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PRELIMINARY ANALYSIS OF ICE INTERACTION WITH SUBSEA INFRASTRUCTURE AND THE SEABED

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ABSTRACT
The contact of ice keel features directly with subsea infrastructure or indirectly by ice has the potential to cause damage or failure of these systems. Over the past 30 years, significant experience in the field of ice/structure interaction events has provided insight on a number of technical issues including the significance of contact area and aspect ratio, among other parameters, on the spatial distribution and amplitude variation in ice loads and contact pressures. Greater uncertainty exists on the contact mechanics, load transfer, and failure mechanisms during the interaction of an ice feature with subsea infrastructure through the seabed. These events are complex, nonlinear problems associated with large deformations, plastic material behaviour and contact mechanics. In this study, concepts for ice interaction with a rigid structure at the waterline are extended to numerical simulations, using the finite element software program ABAQUS, on investigations on ice keel interaction with subsea infrastructure and seabed materials with defined compliance. Results from this numerical modelling study are presented where the effects of ice compliance, strength properties and geometries on both rigid and compliant surfaces are examined.

KEYWORDS: Ice structure interaction; pressure area curve; high pressure zones

BACKGROUND
Recent studies have estimated the undiscovered conventional resource potential of Arctic waters to contain 10% oil and 25% gas of the world's reserves (Kenny et al., 2007a; Pike et al., 2011b). Coupled with current energy demand there has been renewed interest in the exploration and field development of offshore hydrocarbon basins in arctic and ice covered waters of the northern hemisphere. The exploration and development of oil and gas reservoirs in these environments present technical and logistical challenges for the engineering design, construction and operation of surface infrastructure and subsea facilities. These challenges may impact cost, technical or commercial viability, and project execution.

One of the key issues is the presence of ice features that may have sufficient draft to interact with the seabed. Under environmental driving forces, the ice keel may penetrate into the seabed and create gouges that can be meters deep, tens of meters wide and hundreds of meters long. Ice keel/seabed reaction forces, however, can be an order of magnitude greater than other pipeline loading events such as anchor dragging and pullover (Kenny et al., 2007a, b; Palmer et al., 1990). From this perspective, for subsea infrastructure such as pipelines and wellheads positioned above or buried beneath the mudline, then ice gouging and ice keel contact events have the potential to cause damage or failure of these systems.

OBSERVATIONS ON ICE/STRUCTURE INTERACTION

Determining realistic design loads for ice interaction with structures is a complex process that may involve crushing, spalling, extrusion, and generation of localized high-pressure zones, Figure 1 (Jordaan, 2001; Jordaan et al., 2006). Experience has shown that small-scale laboratory tests; such as triaxial compression tests (Kenny, 1992), can overestimate the global ice compressive strength by a factor of 10, with respect to interaction scenarios of practical interest for offshore hydrocarbon production structures. The small-scale laboratory and indentation tests do not adequately account for the ice mechanics and failure processes associated with ice/structure interaction events and the general relationship between global indentation pressure, contact area and aspect ratio (Jefferies and Wright, 1988; Jordaan et al., 2006, 2010; Masterson et al., 2007; Palmer et al., 2009; Sanderson, 1988). Masterson pressure-area relationship curve is shown in Figure 2.

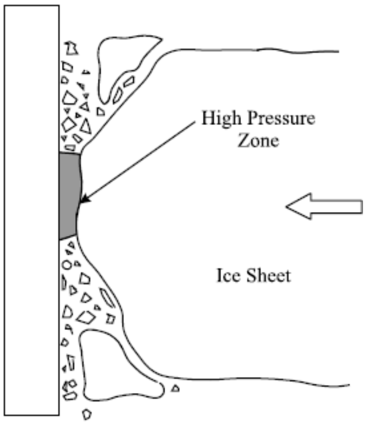

Figure 1. Main processes of spalling, extrusion and high-pressure zone formation (Jordaan, 2001)

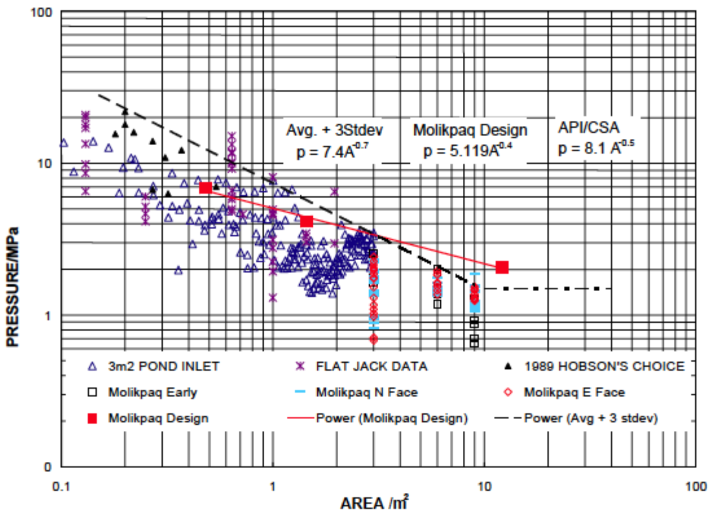

Figure 2. Indentation Pressure Area Relationship (Masterson et al., 2007)

In an effort to better understand this scale effect on global and peak local pressures during ice/structure interaction events, a series of medium-scale indentation tests (e.g. Frederking et al., 1990; Johnson and Benoit, 1987; Kennedy et al., 1994; Meaney et al., 1996) and full-scale experiments (e.g. Danielewitcz and Blanchet, 1987) were conducted. These studies provided significant insight for the improved understanding of more realistic design load estimates for ice interaction of with offshore structures.

From this knowledge base, engineering models characterizing the constitutive behaviour of ice have evolved from early approaches that treated the ice as an elastic-plastic solid, which was incorrect due to the scale effect (e.g. Jordaan et al., 2009, 2010; Palmer et al., 2009). These engineering models treated the structure as a rigid indenter and ice as a compliant material where the effects of viscoplasticity, creep, damage, fracture and spalling and extrusion were simulated (e.g. Jordaan and Xiao, 1992; Jordaan et al., 2006, 2009, 2010; Kennedy et al., 1994; Kenny, 1992; Palmer et al., 2009; Taylor, 2010; Xiao, 1997).

Recent numerical and physical modelling studies have examined the interaction of ice keels with subsea infrastructure (e.g. Barrett et al., 2012; Drover and Kenny, 2012, b; Serré, 2009a, b) and the seabed (e.g. Phillips et al., 2010; Pike and Kenny, 2012; Pike et al., 2011a, b). These investigations have examined compliant subsea structures with simplifications on the ice constitutive model, or a rigid ice keel with compliant seabed soils. This study examines the significance of the ice keel/structure interface where the effects of relative compliance and strength properties between the two bodies, and the contact surface roughness are examined.

ICE INTERACTION EVENTS WITH COMPLIANT BODIES

ABAQUS Standard is capable of modelling simple contact problems; more complex contact problems require repetitive calculations due to the implicit iterative solution method in ABAQUS Standard. In this study, a finite element model was developed using ABAQUS Standard to simulate the initial interaction of an ice feature with subsea infrastructure and the seabed. ABAQUS Coupled Eulerian-Lagrangian (CEL) models are currently under development to extend the interaction scenario. Eulerian analyses are effective to use in applications involving extreme deformation. Traditional Lagrangian elements modelling extreme deformation can become highly distorted and thus lose their accuracy. Coupled Eulerian-Lagrangian contact allows the Eulerian materials to be combined with traditional nonlinear Lagrangian analyses (ABAQUS 6.12, 2012).The CEL method is used to conduct a relative comparison on the effects of macro-roughness and compliance due to its ability to accurately model the soil deformation around the ice feature. The ice feature dimensions were modelled based on one of the indenters used in the Hobson's Choice Ice Island Experiment (Frederking, 1990). The ice, soil and steel properties used in the analysis are as shown in Table 1. The ice properties selected represent lower bound strengths, see for example Figure 2, for the interaction events examined in this study. The steel material behaviour was modelled as rigid surface that has infinite stiffness and zero deformation. The soil properties are typical of firm clay. Utilizing information from the medium scale ice indentation experiment provided a basis to calibrate the model.

Table 1. ABAQUS Model Material Properties

Analysis Case	Ice				Soil		
	Elastic Modulus (MPa)	Yield Strength (MPa)	Poisson's Ratio	Yield Strength (MPa)	Elastic Modulus (MPa)	Yield Strength (MPa)	Poisson's Ratio
Elastoplastic Ice/Steel	9000	1.5	0.3	∞	-	-	-
Elastoplastic Ice/ Elastoplastic Soil	9000	1.5	0.3	-	10	0.1	0.499

Ice during an impact may be indented by a waterline structure around a metre (Stuckey, 2008). Ice scours may continue over hundreds of metres. The ice was modelled using four different indenter surfaces: flat; wavelength 1.5, 3 and 5; and displaced 0.015m to simulate only initial indentation with the soil or steel. Figure 3 depicts the ice indenter. The indenter surface with various wavelengths was also modelled with two different amplitudes of 5 mm and 10mm.

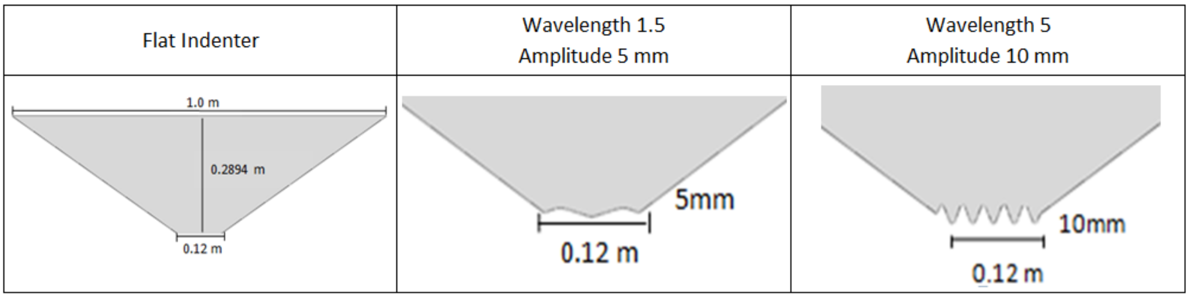

Figure 3. Schematic of Ice Indenter

It is well known that the ice will fail prior to the steel; however, in the case of ice interacting with soil the effect of a coarse and fine wavelength in the indenter and the resulting stress distribution and failure of the ice and soil was assessed. The purpose of varying the frequency and amplitude on the indenter surface was to introduce intermittent contact to determine the impact of varying the local contact area within the same global contact area as the flat indenter. The influence of the initial contact surface was determined by comparing the results of ice interacting with steel and ice interacting with soil.

In general, the findings of this preliminary analysis indicate both the soil and the intermittent contact reduce the load. To date several studies have investigated the relationship between contact area, bearing pressure and load (Jordaan et al., 2006, 2009, 2010, Palmer et al. 2009, Palmer, 1991). It is observed that the contact area between the ice keel and seabed for pressure ridges and icebergs can be metre's deep and 10's metres wide, equating to a total contact area of approximately 20 m^2 to 150 m^2. Upon evaluation of the pressure area curve shown in Figure 2, the pressures for this magnitude of contact area does not achieve the pressures needed for ice failure. The response of ice interacting with a rigid structure is investigated and well documented in previous work, thus, the present study evaluates and addresses the known trends as ice interacts with a rigid structure such as steel and applies the same thought processes to evaluate the response of ice interacting with soil.

FORCE-DISPLACEMENT

Analyzing the total force necessary to displace the ice feature provides a clear indication that introducing an intermittent contact area to the ice feature delays the load development within the indenter, Figure 4. The magnitude of the load as ice interacts with steel is similar for both contact scenarios after the ice teeth have failed. There is a significant reduction in load as ice interacts with soil rather than steel. A more gradual increase in force is observed as ice interacts with soil, upon further penetration into the soil the load values of indenters with an intermittent contact area converge towards the loads of the flat indenter. This phenomena is associated with soil infilling the irregularities of the indenter thus increasing the bearing area penetrating the soil.

The increased bearing area decreases the potential failure methods as shown in Figure 1 and soil infill pathways by which the crushed ice would have been extruded. This leads to the theory that there is the potential for the soil to fail as opposed to the ice but will the ice-soil area ever be large enough for the ice-soil pressures to be greater than those of ice interacting with steel.

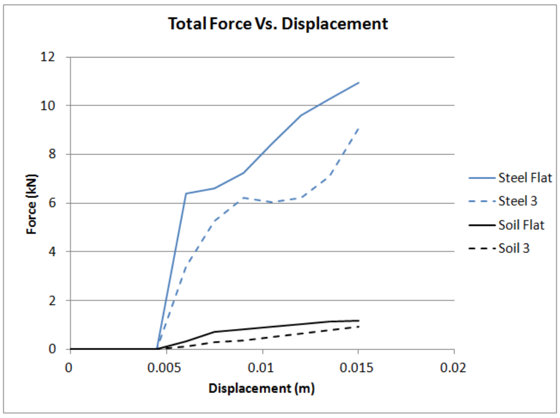

Figure 4. Total Force Vs. Displacement Plot

VON MISES STRESS

Figure 5 illustrates the distribution of Von Mises Stress produced within the ice at the displacement of 0.0076m. The figure addresses the influence of macro-roughness and more importantly relative stiffness at low deformations, this is similar to ice-structure interaction scenarios where crushed ice and viscous layer reduce the loads and peak pressure during ice interaction events. Analysis indicates that the values of stress increase with increasing wavelength and amplitude; however, the distribution of stress throughout the ice feature is significantly reduced as the contact area of the indenter increases in irregularity. As well, the stress distribution within the soil is more concentrated with the irregular indenter when compared to that of a flat contact area indenting the soil. This can be attributed to the effect of increasing the amplitude and intermittent contact area of the ice feature thus incorporating more discrete contact points into the indenter surface. This is an artifact to the Standard technique which was used to provide a simple modelling procedure to illustrate the effects of soil compliance due to ice keel interaction events. Future work, as demonstrated in this paper, using CEL techniques does not have this technical constraint, the soil is free to move into the void space and provide continuous distributed contact between the ice keel and seabed.

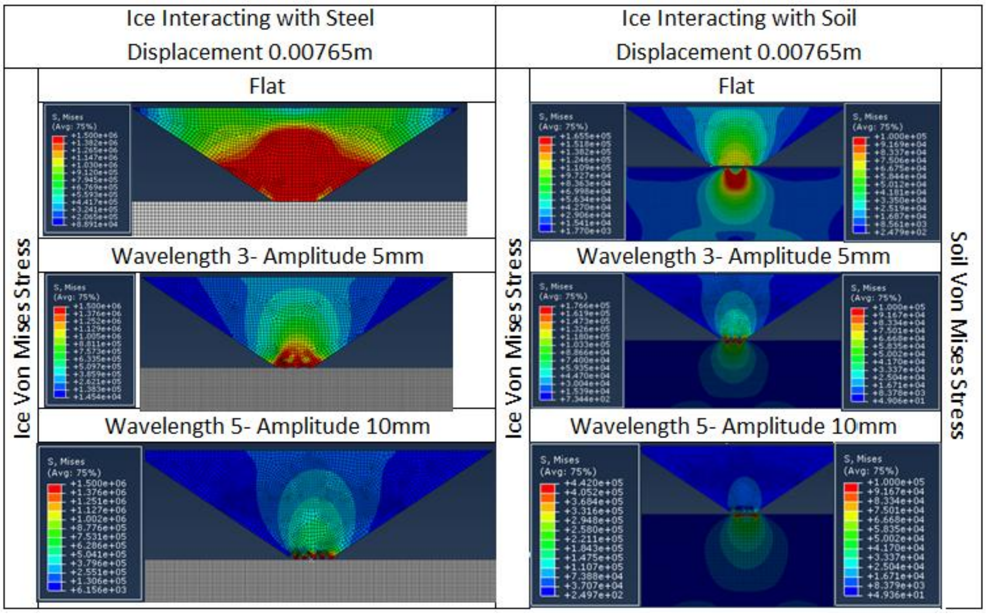

Figure 5. Von Mises Stress Plots

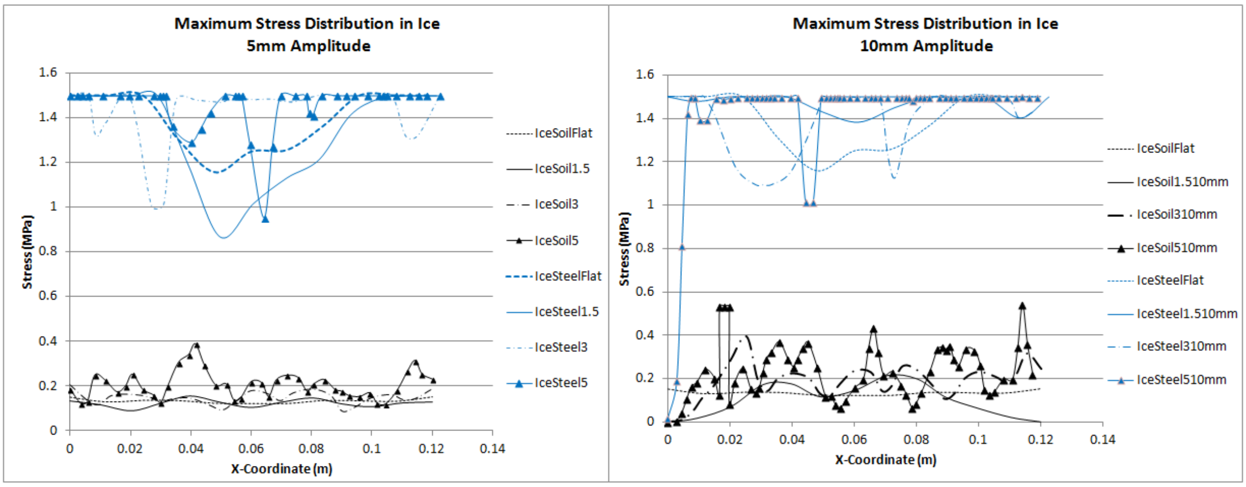

Figure 6. Von Mises Stress in Ice Upon Indentation with Steel and Soil

The stress distributions depicted in Figure 5 and Figure 6 indicate that in all scenarios there is an onset of ice failure early within the simulation, however, as ice interacts with soil there is no onset of ice failure. As the penetration of the indenter into the soil interface continues it is likely that the ice feature will not fail. This introduces the concept that as the ice interacts with the soil the soil will yield and infill the intermittent contact area of the indenter thus minimizing the chance of the local bearing pressure of reaching the crushing limit.

For the significant or rare ice features of interest for the design of subsea infrastructure the analysis suggests ice keel failure processes may occur during the transient build-up of interaction forces but in the steady-state condition this potential is significantly reduced. The ice keel failure processes and limits to ice gouging for some environments (e.g. shallow water, weak unconsolidated keels) could fail (Croasdale, 2005). This analysis would be consistent with multi-beam surveys of ice gouge tracks in the southern Beaufort Sea that do not show any significant variation in the gouge cross-section throughout the ice feature extent that could be on the order of kilometres in length (Blasco, 1998).

Initial CEL Model Comparison

The initial CEL model shown in Figure 7 provides a clear indication that as the ice indents with the soil the soil conforms around the indentation surface. Thus, the stress developed within the ice is significantly reduced in comparison to the stress developed as ice interacts with steel.

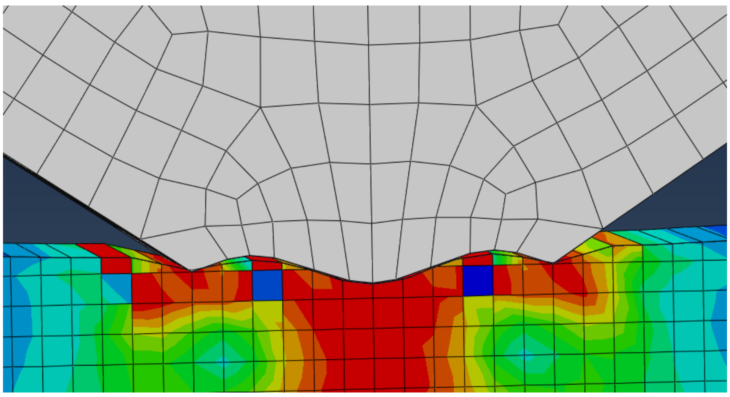

Figure 7. ABAQUS CEL Model

SOIL STRESS

During the simulation of ice indenting the elastoplastic soil, the highest stress values occur when a flat indenter is displaced into the soil. The effect of wavelength and amplitude on the distribution and magnitude of soil stress can be assessed by analyzing the stress values within the soil. The lowest stress values within the soil are observed with the indenter with the highest irregularity and amplitude. The general trend is observed that the stress within the soil decreases as the wavelength and amplitude increase in the contact surface.

EVALUATION OF STRAIN

The development of plastic equivalent strain within the model is shown in Figure 8 below. In the case of ice interacting with steel there is a significant reduction in the plastic equivalent strain developed within the ice indenter as the irregularity of the sinusoidal wavelength at the contact surface increases. At the same time, as ice interacts with soil plastic equivalent strain develops within the soil and as in the case of steel there is a significant reduction in the amount of plastic strain developed in the model with increased intermittent contact area. It should also be noted that the elastic strain within the ice feature significantly reduces as the wavelength and amplitude of the sinusoidal contact surface increases.

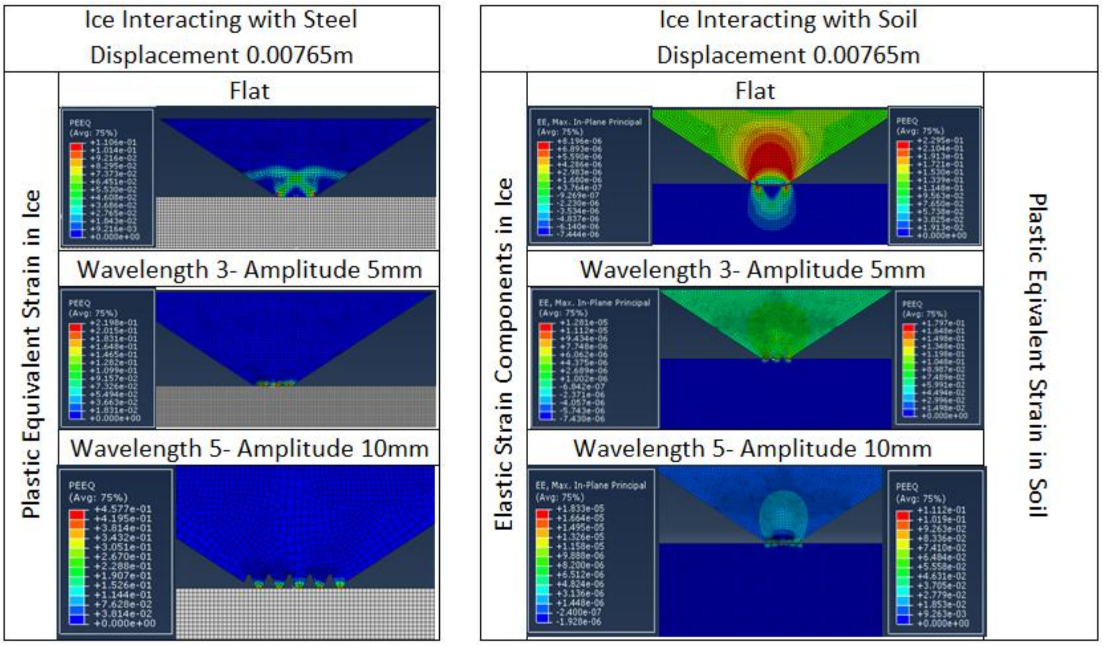

Figure 8. Plastic Equivalent Strain Plot

DISCUSSION & CONCLUSIONS

A numerical model was developed to depict an ice feature displacing 0.015m to interact with steel and soil. An analytical sensitivity study was performed at first yield and at a displacement of 0.0075m to determine the impact of introducing a sinusoidal contact area to the ice feature. Adjustments made to the amplitude of the ice feature's sinusoidal contact area provided more discrete contact points.

The results of the ABAQUS model indicate that the introduction of an intermittent sinusoidal contact area within the ice feature significantly reduces the values of stress, total forces, as well as global and local bearing pressures. With the onset of further penetration, a reduction in load is observed as ice interacts with the soil, as the soil yields it conforms around the irregularities within the ice indenter impeding the local pressure of ice to reach the crushing limit. The results of the ABAQUS Standard model are consistent with previous ice interaction studies performed, providing an accurate basis for future ice interaction analytical studies.

In the future, the intention would be to integrate the observations obtained from this study into a comprehensive ice interaction model utilizing ABAQUS CEL. The properties of ice within the CEL model would be adjusted from the current model to provide a more realistic interaction scenario.

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