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Development of experimental methods for ice-pipe-soil interactions

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ABSTRACT: Offshore developments in northern regions are faced with the unique issues presented by iceberg interactions with surface and subsea infrastructure. Surface laid subsea pipelines and cables are especially susceptible to Ice-Pipe-Soil interactions due to their vast layouts and the difficulty of deploying mitigation measures. Both physical and numerical modelling tools were developed to assess the risk presented by such interactions. Physical modelling techniques were developed for small, medium and large scale testing, each designed for parameter verification for numerical analysis. To facilitate the evaluation, the problem was subdivided as the Ice-Pipe and Pipe-Soil interactions. To assess the Ice-Pipe interaction a Rapid High Intensity Testing Apparatus (RHITA) was developed, inverting the problem and driving full scale pipes or cables over lab grown 'iceberg' keels. This apparatus measures ice failure loads and localized pipe pressures. The Pipe-Soil interaction is influenced predominately by the resistance of the soil to pipe penetration and was studied using a geotechnical centrifuge. A new centrifuge longbox capable of supporting tests on significant pipe lengths was developed. Using this new tool, a series of tests were developed to assess pipe strains and tensions during an ice pipe interaction. An additional series of high rate penetration centrifuge tests were conducted to measure the soil response. The data collected from this suite of tests contributed to the development and verification of numerical models, reassembling the various aspects of the Ice-Pipe-Soil interaction to assist with analysis and design.

1 INTRODUCTION

Energy developments on the Grand Banks offshore Newfoundland and Labrador must consider the occurrence of icebergs and the risk of ice contact with subsea infrastructure including rigid pipes, flexible flowlines and electrical cables. There is a limited understanding of actual ice-pipe-soil interactions and this has traditionally led to conservative approaches. Solutions such as subsea excavation, trenching, and breakaway solutions (i.e. weak-links) can be cost-prohibitive. Before improving these solutions, it is important to understand the nature of an interaction event in this region. Based on iceberg drift speed and keel size this is a rare event that would be typically less than 15 seconds in duration, and include the ice failing as the line is pulled laterally and pushed into the seabed until the keel passes over-top, Figure 1.

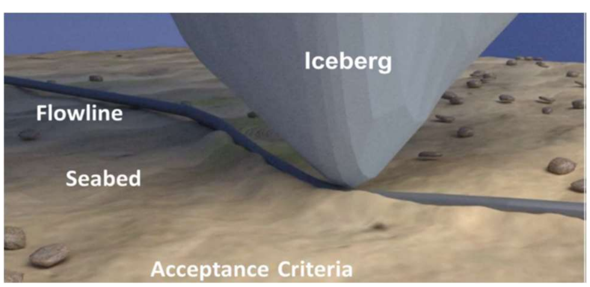

Figure 1. Expected flowline response on sand from impacts with free-floating icebergs

C-CORE has completed several programs, most recently the Subsea Ice Interaction Barriers to Energy Development (SIIBED) program, that includes tasks aimed to further develop, validate, and calibrate a numerical ice-pipe-soil interaction model. The primary SIIBED objectives included an increase in understanding the ice pressures developed, the soil resistance, the distance pulled, and the end tensions and corresponding pipe strains developed, to improve a Ice-Pipe-Soil interaction numerical model. This paper outlines the unique equipment and testing developed to achieve these goals.

2 BACKGROUND

2.1 Ice pipe seabed modelling

The development of an iceberg interaction Finite Element (FE) model is core to further understand load transfer from the ice to the subsea infrastructure. Pike and Blundon, (2018) described one such model with application to rigid steel pipes. Such a model has also been used in risk analysis for pipelines and cables on the Grand Banks (King, 2019). Bailey and Phillips (2018) presented preliminary physical tests relevant to the scenario of a free-floating iceberg interacting with a pipe laid on the seabed, Figure 2, which led to the Energy Research and Innovation Newfoundland and

Labrador (ERI-NL) project Alternatives to Flowline Trenching (AFT) studying the interaction, (C-CORE 2020).

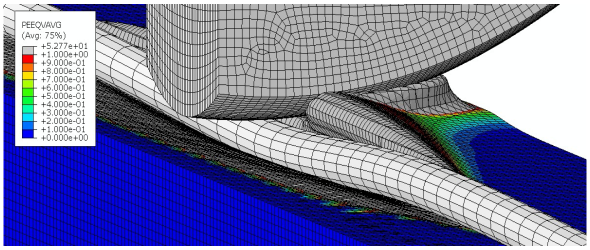

Figure 2. Finite element model of keel interaction with cable on seabed (C-CORE, 2020).

One of the objectives of both AFT and SIIBED was to incorporate the outcomes of laboratory and physical testing in order to develop, calibrate and validate a design tool for assessing risk to subsea infrastructure due to ice keel interactions with rigid pipes, flexible flowlines and electrical cables.

A numerical modelling procedure was developed using the FE analysis software Abaqus, where the large deformation process of ice-pipe-soil interaction can be accommodated using the Coupled Eulerian-Lagrangian (CEL) technique (Barrett *et al*. 2023). The complexity of the ice-pipe-soil interaction is captured by varied contact strategies in different areas of the model. Model advancements include incorporation of soil behaviour measured from the physical testing and flexible flowline mechanical response. Emphasis was placed on optimizing computational efficiency of the analysis.

To obtain the data required to improve this model and provide appropriate inputs, physical testing was required. Given the complexity of the project the most effective method to collect each of the inputs was through independant experiments aimed to address each data shortcoming. This testing included three key areas, ice pipe interaction, free floating ice-pipe soil interaction and undrained soil response modelling.

A Rapid High Intensity Testing Apparatus (RHITA) was designed and commissioned to better understand the forces developed when ice interacts with subsea infrastructure and to better determine ice crushing criteria, allowing for a more realistic simulation of the interaction process.

A centrifuge longbox was developed to test the response of long sections of surface laid flowlines when interacting with a free floating iceberg. Additional centrifuge testing equipment was developed to study the potential rate effects and undrained soil behaviour resisting pipe penetration.

2.1.1 Centrifuge modelling

Centrifuge modelling offers a reliable, time-efficient, and cost-effective approach for studying complex geotechnical problems. By reproducing realistic stress conditions at a small scale, this technique provides physical data on soil behaviour and soil-structure interactions.

All centrifuge modelling conducted to support this test development program was completed using C-CORE's geotechnical centrifuge facility. C-CORE operates a 5.5m radius beam centrifuge, Figure 3, capable of subjecting payloads to gravitational forces ranging from 10g to 200g, with a maximum rotational speed of 189 rpm. The system can accommodate 2200kg to 100g or 650kg to 200g.

Figure 3. C-CORE 5.5m geotechnical centrifuge.

3 TEST DEVELOPMENT

3.1 Ice failure testing - RHITA

The development detailed below is the most recent in a series of testing mechanisms designed and manufactured with the purpose of increasing the understanding of ice mechanics and potential loads developed during an ice structure interaction. RHITA was developed specifically to simulate at full scale (or near full scale) the loads imparted and responses generated when a free-floating iceberg keel, moving at representative speeds, contacts a pipe, flowline or cable laid on the seabed. This apparatus has provided valuable data for input and calibration of the numerical models of the ice, structure and soil interaction problem. Given that ice reaction forces are dependent on interaction speed the significant advancement that RHITA has made to this research is the provision of data at realistic iceberg speeds. RHITA has been designed, constructed and subsequently used to conduct interaction tests between a large 3.5 metric ton ice sample and various impactor geometries and sample line types.

Given the uniqueness of the test equipment needed to simulate the iceberg interaction with subsea infrastructure the design of RHITA was undertaken internally by C-CORE staff. Design considerations for RHITA included the desired test configurations (various flowline and cable diameters and wall thicknesses), adaptability for future testing, clear access for recording visual results, ice sample dimensions, apparatus loading magnitudes and the geometry of the space available in the facility to house the machine. Also considered was the technical difficulty of incorporating the design, supply and operation of large force capacity actuators and large volume and flow rate accumulators. C-CORE's cold room was too small to contain the machine, so the ice sample is produced in the cold room and moved onto the machine located in the main lab facility. An ice sample size of 2.5m x 1.5m x 1.0m (Length x Width x Height) allows for manufacturability, while also resulting in a reasonable ice interaction area with the indenters (pipe/cable/flowline). In the field the ice moves and interacts with the stationary seabed infrastructure below it. To allow the equipment design to be practically achieved, the problem was inverted and reversed for RHITA. The heavy ice block is held stationary to the machine's base while the lighter indenter is moved from above at the typical iceberg speeds to achieve the interaction. The RHITA machine consists of six primary elements, the self-reacting frame, the hydraulic and control system, the track and roller system, the carriage, the indenter and the ice mold. The concept schematic of RHITA is shown in Figure 4 with the completed apparatus seen in Figure 5.

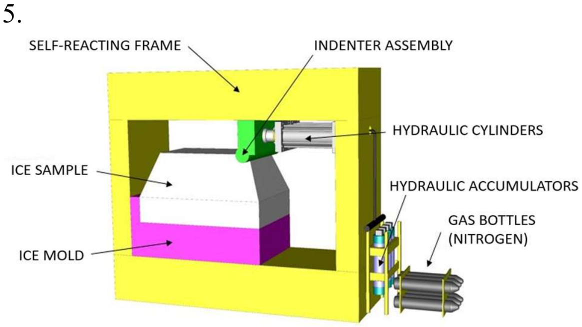

Figure 4. Concept of Rapid High Impact Test Apparatus.

Figure 5. Completed RHITA Frame.

The apparatus frame is a self-reacting and mechanically rigid assembly of steel beams, columns and plates. To allow for manufacturability, transportation and assembly in the facility the multiple structural parts were welded and/or machined off site and assembled through bolted joints. All design and finite element analysis (FEA) was carried out by C-CORE, with fabrication services needed from multiple machine shops and welding facilities. Maximum design loads were selected to be 2MN horizontally and 4MN vertically. A dynamic load factor of two was selected to give reserve structural capacity in the frame, and served to minimize deflections in critical welded assemblies. Throughout the design process FEA was used to verify calculations for stress magnitudes and member deflections.

Design of the hydraulic and control systems was carried out by two external contractors specializing in these fields. Final assembly, hydraulic tuning and testing was completed by C-CORE personnel and external contractors. Actuation of the indenter is accomplished with a hydraulic system that powers two hydraulic rams, each with a piston diameter of 7" and a stroke of 2m. The required flow rates were too large to use a hydraulic pump with given facility constraints. The design resulted in the use of an accumulator bank and nitrogen gas bottles to create the required flow through a pair of servo valves giving a maximum test velocity of 0.5m/s. The hydraulic rams are pinned to the test carriage which they guide along the carriage rails that are incorporated into the top beams. Photographs from the commissioning test with a rigid semicircular indenter are shown in Figure 6.

The carriage rails consist of tracks and rollers that carry the vertical and moment loads during the ice structure interaction. A set of rollers contact both sides of the carriage rail and transfer loads into the main beam. Rollers are designed to absorb yaw movements of the carriage. The test carriage was designed as an arrangement of steel plates housing the load cells and interfacing with the track plates while carrying the test indenter. Two instrumentation assemblies mounted in the interior of the carriage each contain two vertical and one horizontal load cell, with capacities of 200,000lbs each. Each load cell has a clevis attached to allow connection to a link via 3" diameter pins. The pins decouple any moments generated from the load cells.

The indenter assembly can be configured with a variety of circular and semicircular indenters. Rigid indenters, pipeline and flexible segments and a model ship hull have been among the indenters tested, Figure 7. Indenters can be equipped with tactile pressure sensors to measure ice crushing pressures during testing.

Figure 6. RHITA commissioning test.

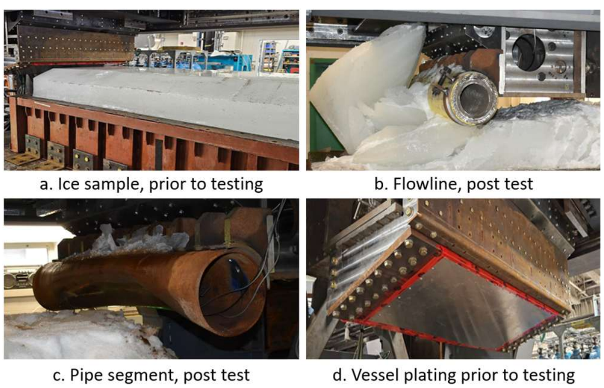

Figure 7. RHITA test configurations.

Two molds were designed and constructed for creating ice samples for testing, Figure 8. The ice sample and ice mold have a combined mass of 5000kg. Ice is grown over a two week period by layering a mixture of crushed ice and water in a manner that best approximates iceberg ice properties. These methods of growing ice had been developed through multiple previous ice strength studies. The top half of the mold is removed prior to testing to expose 0.5m of ice for interaction with an indenter. For testing, the mold is loaded onto the machine's table and secured through a series of mounting brackets.

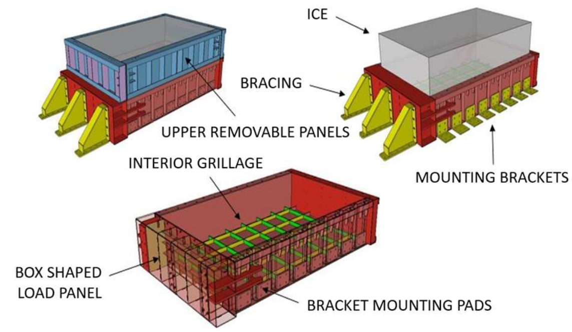

Figure 8. RHITA ice mold design.

More than 25 tests have been completed over the first two years of the system operation. Test variables include the test structure type and geometry, ice block temperature and geometry and the interaction speed. Ice blocks with rectangular and sloping contact faces have been tested. In addition to the rigid indenters, tests were also conducted with pipe samples of varying wall thicknesses, flexible flowline samples and electrical cables. Following initial testing with subsea structures, tests have been completed using a segment of a vessel hull as the indenter. Typical time series of horizontal, vertical and resultant loads are shown in Figure 9. The global loads, measured using load cells and loads calculated using pressure data from the tactile pressure sensors have shown good agreement. In addition to force, pressure and displacement measurements, videos of each test have been captured. After each test the ice samples are removed from RHITA and cut with a chainsaw mill to discern details of the crack patterns within the remnants of the ice block.

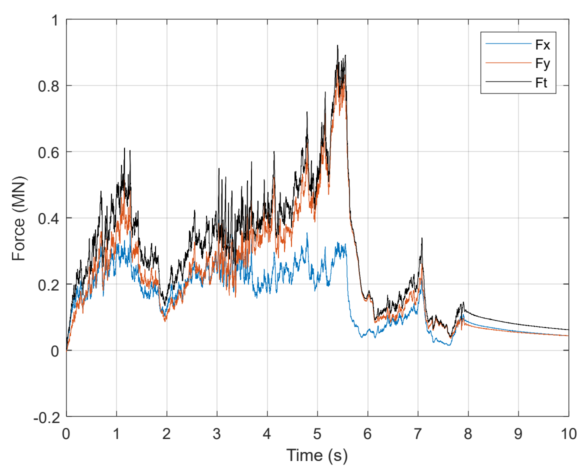

Figure 9. Typical RHITA load trace.

The results of RHITA testing have been used to calculate first-order estimates of keel ice pressures on a pipe or cable. These values allow for the incorporation of ice failure limits into the ice-pipe-soil numerical model and limits the compressive forces generated on the line and therefore also limits the ability of the ice to drag the line once those pressures are exceeded. Conducting the design and fabrication effort of this test apparatus also resulted in more advanced design and manufacturing methods that are proving useful for other large scale mechanical testing facilities, such as Memorial University's Faculty of Engineering Harsh Environment Research Facility (HERF), scheduled for completion in 2026.

3.2 Pipe soil testing - centrifuge longbox

Physical test data was needed to verify and calibrate the FE models for the response of a surface laid flowline or cable when interacting with a free floating iceberg. Beyond understanding the potential risk and results of an iceberg-pipeline interaction on the pipe itself, protecting the assets at the pipeline tiebacks is of utmost importance. As an iceberg keel passes over a pipe or cable, some horizontal translation is expected, and will increase as the seabed soil resistance increases. This translation creates pipe strains and develops tensions within the line, potentially reacting at a tieback point. Understanding the behaviour of the pipe during this interaction will allow for predicting the magnitudes of the tensions developed at these tiebacks due to an ice interaction. Early predictive finite element analysis of this interaction by C-CORE (2017) and Pike and Blundon (2018) suggest that a significant and often prohibitive influence zone length is required to simulate the appropriate pipeline displacement behaviour and end conditions of this interaction.

To accommodate an evaluation of these models C-CORE began developing lab scale physical models. These models consisted of various wooden longboxes, up to 12m in length, which could accommodate dry granular soils.

This initial lab scale testing utilized a flexible hydraulic hose, of known properties, laid on or embedded in a compacted coarse sand surface and displaced laterally by a scaled rigid keel. While these results provided value, they were not without limitations. As initial tensions and lateral displacements both increased, the behaviour of the model became heavily influenced by the end conditions and would no longer be representative of the true interaction length.

To begin addressing the limitations of the lab scale physical modelling, centrifuge modelling was investigated as a potential solution. This modelling method could scale the problem further by increasing the g-level at which the interaction was tested, therefore representing a much longer interaction zone in a smaller physical space. While C-CORE's geotechnical centrifuge is one of the larger centrifuges available, the length available in the basket to accommodate a model pipe was still inadequate. To counteract this limitation C-CORE drew on past experience. A 3m by 0.2m model test box was previously developed at C-CORE for the modelling of catenary risers, with the box extending beyond both edges of the centrifuge test basket. While this original longbox was useful for modelling a significant interaction length, it was not appropriate for modelling the lateral displacements required to represent an iceberg keel passing atop a pipeline or equivalent.

To execute these tests C-CORE designed, manufactured and commissioned a new wide and long strong box, measuring 360mm in height, 1140mm in width and 3030mm long, Figure 10. Large I-beams run the length of the box and overhang the centrifuge basket, providing support and sufficient stiffness to the box to avoid model disturbances up to above 80g. A large beam structure spans the center of the box and carries the rails that the model ice keel is supported on during the interaction. As the ice is considered rigid for this experiment the ice keel is modelled as an ellipsoid constructed from machined modelling block and later machined aluminum plates with a roughened surface finish. Smaller beams cross the top of the box along its length, adding to the wall stiffness and also carrying cameras and lights. Structural calculations and finite element modelling were used as part of the design process to produce a stiff and lightweight box that can be used for these tests but is also versatile for future testing programs.

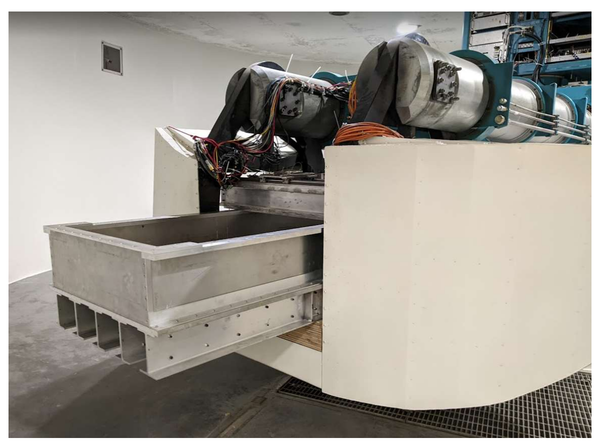

Figure 10. Centrifuge longbox aboard the test basket.

Even with an extended box length axial pipe movements can extend beyond the ends of the box. To mimic pipe axial feed-in and accommodate pipe lateral displacements axial springs were placed at either end of the pipe section, in a similar manner used for steel catenary riser modelling by Elliott et al. (2013). Preliminary FEA was undertaken to assist in the design of the springs.

Prior to centrfuge operation a light-weight cover is added over the long box to prevent sand erosion from the over 200km/hr wind speeds acting in the centrifuge chamber at the box location.

Development areas on the Grand Banks typically contain dense to very dense sand. Both the centrifuge testing and numerical models described below used dense sand for the soil models. Shaw 00 uniform fine silica sand was used and with a mean particle size of 0.2mm it does not introduce significant particle size effects into the centrifuge modelling. The longbox model sand beds were dry and not saturated.

Two pipe models were tested in the initial program, one modelling a rigid pipe and a second a flexible flow line. The model rigid pipe was manufactured from a 6mm diameter stainless steel tube. With a centrifuge acceleration level of 54g the model pipe simulated a 324mm diameter pipe, 140m long.

To model the flexible pipe several options were considered. The final design called for the use of a RG-11 coaxial cable with the outer jacket and braided shield removed while the copper core remained well bonded to the dielectric. Once strain gauged and heat shrunk the cable had an outside dimeter of 7.9mm and was tested using a centrifuge acceleration level of 54.7g. The flexible‘s prototype dimensions were 430mm diameter and 150m long. Experimental methods were developed using collars, pullies and suspended weights to measure both axial stiffness and bending stiffness for the cable.

The installation and commissioning of a Micron Optics HYPERION si155 fibreoptic interrogator, manufactured by Luna, onto the C-CORE centrifuge was part of this project. The interrogator was mounted at the center of rotation of the machine inside the spinning electrical cabinet. An onboard computer collects data from the interrogator. Permanent and ruggedized fibre lines extend the length of the centrifuge arm to bulkhead points in the centrifuge basket. Each of the models described above are instrumented with 2 DTG inside low bend loss 125µm fibre optic strain gauges. The fibres used for this program were custom sensor arrays with a total of 27 strain measurement points per fibre.

Six GoPro cameras were mounted on the cross beams of the box capturing video and images of the pipe movement during the keel pipe interaction, with the scaled reference targets and markings along the pipe length track lateral displacement throughout the interaction.

The resulting measured strains, end tensions, and displacement profiles of longbox testing have been used to validate pipe-soil numerical models for tension development and pipe displacement behaviour during contact scenarios.

3.3 Pipe soil testing - rapid inclined loading

The pipe-soil interaction proved challenging to capture an analysis of all the parameters and behaviours necessary with a single test setup. Therefore, this interaction was further subdivided, specifically to appropriately analyse the more localized impacts of high speed interactions.

To assess the response of the soil to being impacted at high rates by a pipe, it was choosen to remove the deformation and long influence zone of the pipe and introduce pore pressure effects. This was achieved by performing a rigid penetration test into a saturated dense sand model.

Physical testing was conducted as a series of nine centrifuge tests at 16.2g, with a model rigid pipe 20mm in diameter (324mm in prototype) using saturated dense silica sand. Previous C-CORE testing and FE models provided insight as to an expected pipe penetration angle, and this was kept constant.

The target of test develop was produce a setup which could model drained, partially drained and undrained soil response conditions by varying the interaction speed to correlate its effect on soil resistance. Saturated sand is known to exhibit very different shear behaviours under increasing loading rates. When dense sand is forced into slow shear failure a volume change, known as dilatancy occurs as particles realign and pass over one another. As the loading rate increases, this dilatancy is suppressed by increasing suctions (negative pore pressures) as the soil deformation occurs.

Technically challenging to the development of this test was developing a pipe actuator capable of approaching undrained conditions. Needing to assess the interaction under sufficient water depths as to not influence the pore pressure response, while also reaching average iceberg drift speeds of 0.3m/s.

An existing strongbox was selected with a viewing window on either side to observe the sand failure mechanism development. The test vessel was capable of withstanding a back pressure. The application of back pressure simulates a larger pressure head, simulating a larger column of water above the soil, in this case approximately 50m, versus 7m without the back pressure.

A single cylinder hydraulic actuator provided rigid support and motion control for the model pipe, with a custom load cell set, consisting of 3 uniaxial load cells to provide feedback of the soil resistance, Figure 11.

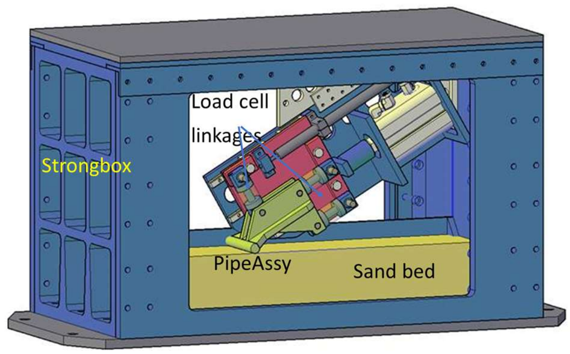

Figure 11. Rapid inclined load test apparatus.

To assist in achieving the desired penetration rates the dense sand was saturated using a 60cSt viscous pore fluid allowing for scaled impact speeds. The rigid pipe was then displaced one pipe diameter into the model seabed at a constant rate.

Loads, displacements, pressures and temperatures were recorded for each centrifuge test. High speed video was also used to capture the pipe–soil interaction and allow for a thorough review of the failure mechanisms.

A rotational type of soil failure initiated under the pipe in the direction of movement and further developed towards the adjacent soil surface with a passive failure mechanism. The pipe penetration was accommodated by the development of a large berm of sand above the passive failure mechanism, Figure 12.

Figure 12. Post test of rapid inclined loading.

The horizontal and vertical resistances profiles have similar trends and the measured resistance increases significantly with penetration rate but is somewhat independent of back pressure, Figure 13.

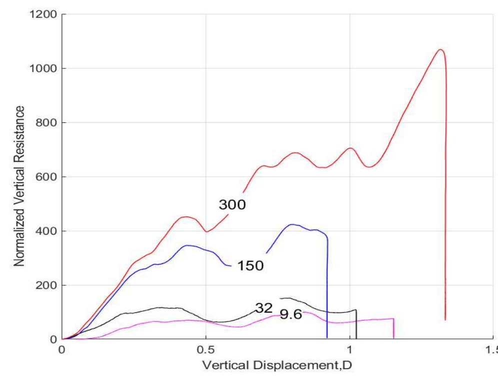

Figure 13. Pipe penetration soil resistances at varied loading rates.

Dense sand behaviour hasan important role in ice-pipe–soil interaction events. Rate effects measured at 300 mm/s, equivalent to the observed mean iceberg drift speed at the Grand Banks, show a vertical soil resistance increase of at least an order magnitude greater than drained sand response of slower interactions.

These results are important to the numerical modelling analysis as a soft soil response would allow the pipe to penetrate with little resistance and small horizontal translations. Where as a stiff soil response would force the pipe to endure the ice interaction bearing pressures and potential tensions from larger translations along the seabed.

4 FINITE ELEMENT MODELLING

4.1 Global ice interaction analysis

Throughout the development of the equipment highlighted here, the ultimate goal was to provide confidence in the parameters utilized and subsequent results of a global numerical model analysing the ice-pipe-soil interaction.

The numerical modelling approach was developed in Abaqus using the Coupled Eulerian Lagrangian method, which is able to simulate the large deformations resulting from the ice–pipe–soil interaction, Figure 14. The complexity of the interaction is broken into components and informed by the physical testing results. Ice failure limits with respect to rate effects in the ice were adopted from RHITA testing. Undrained soil resistance was incorporated with consideration to the rapid inclined loading penetration tests.

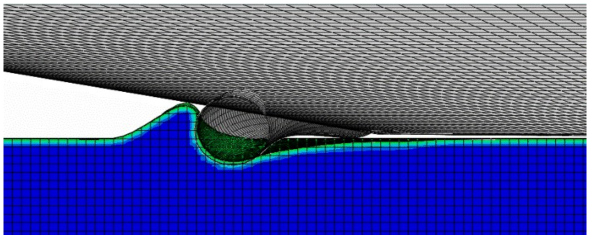

Figure 14. Local soil and ice penetration.

Integrating undrained behaviour into the global numerical analysis results in an increase in overall displacement and stress of the pipeline or cable. Introducing failure limits for the ice, moderates this displacement and increases the likelihood of the pipe or cable will remain undamaged as result of interaction.

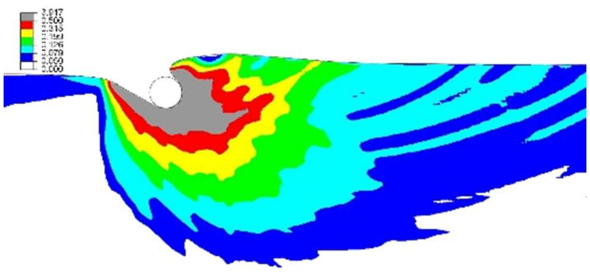

Figure 15. Numerical modelling of inclined penetration.

5 CONCLUSIONS

While introduced as Grand Banks focused, this study crosses many application areas including subsea marginal fields, renewable energy, gas development as well as contacts with subsea infrastructure from fishing activity. Vital to such engineering applications is the development, validation and verification of numerical FE models that allow for a comprehensive analysis of ice to pipe/flowline/cable to seabed interactions. The verification process includes laboratory testing of both ice keel failure and ice/pipe/soil interaction. The specialized tools and methods developed and detailed in this paper, will continue to be advanced and utilized to complete additional improvements to the understanding of the problem and finding reductions in both project risk and project conservatism.

Future plans include building the database of ice tests with RHITA to increase measurement certainty, expanding the undrained tests by reducing to smaller interaction angles and expanding the use of the long box to include ice gouge testing.

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