calculate the return rate of similar gouges.

LITERATURE REVIEW OF TEST DATA

Literature Review of Test Data

Physical Testing:

- Physical tests are conducted in the field or in laboratory settings, indoors or outdoors
- Small– or large–scale instrumental setups
- Offer better control of modeling parameters (seabed, keel etc.)
- Low–cost and time–efficient approach to improving the ice gouge knowledge base
- Produces a more complete set of data than field observations since loads, displacement, scour geometry etc. can be measure pre and post testing

Physical Simulation Components

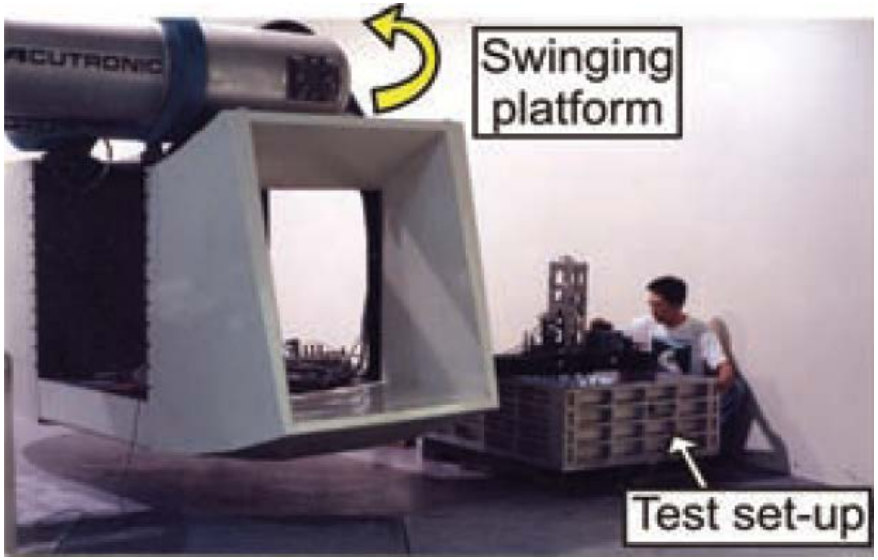
- Test facility
- Experimental Set-up
- Seabed Properties
- Keel Properties (material, geometry)
- Subsea Structure (pipeline, wellhead)
- Data generated

Physical Simulation Components

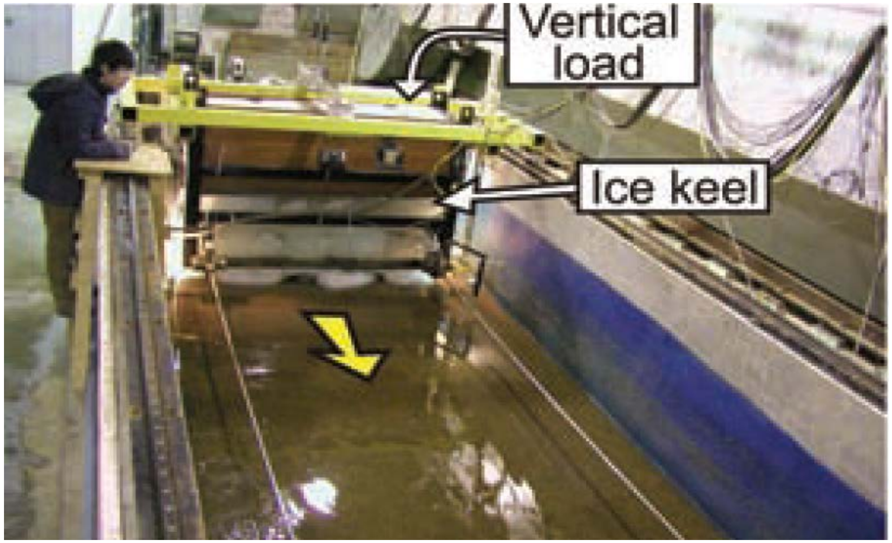
Test facility:

- Normal Gravity
  - Small scale (indoors)
  - Large scale (outdoors in flumes or basins)
- Centrifuge Facility

Test Facility

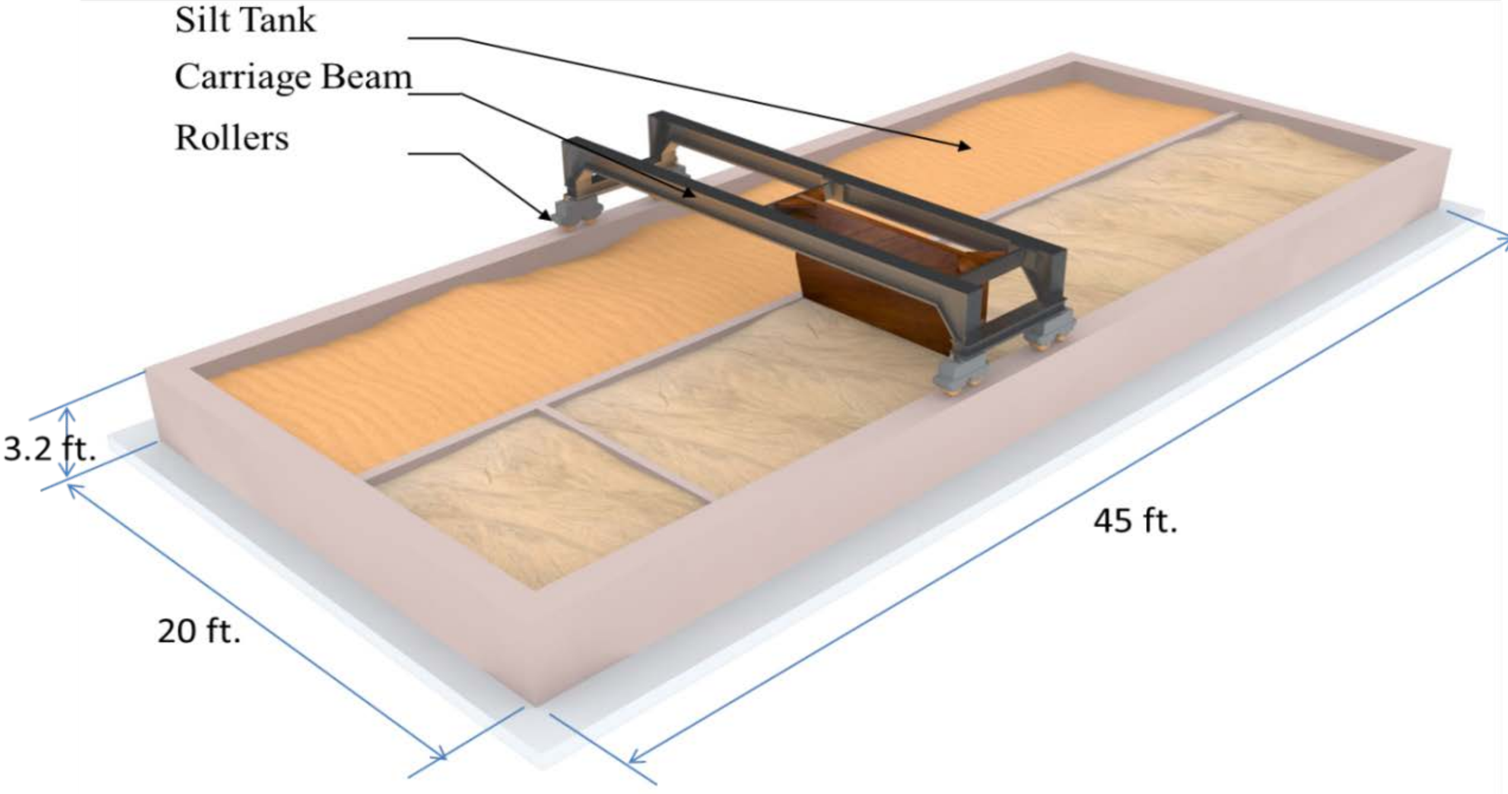


Typical Centrifuge Testing Facility (Barrette et al., 2012)



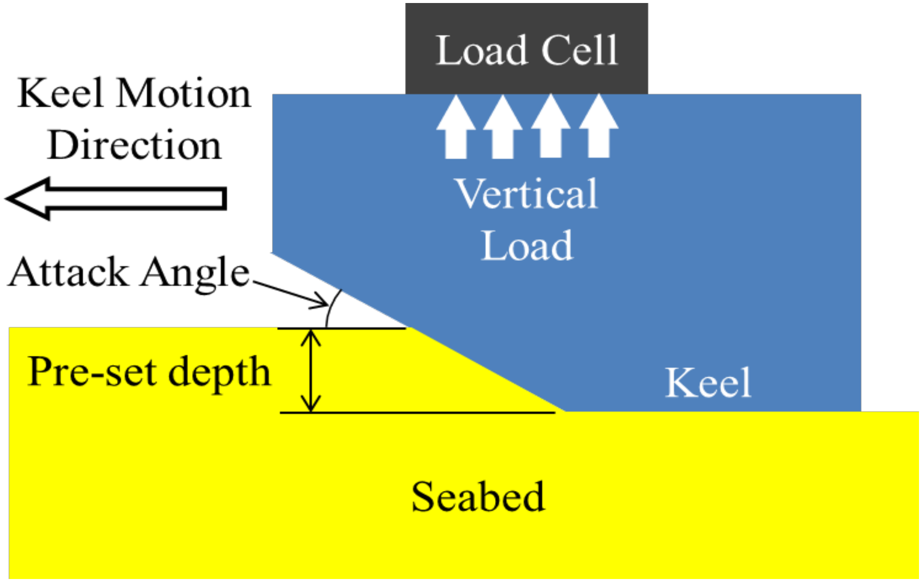
Typical Normal Gravity Testing Facility (Barrette and Sudom, 2012)

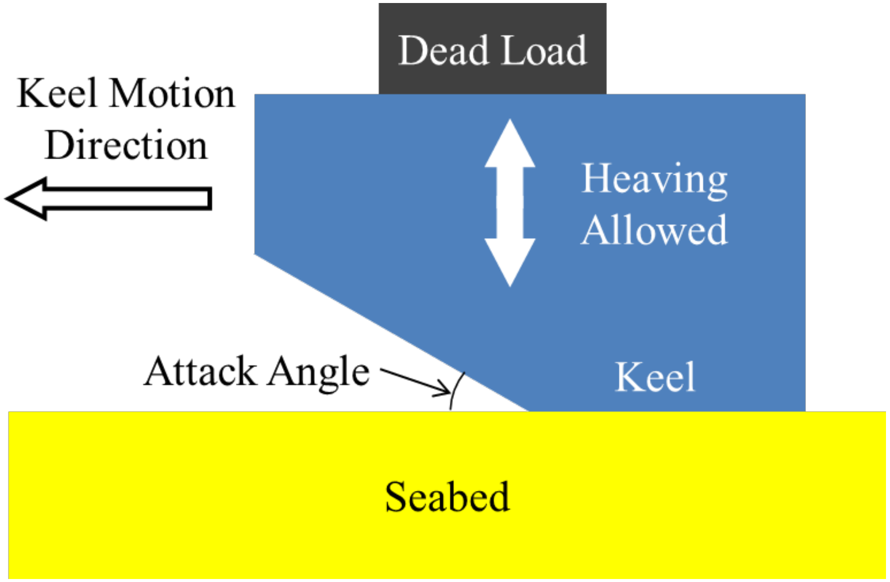
Experimental Set-up



Schematic of Typical Ice Gouging Tank (Green, 1983)

Experimental Set-up





Test Setup 1(Barrette and Sudom, 2012)
Keel is prevented from lifting

Test Setup 2 (Barrette and Sudom, 2012)
Keel is allowed to lift/heave

Physical Simulation Components

Seabed:

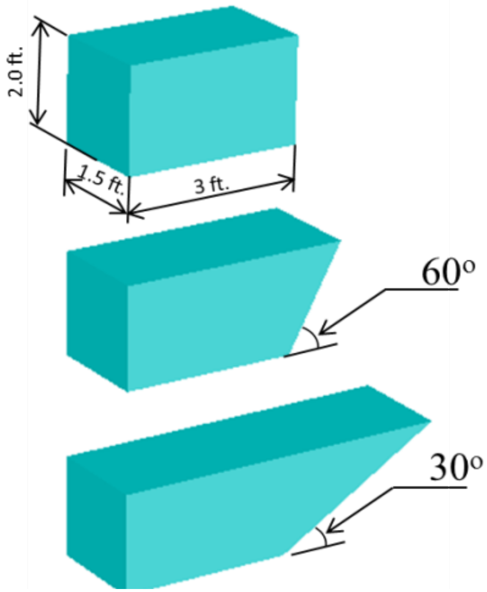
- Soil Type
  - Cohesionless (sand)
  - Cohesive (clay)
  - Other (silty sand)
- Saturation (Dry/Saturated)
- Soil characterisation (density, strength, consolidation, etc.)
- Bathymetry (level or slope)
- Stratigraphy (uniform, layered)

Physical Simulation Components

Keel:

- Material
  - Rigid (solid block)
  - Real Ice
- Keel Geometry and Dimensions
  - Attack Angle
  - Length/Width
  - Gouge Depth

Keel Geometry



Keel Model Shapes Used by Prasad, 1985 [108]
(Modified by WGK)

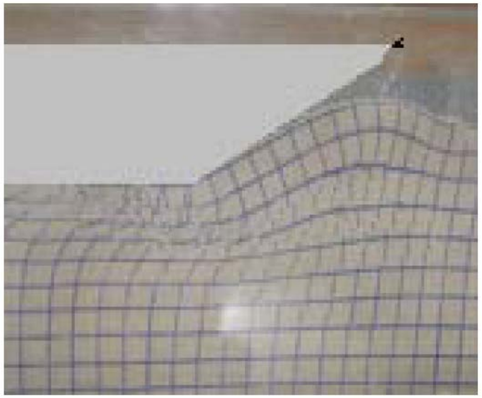
Subsea Structure

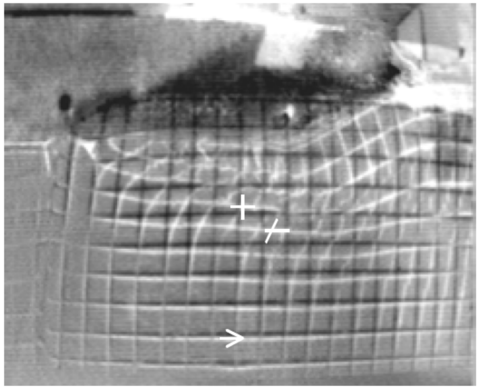
- Buried pipeline
  - Pipe outer diameter and wall thickness
  - Material properties
  - Crown depth (below seabed)
  - Constraints (free to move or anchored)
  - Instrumentation

- Wellhead
  - Height above Seabed
  - Constraints (free to move or inside protective caisson)
  - Instrumentation

Data Generated

- Horizontal load
- Vertical load
- Assessment of steady–state condition
- Keel heaving (depending on test setup)
- Pore pressure
- Subscour deformation
- Post–test bathymetry (scour depth, width, side berms, front mound)





Shear Planes Observed in Test and Visualization of Soil Deformation (Allersma and Schoonbeek, 2005)

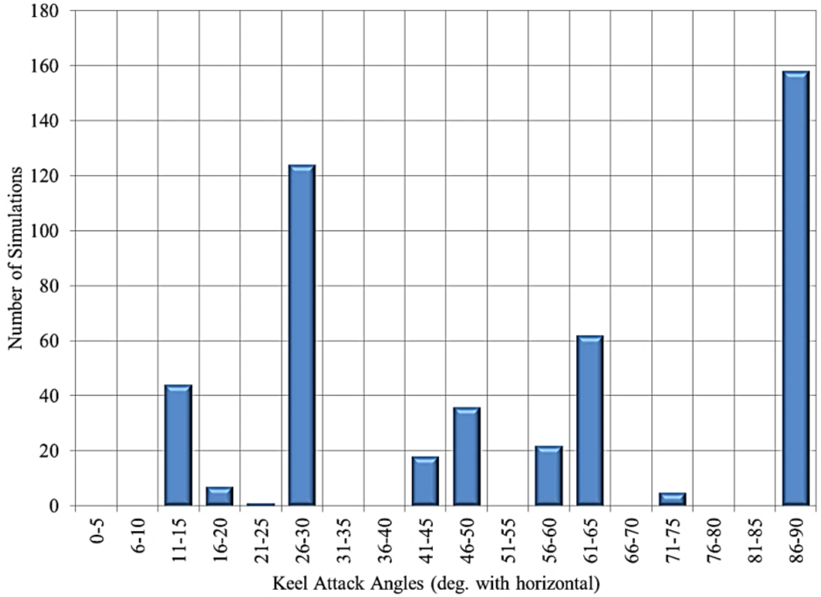
Gap Analysis

Keel

- Steel or concrete
- Varies in shape and size
- Icebergs have irregular shapes.
- Keel was idealized to common shapes.
- A limited number of studies used ice keels for physical testing.

Attack Angle

- Most of the experiments conducted 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°.



Number of Simulations (Barrette et al., 2012)

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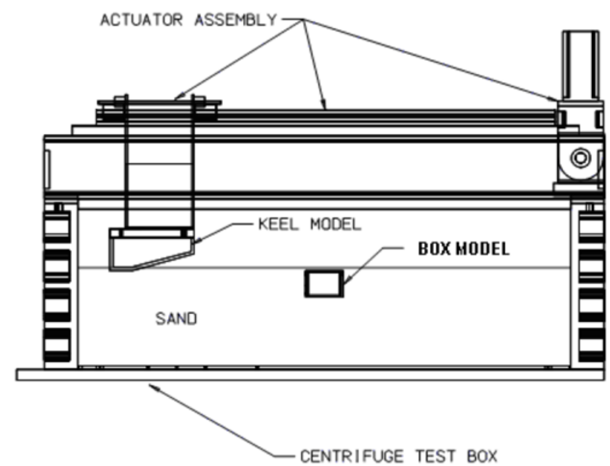
Gap Analysis



Pipe

- A limited number of tests were performed using buried pipes (127 simulations)
- Pipe was free to move in 79 simulations– fixed in the rest

Wellhead

- Only one experimental study (Ralph et al., 2011)

Test Data

Advantages:

- Allows for full control of most gouging test parameters.
- Low–cost and time–efficient approach to improving the ice gouge knowledge base.
- Allows for correlation with data obtained by seabed mapping
- Establishes general trends of soil behavior and leads to development of empirical formulations
- Validates numerical models

Test Data

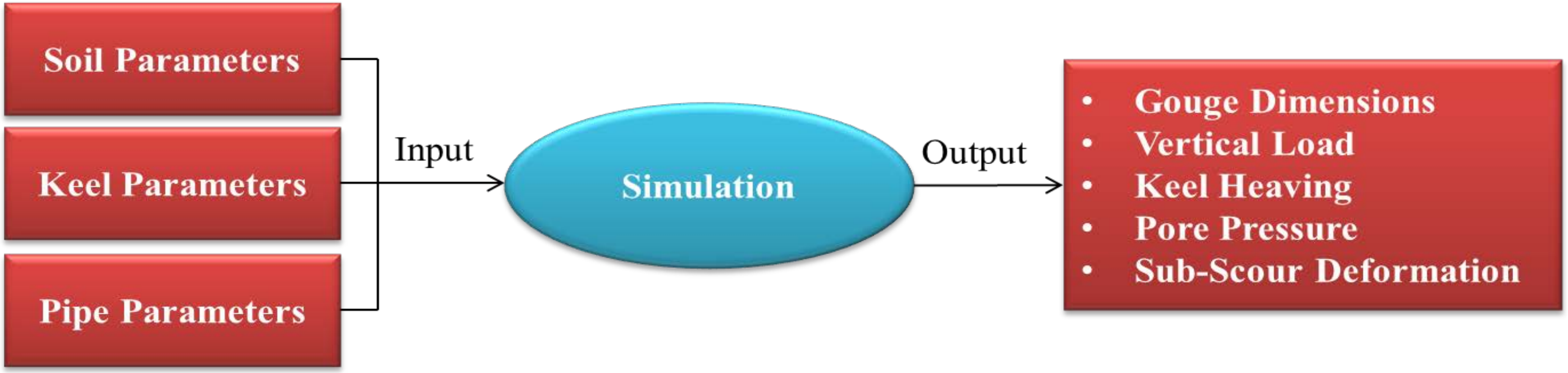
Disadvantages:

- Results from 1–g physical models must be extrapolated to full–scale for extreme ice gouge events.
- Most tests focused on estimating the induced subgouge deformations and reaction forces acting on the keel during gouging.
- The load transfer to the pipeline or wellhead is directly related to these parameters, but with better instrumentation, a better distribution of stresses and strains on the structure can be obtained.
- Limited data on wellhead response (1 experimental investigation)

LITERATURE REVIEW OF NUMERICAL MODELING

Review of Numerical Modeling

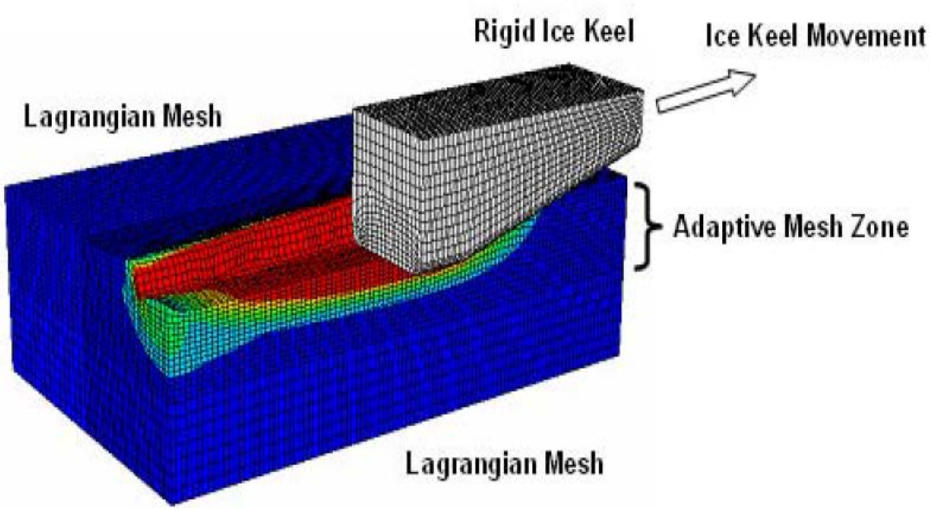
- Advanced numerical analysis plays a significant role in addressing the complexity of the ice keel–soil–structure interaction.



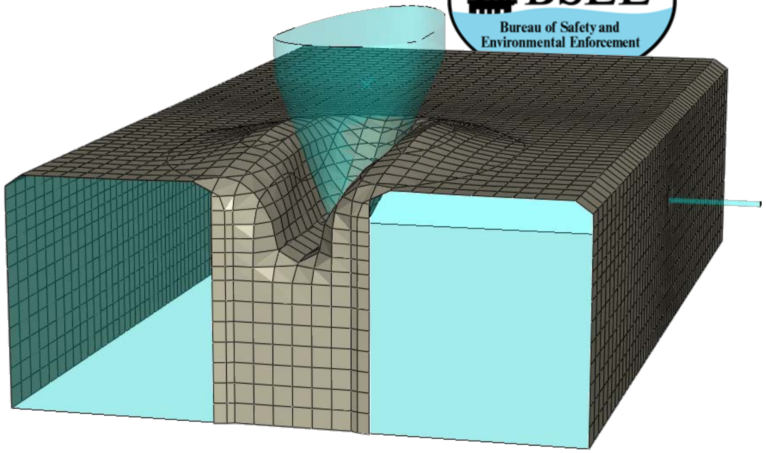
Review of Numerical Modeling

Numerical studies can identify the parameters that strongly affect the keel–soil–pipeline response:

- Ice Attack Angle
- Ice Keel Geometry
- Ice Strength
- Soil Type
- Pipeline burial depth
- Wellhead height above seabed

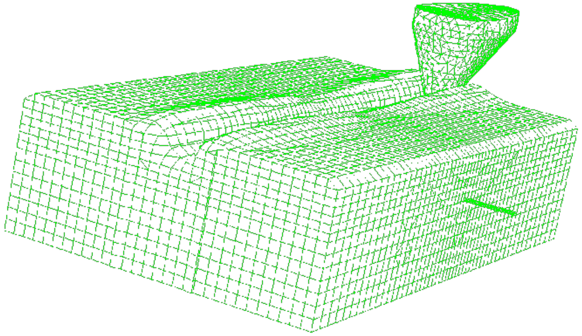


Numerical Modeling



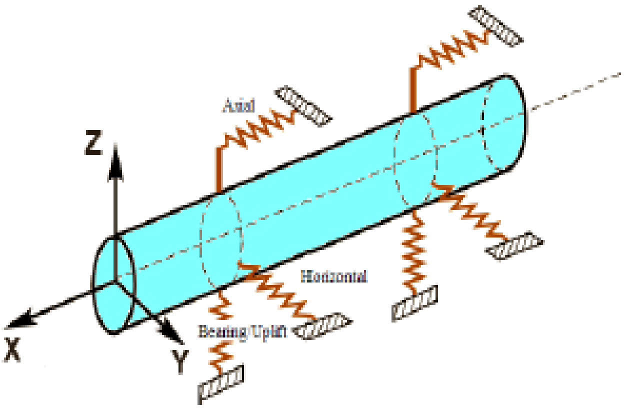
Challenges:

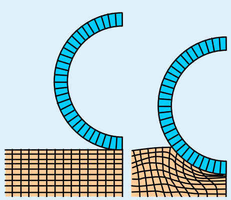
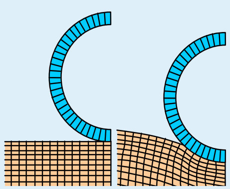
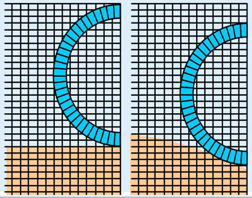
- Large Soil Deformations
  - Implicit and Explicit schemes
- Complex Soil Models
  - Constitutive modeling (Soil and Ice)
- Ice-Soil-Pipe Interaction
  - Contact mechanics



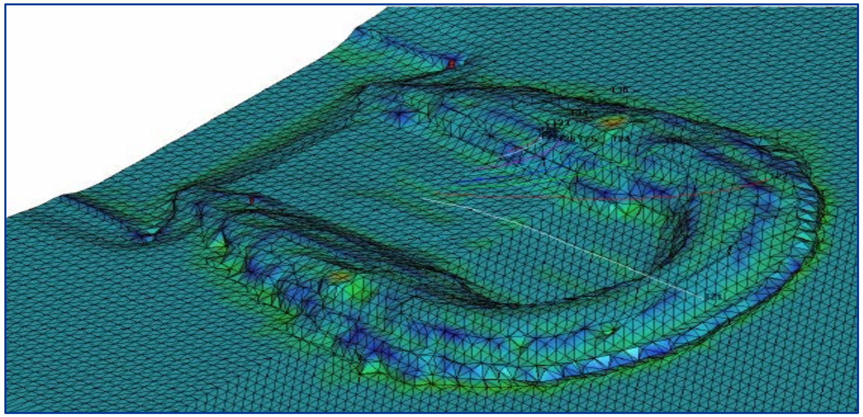
Numerical Modeling

- Structural Beam-Springs Models
- Continuum Models
  - Lagrangian
  - Arbitrary Lagrangian Eulerian (ALE)
  - Coupled Eulerian Lagrangian (CEL)
  - Smooth Particle Hydrodynamics (SPH)
  - Particle-In-Cell (PIC)



Lagrangian	Arbitrary Lagrangian Eulerian (ALE)	Coupled Eulerian Lagrangian (CEL)
Severe mesh distortion	**Remap to minimize distortion**	**No mesh distortion**
		

Review of Numerical Modeling



Typical Output from FE Model with 45° Ice Ridge (Konuk and Gracie, 2004a)

Literature Review

- Structural Approach
  - C–CORE (1995), Nixon et al. (1996)
  - Kenny et al. (2004)
  - Peek and Nobahar (2012)
- Continuum Approach
  - Lagrangian
    - Early Studies: C–CORE (1993 and 1995)
    - Nobahar et al. (2004)
  - Arbitrary Lagrangian–Eulerian
    - Kenny et al. (2007) , Konuk and Gracie (2004a), Konuk and Fredj (2004b), Fredj et al. (2008), Eskandari et al. (2010, 2011, 2012), Peek and Nobahar (2012)

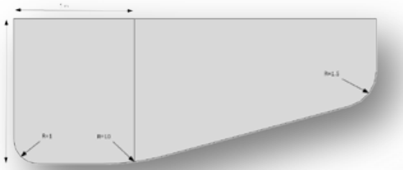
Review of Numerical Modeling

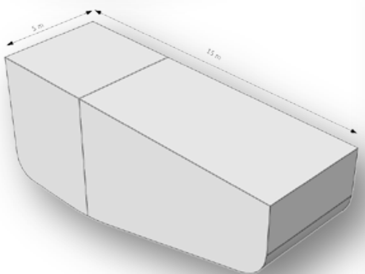
Literature Review

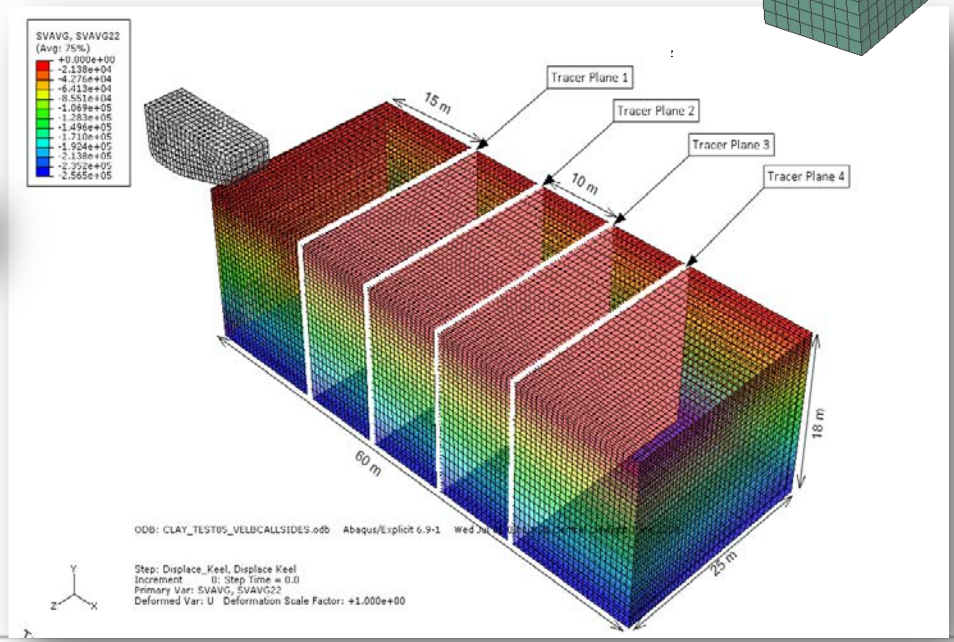
- Coupled Eulerian–Lagrangian
  - Konuk and Gracie (2004), Jukes et al. (2008), Abdalla et al. (2009), Phillips et al. (2010, 2011), Banneyake et al. (2011), Panico et al. (2012), Rossiter and Kenny (2012), Pike and Kenny (2012).etc

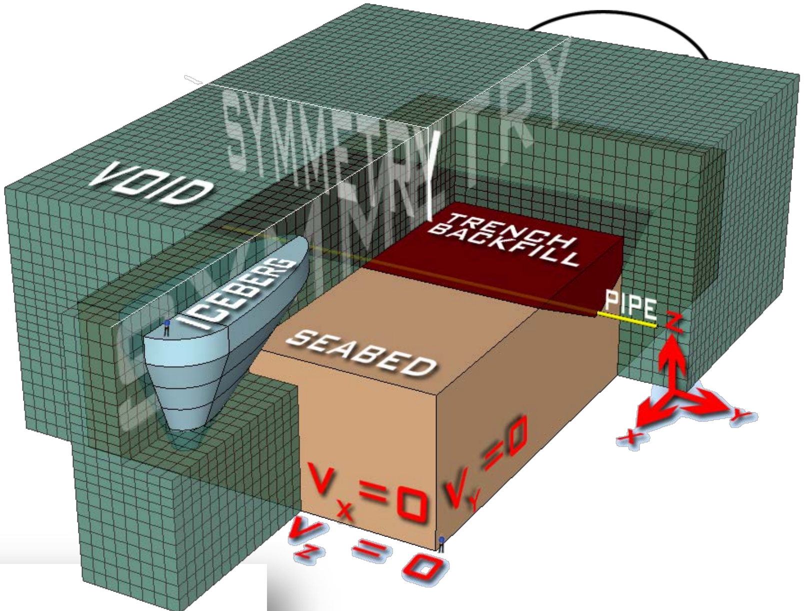
Numerical Modeling

CEL FE Model





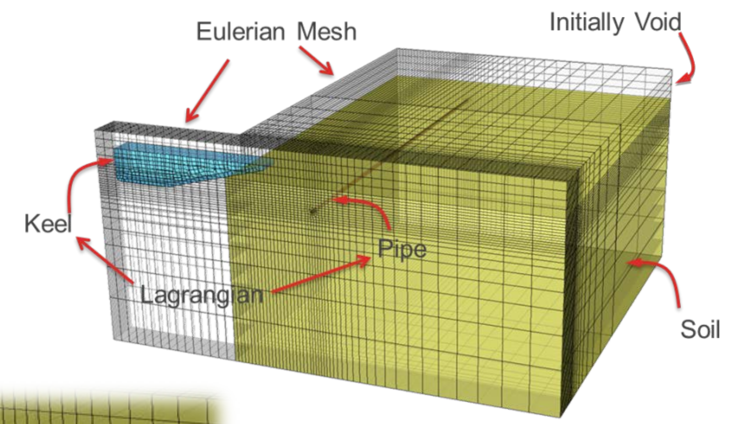


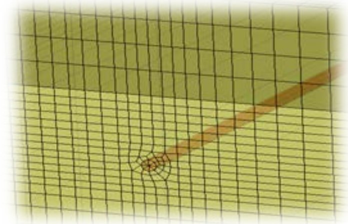


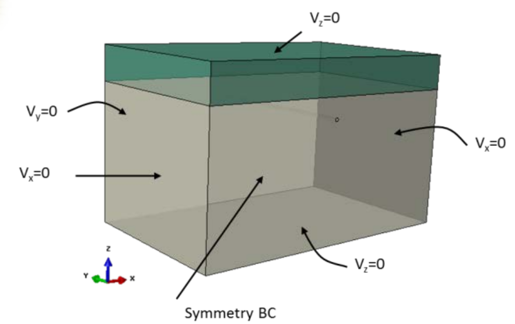
Numerical Modeling

Important practices for models:

- model sizing,
- mesh refinement,
- boundary conditions and
- constraints





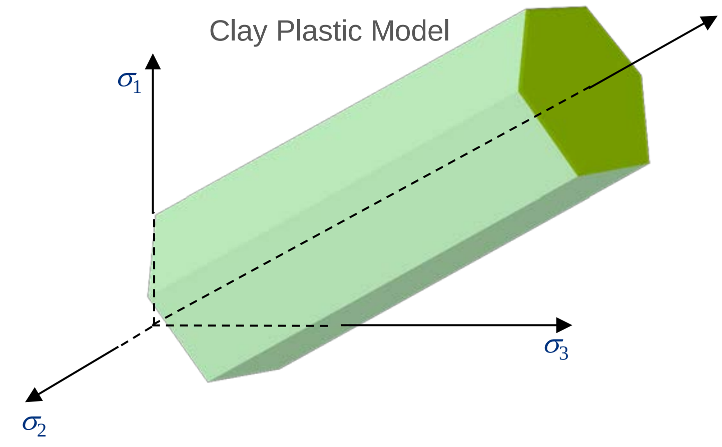


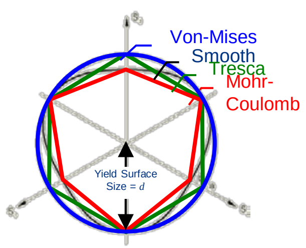
Constitutive Soil Models

Constitutive Models:

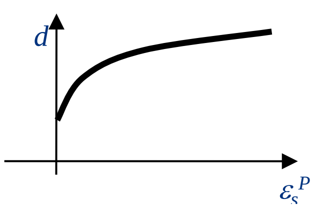
- Von Mises
- Tresca
- Cam Clay and Modified Cam Clay
- Mohr Coulomb
- Drucker-Prager
- Generalized CAP
- In-house models

Clay Plastic Model

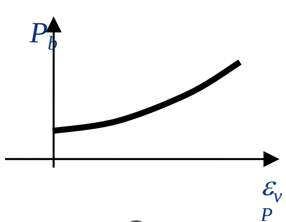




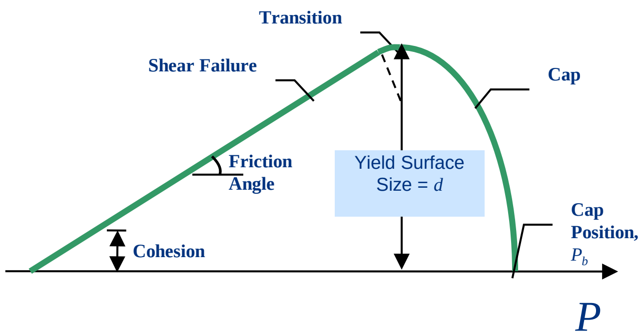
π-Plane



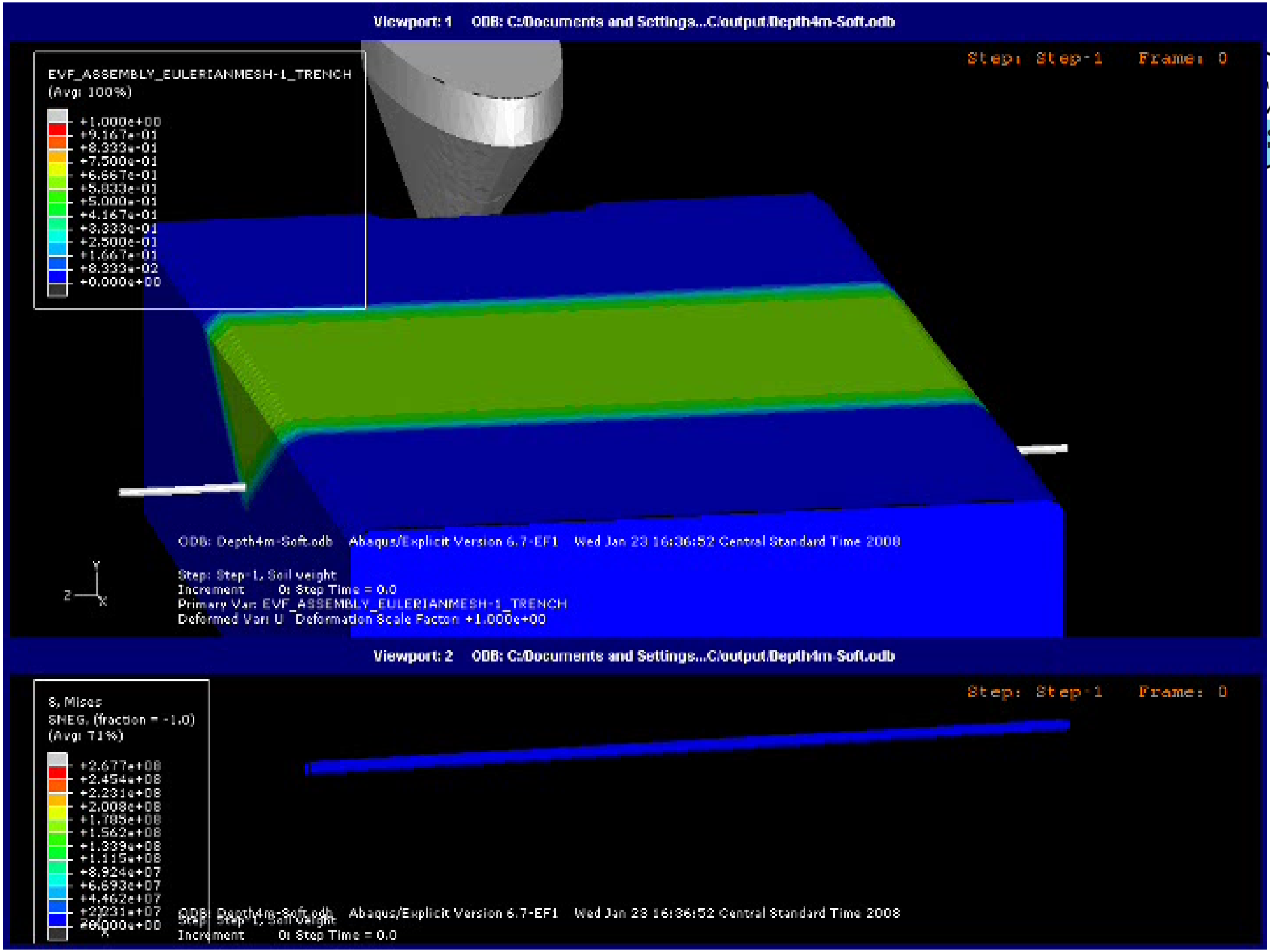
Strain Hardening of Yield Surface



Cap Hardening



Sand Drucker-Prager Cap Model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+1.000e+00
+9.167e-01
+8.333e-01
+7.500e-01
+6.667e-01
+5.833e-01
+5.000e-01
+4.167e-01
+3.333e-01
+2.500e-01
+1.667e-01
+8.333e-02
+0.000e+00
Step: Step-1 Frame: 0
ODB: Depth4m-Soft.odb Abaqus/Explicit Version 6.7-EF1 Wed Jan 23 16:36:52 Central Standard Time 2008
Step: Step-1, Soil weight
Increment 0: Step Time = 0.0
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Deformed Var: U Deformation Scale Factor: +1.000e+00
Viewport: 2 ODB: C:/Documents and Settings...C/output/Depth4m-Soft.odb
S, Mises
SNEG, (fraction = -1.0)
(Avg: 75%)
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+2.454e+08
+2.231e+08
+2.008e+08
+1.785e+08
+1.562e+08
+1.339e+08
+1.115e+08
+8.924e+07
+6.693e+07
+4.462e+07
+2.231e+07
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Step: Step-1 Frame: 0
ODB: Depth4m-Soft.odb Abaqus/Explicit Version 6.7-EF1 Wed Jan 23 16:36:52 Central Standard Time 2008
Step: Step-1, Soil weight
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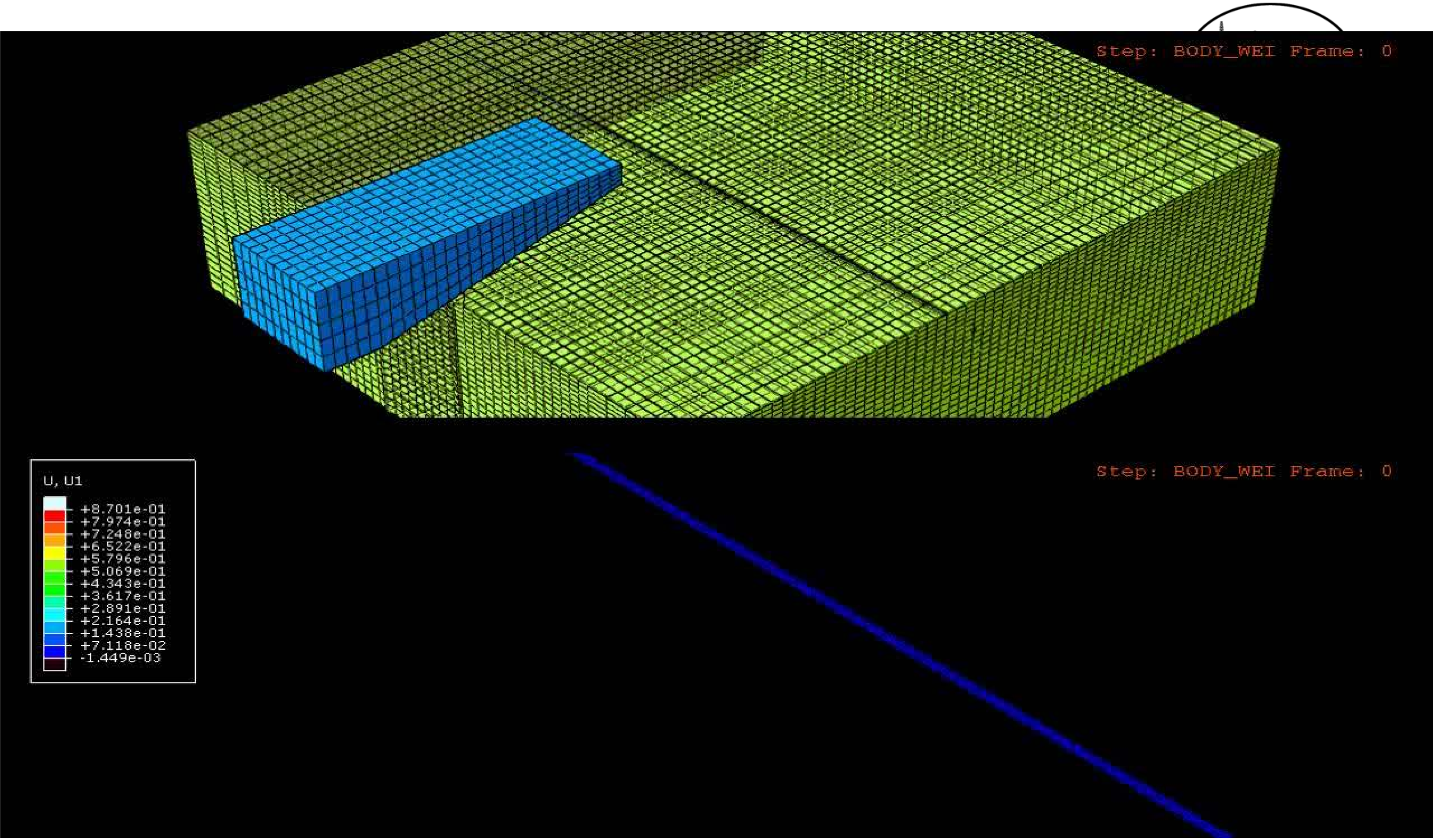
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Step: BODY_WEI Frame: 0
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+8.701e-01
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+7.248e-01
+6.522e-01
+5.796e-01
+5.069e-01
+4.343e-01
+3.617e-01
+2.891e-01
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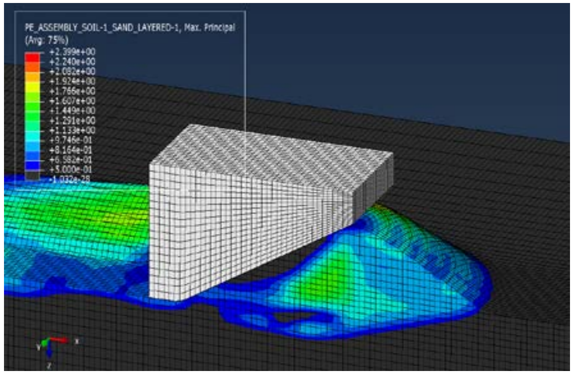
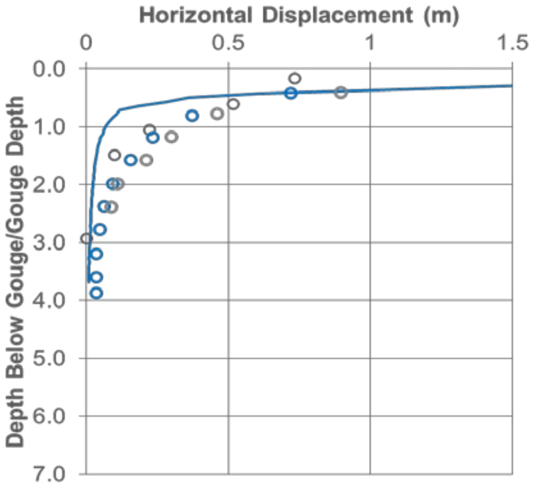
-1.449e-03

Model Validation

Application of advanced numerical modeling to simulate ice gouge events has been based mostly on partial calibration, over a narrow range of parameters



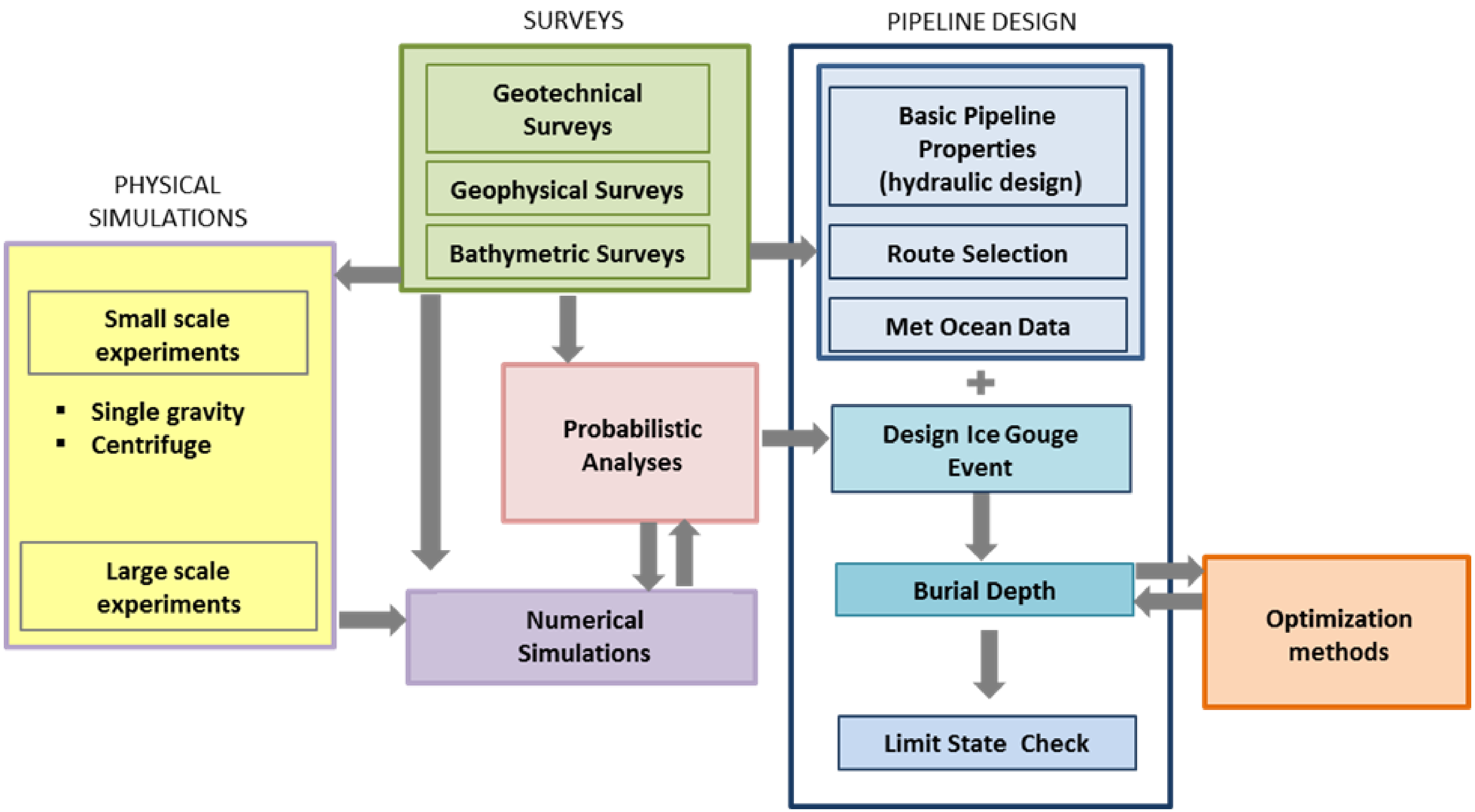
Comprehensive and systematic approach is required to assess the limitations of current physical models used to qualify numerical modeling procedures.



Gaps / Recommendation

- Reduce uncertainty in input parameters.
- Improve the numerical processes through advancements in software package capabilities. Advancements in the software package capabilities are required to incorporate:
  - Two–phase material within an effective stress analysis to account for the effects of pore pressure and associated volumetric changes caused by plastic shear strain (e.g., modified Cam–Clay plasticity model).
  - Improvements of constitutive models for ice and soil (e.g., effective stress analysis, nonlinear behavior, strain softening/hardening response) through calibration of the numerical procedures to physical experimental and laboratory testing data.
- Reduce uncertainty in output parameters through validation using large–scale data form field surveys or physical testing.
- Lack of numerical models that included the wellhead

Summary



SURVEYS
PIPELINE DESIGN
PHYSICAL SIMULATIONS
Geotechnical Surveys
Geophysical Surveys
Bathymetric Surveys
Basic Pipeline Properties (hydraulic design)
Route Selection
Met Ocean Data
Small scale experiments
Single gravity
Centrifuge
Large scale experiments
Probabilistic Analyses
Numerical Simulations
Design Ice Gouge Event
Burial Depth
Optimization methods
Limit State Check

THANK YOU

Safety & Assurance | Relationships | Social Responsibility | People | Innovation | Financial Responsibility | Integrity