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Laboratory Memorandum

Ice/structure interaction: laboratory and numerical modelling of iceberg impact: summary and progress report

J. J. Murray

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ICE/STRUCTURE INTERACTION

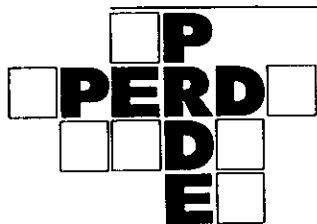
Laboratory and Numerical Modelling of Iceberg Impact

Summary and Progress Report

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SUMMARY This is a summary and progress report on the development of an ice/structure interaction computer model being developed under PERD/NEB funding. The report describes the overall approach to the development including numerical and physical testing. A summary of the state-of-the-art practices are provided together with an identification of issues requiring further investigation and development.			
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ICE/STRUCTURE INTERACTION

Laboratory and Numerical Modelling of Iceberg Impact Summary and Progress Report

1.0 INTRODUCTION

This document is a summary report describing the work carried out to date on PERD Project 6A5016.1.96. The overall objective of the project is to develop a computer model to simulate the interaction between an ice mass of arbitrary shape and size and an offshore structure. The purpose of the simulation is to investigate the impact forces imparted to subsea and/or an offshore structure during a collision.

The related work requires expertise from several disciplines and is therefore divided into the following tasks:

- the hydrodynamics associated with iceberg collisions,
- the physical process of contact between ice masses and structures,
- computer simulation of the impact forces and reactions of both iceberg and structure.

The final product will be validated through physical model tests.

This work is intended to be carried out over a three year period. The first year is focused on reviewing existing techniques for predicting the impact kinematics of ice masses including identification of available computer software. The review provides a critical evaluation of conventional techniques used to model ice-structure interaction, with particular emphasis on the associated hydrodynamics. The review also addresses the ice mechanics associated with this interaction. Some preliminary simulations based on the available software are presented for illustration purposes and to help outline plans for a model testing program scheduled for next year.

The review of existing numerical and analytical methods based on conventional hydrodynamic modelling techniques, including software inventory and preliminary simulations, was contracted out by IMD and is complete. The delivered reports are found in [1] and [2]. The work related to the ice-structure interaction was also contracted out but is not fully complete at this time. However, a status report

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including intended deliverables and their application to the overall project are provided in this summary report. The purpose of this document is to summarize the main findings and to provide a rationale for work in the next phase aimed at the areas identified as requiring further research and development.

2.0 PROJECT PLAN

The project takes a staged approach intended to be carried out over a three year period. The activities for a particular year are as follows:

I. Year 1 (95/96)

1. Literature Review on Existing Numerical and Physical Models

The report on conventional hydrodynamic techniques that are, or may be, applicable to ice-structure collisions are found in [1]. Over 100 papers and articles available in the open literature were reviewed and summarized. Topics covered a wide range of hydrodynamics applicable to the computer model being considered. Publications on numerical and physical models related to ice mass interaction with structures are also included. A summary of the findings is given in the following Section 3.0.

A similar review is also ongoing to identify the current state-of-the-art with regard to the mechanical processes of ice-structure interaction. A status report on this is found in Section 3.1.

2. Derivation of Numerical and Theoretical Formulae

The intended model is aimed at using a hydrodynamics model of two bodies interacting under the environmental forces of waves and current. This first stage mainly addresses the hydrodynamics of the rigid body interaction. Once contact is made with the structure a separate analysis technique is required to describe interaction between the structure and the ice mass.

The discussion of the associated hydrodynamics is found in [1] including detailed formulations. The discussion is aimed at identifying those areas where conventional procedures in hydrodynamics are adequate for the present application while explaining any limitations that may exist.

3. Outline Solutions and Procedures to Implement Formulations

Existing techniques to model both the hydrodynamics and ice-structure interactions are implemented where possible. However, this part of the study has shown that some processes associated with the interaction are very complicated and will have to be dealt with through a combination of physical and numerical procedures. Lack of adequate development in this area and use of approximate techniques to circumvent the problem can lead to highly conservative estimates of the impact forces. Such areas are identified and discussed.

4. Inventory Existing Software

At the beginning of this study it was anticipated that considerable progress could be made towards developing the required computer model through use of existing hydrodynamic software. IMD and other organizations have in their possession a number of the kernel components that can be integrated to develop the final product. These will be identified and their range of applicability specified.

II. Year 2 (96/97)

5. Develop Hybrid Techniques

Following work carried out by the end of the first year (95/96) the framework for the final model will be established. Those aspects of the model that are deemed too complicated to be handled numerically will be set up to accept empirical coefficients to deal with these more complicated situations. It is expected that the majority of the effort in this second year will be directed towards physical model tests.

6. Validate Simulation Model

Systematic model tests will be carried out to validate the computer model developed for the simulations. Some of the tests may be limited and serve only to confirm certain of the more reliable numerical hydrodynamic procedures. Other sequences of the testing will concentrate on developing aspects that remain questionable or may be specific to the application of the ice mass collisions. These tests will be conducted on the ice masses in open water as well as in the presence of a moored structure. Particular attention

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will be given to those parameters that are not adequately covered in the open literature.

III. Year 3 (97/98)

7. Finalize Model

The final year will focus on completing the computer model and may involve some additional model tests and analyzing specific scenarios.

3.0 PROGRESS IN YEAR 1 (95/96)

3.1 Hydrodynamic Responses

The hydrodynamics associated with an ice mass colliding with an offshore structure as reviewed and discussed in detail in [1], can be broken down into a systematic approach that considers the following combinations of conditions regarding the ice mass and the structure:

- A. The ice mass and the structure are first considered individually (open water condition).
 - A.1 the ice mass is free floating,
 - A.2 structure is fixed or moored,
 - A.3 each body subjected to waves or current only,
 - A.4 each body is subjected to a combination of waves and current.

- B. The interaction between the two bodies is considered.
 - B.1 the ice mass is free floating and the structure is fixed or moored,
 - B.2 the two bodies are subjected to waves or current only,
 - B.3 the two bodies are subjected to a combination of waves and current.

The schematic shown in Figure 1 can be used to describe the various parameters related to the motions and possible interaction of an ice mass with a floating vessel. The figure shows an ice mass of arbitrary shape having a some characteristic dimension D . Waves of length λ are assumed to be long-crested and propagating towards the bow of the moored vessel. Both vessel and ice mass can be simultaneously subjected to waves and current. The main points identified in [1] are summarized in Tables 1 and 2.

In general, the behaviour of either the ice mass or the vessel in waves is governed primarily by its D/λ ratio. For the purpose of discussion four classifications based on this ratio are defined in Tables 1 and 2. These classify the ice masses as: small, medium, large and very large.

When the body is small in comparison to the wavelength it behaves as a water particle. Both numerical and experimental studies have shown that small masses attain the accelerations and velocities equal to those of the water particle. Estimates of the kinematics of very small ice masses can be determined from open water wave theory. Figure 2 illustrates the motion of a small mass moving in a wave in open water conditions. The motions are dominated by first-order displacements, i.e. those directly proportional to the wave height, and oscillate in a circular or elliptical path at a frequency equal to the wave. The path shape is dependent on water depth. There is also a net drift component associated with each cycle. Impacting masses that are so small they behave as particles may however, be of little consequence from a practical point of view.

The medium classification ratio is more applicable to a body size describing the ice mass than the structure. In this ratio, the mass does not affect the wave but its motion is affected by inertia effects. There exists a wide range of combinations of relative sizes between the ice mass and the structure that can satisfy this ratio from a practical point of view. In this ratio range the body will experience both first-order and steady drift motions that are dominated by the steady drift component. Figure 3 shows a sample of the motions experienced by a 1,000 tonne ice mass in open wave conditions. As illustrated in the figure the velocities are smaller than those attained by the water particle. These results were generated from a numerical model based on a semi-empirical approach.

When the body's inertia effect is significant its motion is described by an equation which includes an added mass and drag coefficient commonly referred to as the Morison's equation. Written in its simplest form the equation is expressed as,

$$M(1+C_a)\ddot{x} = C_m\rho\nabla\ddot{u} + C_d\rho\nabla^{2/3}|\dot{u}-\dot{x}|(\dot{u}-\dot{x}) \quad (1)$$

Here \ddot{x} is the acceleration of the ice mass and \dot{u} and \ddot{u} are the velocity and acceleration, respectively, of a surrounding fluid particle usually defined at the centre of the mass, or when the mass is being modelled by a number of discrete elements, at the centre of each element. The terms C_m and C_d represent the added

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mass and drag coefficients respectively and ∇ is the displaced volume of the mass, M . The mass coefficient C_m is equal to $(1 + C_a)$. After some rearrangement of the terms in the equation it can be expressed as,

$$\ddot{x} = \ddot{u} + \frac{C_d}{C_m \nabla^{1/3}} |\dot{u} - \dot{x}| (\dot{u} - \dot{x}) \quad (2)$$

The second term on the right-hand-side of equation (2) results in a very small value for a typical range of added mass and drag coefficient values when the relative velocity is not large. This is the situation when the mass is behaving as a particle. The formula predicts, even for medium size ice masses, kinematics that are equal to those of the wave particles. Following this procedure a calculation found in Table II-1.2 of [2] suggests that an ice mass of 27 000 tonnes will behave as a fluid particle. There is very limited data available to correlate the accuracy of this prediction with either field measurements or physical model tests. Most model test data relevant to the size of icebergs that are found in this category are limited and address only simplified models that are not realistic representations of iceberg shapes. However, the limited amount of data available indicates that it is not realistic for an ice mass of this size to attain accelerations equal to those of the surrounding water particles.

The Morison equation approach has grown from the analysis of small member bodies that are either stationary or experience small displacements if moving in the waves. Free floating ice masses are mainly underwater and experience very different motions. This is especially true for small icebergs that are irregular in shape and highly unstable. Further investigations in both open water and in the presence of another floating body are required to improve the numerical modelling technique for this size of ice mass. The Morison's equation approach for this medium ratio range does not allow for the convective effects in the fluid around the mass. The inertia in the equation should be replaced by a Froude-Krylov force component.

As in the case of the ice mass, the motions of offshore structures constructed of small members that do not disturb the wave field are also predicted from a Morison's equation approach. There exist considerable data to validate this approach for first-order responses. Generally, construction geometry is confined to cylindrical or other simple shapes for which the inertia and drag coefficients are well known.

When the body is large, as defined by the classification ratio, the ice mass motions generate their own waves referred to as *scattered* or *radiated* waves. Radiation is created by each of the six-degree-of-freedom motions of the body. If the mass is large but fixed in the waves it will have a reflection effect known as *wave diffraction*. This wave diffraction is also present when the body is moving but is distinct from the scattered waves. Wave diffraction is computed as if the body is stationary, justified by the assumption of small body motions. Numerical models to predict the hydrodynamic coefficients and subsequent motions of large bodies are based mainly on boundary element models assuming small motion and linear boundary coefficients. These techniques require idealized versions of the structure and solve for the diffraction potential ϕ_D and scatter potentials ϕ_j at specific locations on the body surface. These potentials are linearly added together to form the total potential ϕ such that,

$$\phi = \phi_0 + \phi_D + \sum_{j=1}^6 \phi_j \quad (3)$$

Here ϕ_0 is referred to as the undisturbed incident potential. These first-order potentials are used to determine the wave forces on the body as well as the hydrodynamic coefficients required to solve the equations of motion. The potentials are also used in other numerical techniques, commonly referred to as the *near-field* and *far-field* techniques to determine the steady drift forces. These steady drift forces are used in other approximate techniques to estimate the slowly-varying drift motions of the vessel. When the body is moored, as in the case of most floating offshore structures, its motion will be dominated by these slowly-varying drift oscillation related to the vessel's mass and the global stiffness effects of the mooring. These motions can introduce an additional relative velocity component that must be taken into consideration. This response is characteristic of either a small member structure such as the semisubmersible or an FPSO monohull.

The other extreme in the D/λ ratio is when the mass is very large. In this case the body, whether structure or ice mass when free floating, will drift at a steady drift velocity and be insensitive to first-order effects. The same numerical procedures as described above for solution of the potentials are used but the solution of the equations of motion will indicate that the first-order motions are very small and the body is responding with a mean drift velocity only. In the present context this ratio D/λ will be most applicable to ice masses rather than offshore structures. Free

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floating or moored structures of this size do not seem to have any practical application.

The hydrodynamics become more complicated when current is introduced into the flow field. This whole area of wave-current interaction is not well developed in theoretical hydrodynamics. Depending on the shape of the body there are some analytical expressions that can be used to define the flow around it. These are generally based on stream or potential functions. Uniform flow around a stationary body modelled as potential flow is expressed as the sum of the incident current potential and a steady diffraction potential. The steady diffraction potential can be considered as the zero-frequency diffraction wave component described above. If, for example, a ship hull is held stationary in a current a bow-wave will form as if the ship was moving through calm water.

The total current potential ϕ_C is expressed as the linear summation of the component potentials due to the incident current ϕ_{IC} and diffraction ϕ_{DC} as,

$$\phi_C = \phi_{IC} + \phi_{DC} \quad (4)$$

When modelling current and waves combined, the usual approach is to describe total velocity potential ϕ_T as the sum of the potential representing the current and the wave potential as described by equation (3), such that,

$$\phi_T = \phi + \phi_C \quad (5)$$

Figure 4 compares the flow velocity near the front of a hull and an equivalent cylinder. The flow related to the hull is determined from potential theory assuming an extremely long wave period. Flow around the cylinder is determined from an analytical solution. As shown in the figure there is fairly good agreement between the two solutions for distances greater than 200 meters away from the bodies. Inside this distance the flow becomes more sensitive to the body shape. Also, as this distance decreases the prediction from the potential model becomes unstable and shows the current to increase dramatically. However, the analytical solution monotonically approaches zero at the body surface as expected. This instability in the potential method is also a problem in defining the wave potential for higher wave periods as well, i.e., those associated with a practical range of wavelengths. This problem will have to be overcome since the flow has to be defined up to, and including, the body surface.

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Model tests and numerical results indicate that the current has a significant influence on the drift motions. Increased motions have a tendency to increase the probability of a collision.

Interaction between the two bodies is dependent on their relative sizes and their individual D/λ ratios. When the bodies are large enough they will each generate waves which in turn influence the motions of each other. There are a number of scenarios that can be presented for the relative sizes of the two bodies. These are as follows:

- small ice mass and small structure,
- small ice mass and large structure,
- large ice mass and large structure.

Small ice masses in the vicinity of a structure will behave as wave particles. These wave particles are computed using the same techniques as those described above for open water conditions and are dependent on the size of the structure. When the structure has small members that do not disturb the wave around them the Morison's equation approach is used. Limitations of this approach as discussed in the previous section should also be considered. Model tests have shown that the slow drift induced motions of a semisubmersible are also an arduous issue in defining the relative impact kinematics. The effects of this motion will have to be investigated further.

When the ice mass is small and the structure is large the ice will also behave as a water particle or will be inertia dominated when in shorter waves. Figure 5 compares the motion of a small ice mass as it approaches a tanker with its motion in open water. In either case the water particle kinematics in the field, which may include current will have to be determined. Therefore, the numerical instabilities associated with the conventional methods will have to be addressed. Some model test results in waves alone show evidence that the smaller body can be repelled by the larger one. However, a more practical scenario would include current which will increase the probability of a collision. The slow drift motions of the moored vessel are also highly influential in defining the impact kinematics.

The added mass and drag coefficients in the Morison's equation are sensitive to the proximity effects between the two bodies. This is similar to the classical problem in ship manoeuvring in a restricted waterway. Figure 6 shows the added mass coefficients for the surge motion of a unit length cylinder as it approaches a wall. The problem in the present situation is even more complicated because the larger body is moving whereas the wall is stationary.

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When both the ice mass and the vessel are large, by definition, a two-body diffraction/scattering model will have to be used. The software inventory indicates that a version of this software is available at IMD but is subject to the same numerical instabilities when the two bodies are in close proximity as discussed above. When two bodies are considered the IMD software can account for proximity effects up to a limit. When the bodies are separated by a distance of approximately one wavelength or less the associated numerical scheme becomes unstable and a singularity develops.

Modelling current when two bodies are being considered generally uses the long period approach to define flow around the body. This technique can be extended to include the influence of the bodies on each other. In any case some of the fundamental assumptions that are unique to the hydrodynamics associated with body collisions will have to be addressed in the next phase of the development program with considerable emphasis on model testing.

3.2 Review of Ice-Structure Contact Process

In addition to the review related to the hydrodynamics of ice mass collisions with offshore structures a parallel study is being carried out on those aspects of the collision related to the ice interacting with the structure. At the time of this report the analysis has been underway for three weeks and is being managed by Dr. R. Gagnon of IMD. The major part of the work is contracted to a St. John's based engineering consulting company (Marineering Limited). The objective of this effort is to develop a database and possible formulae that can be used in the simulation program.

To date there has been a literature review of previous results that were published from the Hobson's Choice Ice Island 1990 experiments, and some other relevant test programs. Data from pressure transducers on one of the Ice Island indentors have been correlated with the shape of the ice contact zone at the end of tests and a strong correspondence between hard spots, regions of relatively undamaged ice in contact with the indenter, and high pressures have been noted. The in-situ video records of ice contact, acquired by a video camera that viewed through a window from inside one of the indentors, have been digitized, stored and hard copies made for each image. Normal video provides 60 images for each second of a test. The hard spots appear as blue zones in the video records whereas crushed ice appears white. Assuming that the load was concentrated on the blue zones, a technique described in [3] calculated high pressures for the blue zones (33-92MPa) using load data and the visual condition of the ice face at the ends of tests. This correlated with peak pressures measured with pressure transducers during the

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tests. The dynamic videos provide further evidence that the blue zones are the highest pressure areas because the videos show crushed ice that always flows away from the blue zones, and never towards them.

Strong correlation of the shape of the hard spots (blue zones) and the initial shape of the ice has been noted. For example a truncated pyramidal shaped ice face (Test #4, see Figure 7) produced an x-shaped pattern in the initial part of the test where the main contact zone was visible in the window. The arms of the x corresponded with the four edges of the pyramid where the pyramid faces intersect and where the ice provided more confinement.

Plans are underway to measure the areas of the hard spots as they develop in size during a test and then to relate this to the total load records. Pressures, similar to the after-the-fact calculations of [3], can be calculated from these areas and loads to provide corroborative evidence, from the dynamic system, that the blue zones bear the majority of the load. In experiments on freshwater ice [4], where in-situ visual data were acquired, the relatively undamaged ice was clearly shown to support most of the load, however such results have not been previously reported from in-situ observations in experiments on the scale of the Ice Island indenter tests. Furthermore, the dynamic positions of the hard spots on the indenter face, estimated from the video records, will be correlated with triangulated centre of load positions, as determined from the three load cells attached to the three actuators of the test apparatus. This would provide further evidence that the blue zones play a critical role. It is anticipated that by understanding how the hard spots develop for various test conditions and evolve throughout each test, insights will be gained as to how loads might be reduced, or distributed in a less threatening manner, during ice/structure interaction.

It is also planned to compare the overall loads from the various types of indentors and shaped ice faces tested in the Ice Island 1990 test program. This comparison would also lead to suggestions for structure designs that would reduce global loads during interactions with ice.

4.0 DISCUSSION

The literature review on the hydrodynamic aspects of ice-structure collision has revealed a number of areas that require more research and development. Some of the solutions are very difficult to handle numerically and common practice circumvents this by using approximations that may lead to conservative predictions. Finding a numerical solution may become a monumental task in

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dealing with the associated mathematics or developing techniques to deal with this problem. Such a level of effort is beyond the scope of the present project. A more plausible solution is to investigate such parameters through physical model tests.

A large amount of the necessary software required to develop the framework for the required computer model is available at IMD. Notwithstanding the limitations discussed in this summary report it is possible through a series of systematic model tests to advance the computer model to a level that can be used to simulate a number of scenarios. These can be compared to physical model tests for validation of the final version.

Results of the physical ice database will be incorporated into the final version of the program to provide a complete product that can estimate the loads imparted to the structure once the kinematics of the interaction caused by hydrodynamic loading are determined.

5.0 CONCLUSIONS

Based on the first stage of the research program the following conclusions and recommendations for further work are made:

- mass motions depend on their shape and size relative to wavelength in open water as well as in the presence of a structure,
- motions are highly sensitive to proximity effects, which require further investigation,
- current has a significant influence on drift velocity and techniques to model its effects on colliding bodies need to be developed,
- available numerical models to predict drift velocities assume steady drift motions that are not realistic and should be extended to include unsteady drift predictions,
- relative motion caused by the slow-drift motions of floating moored structures is very important but has not been addressed,
- numerical models based on potential flow theory and semi-empirical models based on the Morison's equation approach will have to be developed into hybrid models specific to deal with ice-structure collisions.

6.0 REFERENCES

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TABLE 1. MOTIONS IN OPEN WATER CONDITIONS

Ice Mass Classification	Hydrodynamic Approach	Motions	Experimental Models	Numerical Models
small mass $D/\lambda < 1/13$	wave particle kinematics	first-order	open water small scale	linear model
medium $1/13 < D/\lambda < 1/5$	inertia dominated unstable	first-order & drift	open water small scale	Morison's Eqn.
large $1/5 < D/\lambda < 1/2$	potential dominated	first-order & drift	limited	steady drift potential theory
very large $D/\lambda > 1/2$	potential dominated	drift	very limited	steady drift potential theory

TABLE 2. MOTIONS IN PRESENCE OF STRUCTURE

Ice Mass Classification	Hydrodynamic Approach	Motions	Experimental Models	Numerical Models
small mass $D/\lambda < 1/13$	wave particle, scatter and diffraction	first-order	open water small scale semisub's	linear model
medium $1/13 < D/\lambda < 1/5$	scatter and diffraction	first-order & unsteady drift	simple geometries	Morison's Eqn.
large $1/5 < D/\lambda < 1/2$	interaction between mass and structure	first-order & unsteady drift	very limited	steady drift potential theory
very large $D/\lambda < 1/2$	small effect from structure	quasi-steady drift	very limited	steady drift potential theory

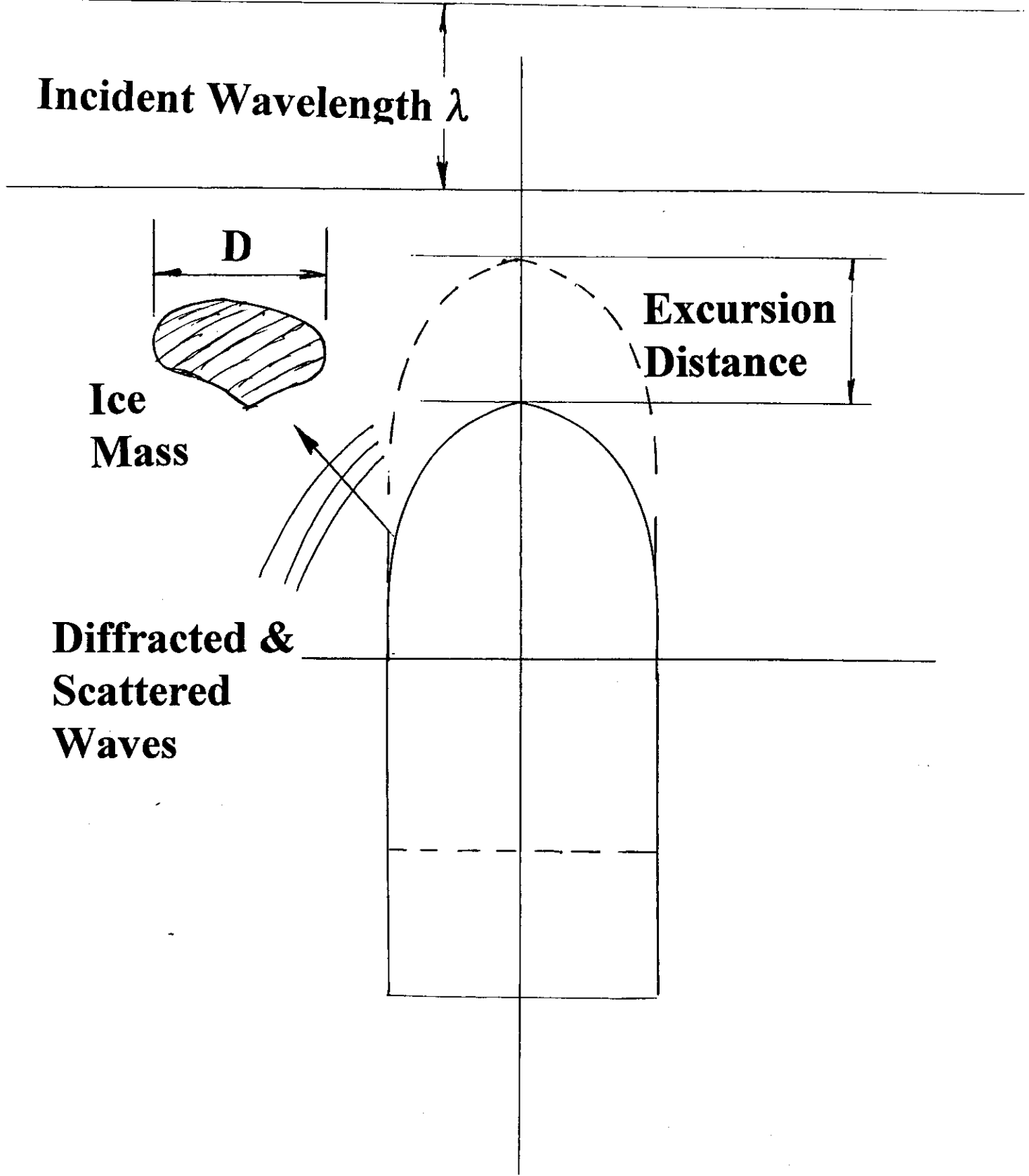


Figure 1. Schematic of Ice Mass and Vessel

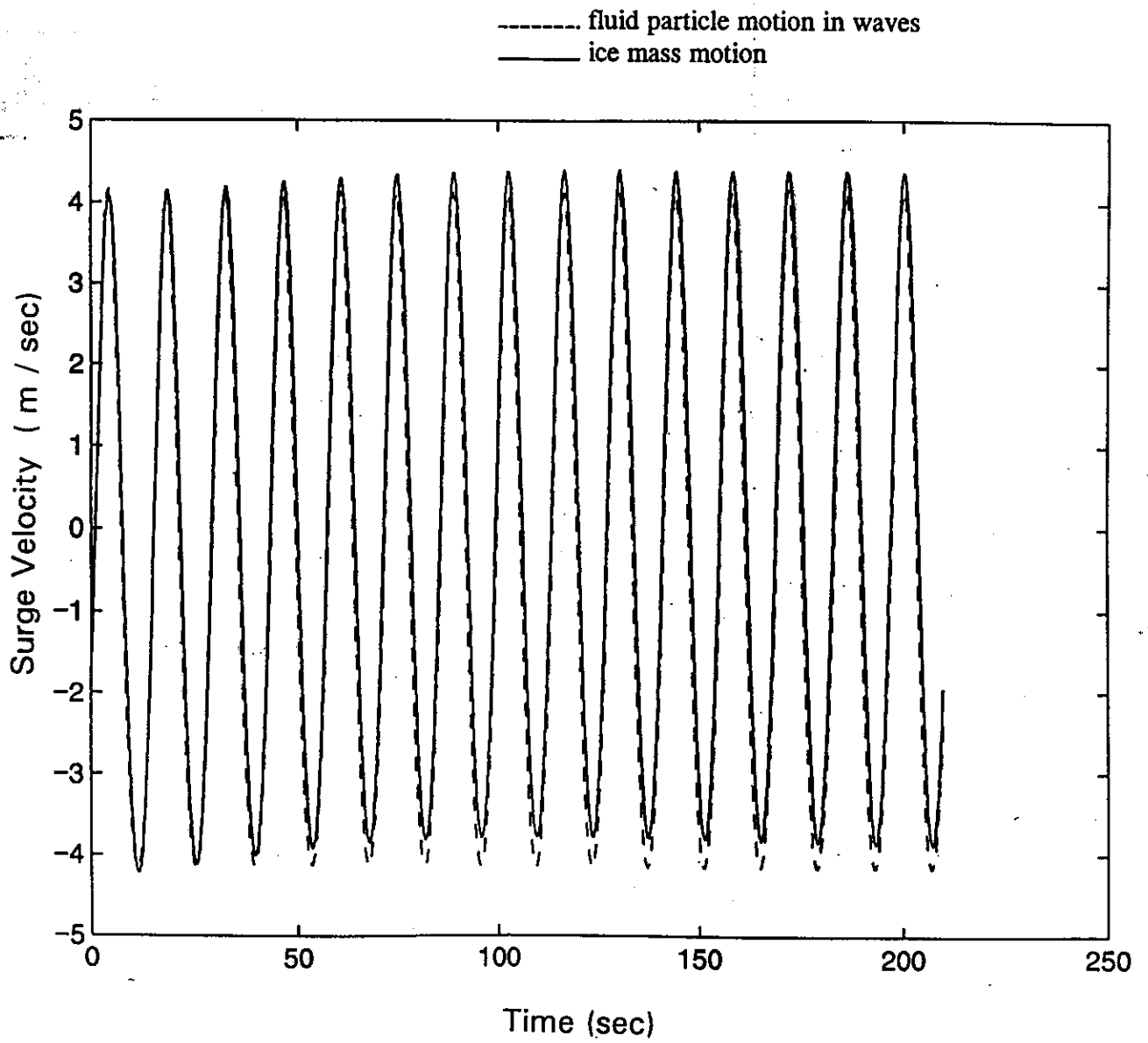


Figure 2. Motion of Small Ice Mass in Open Water

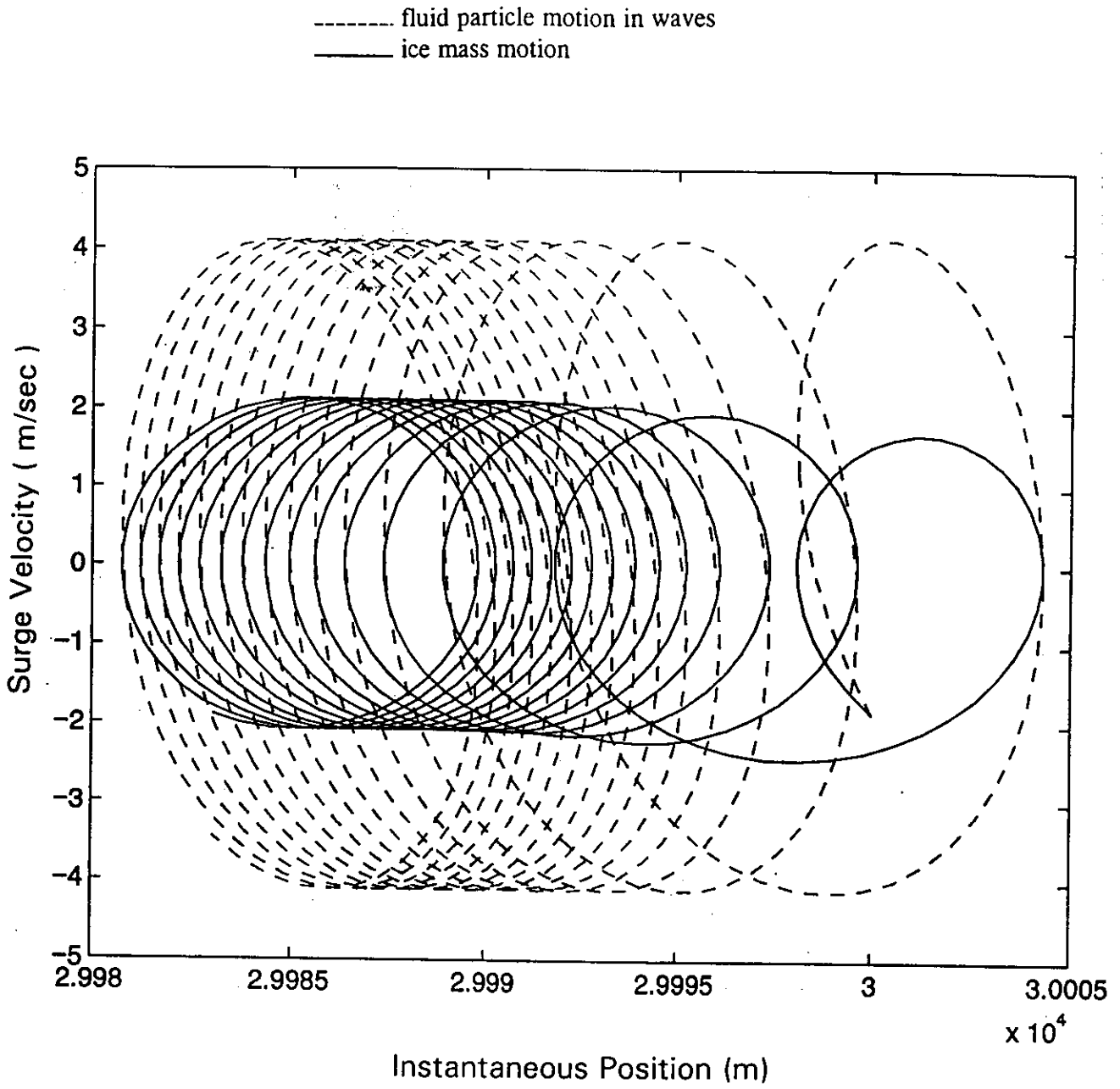


Figure 3. Motion of Medium Ice Mass in Open Water.

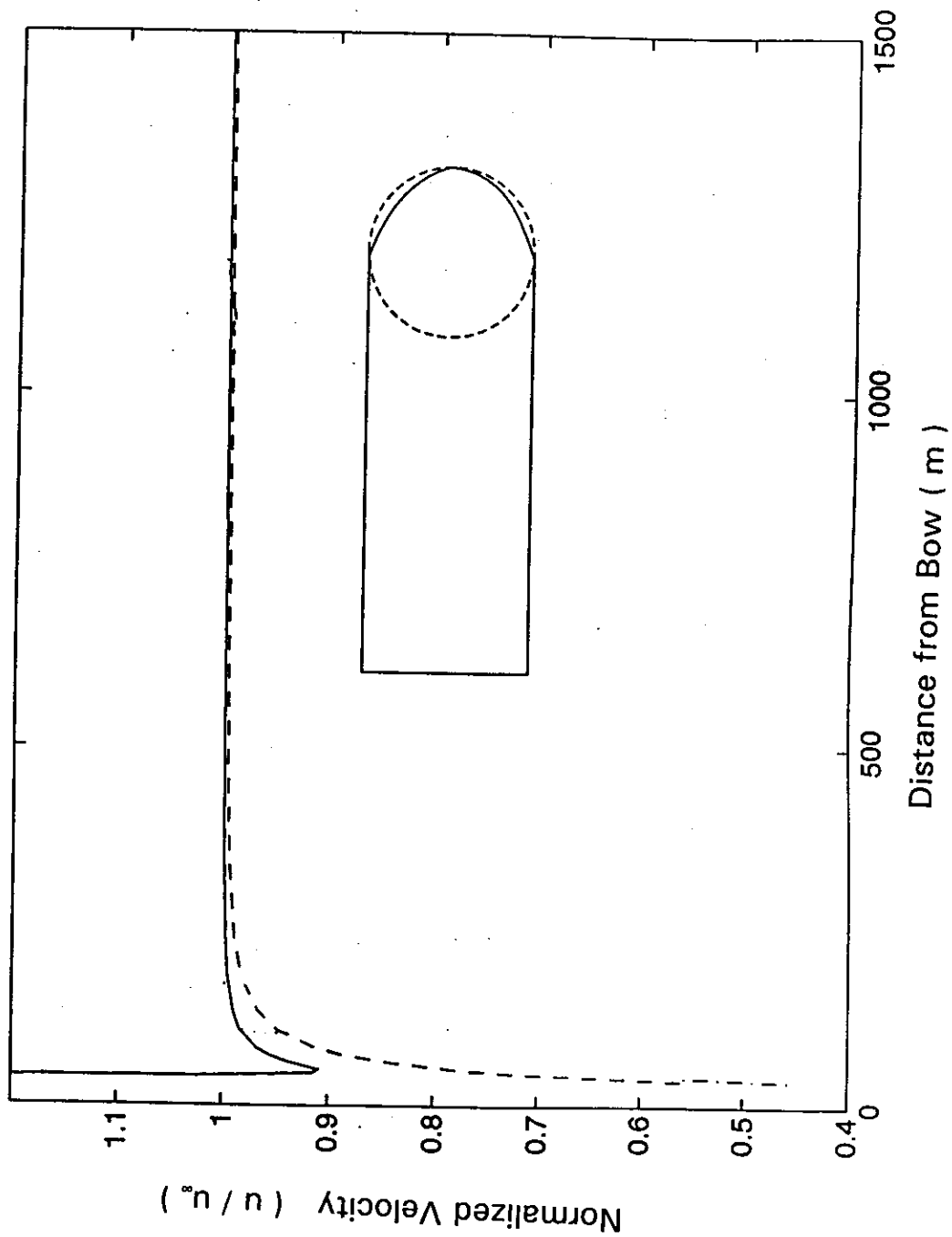


Figure 4. Comparison of Current Flow Models

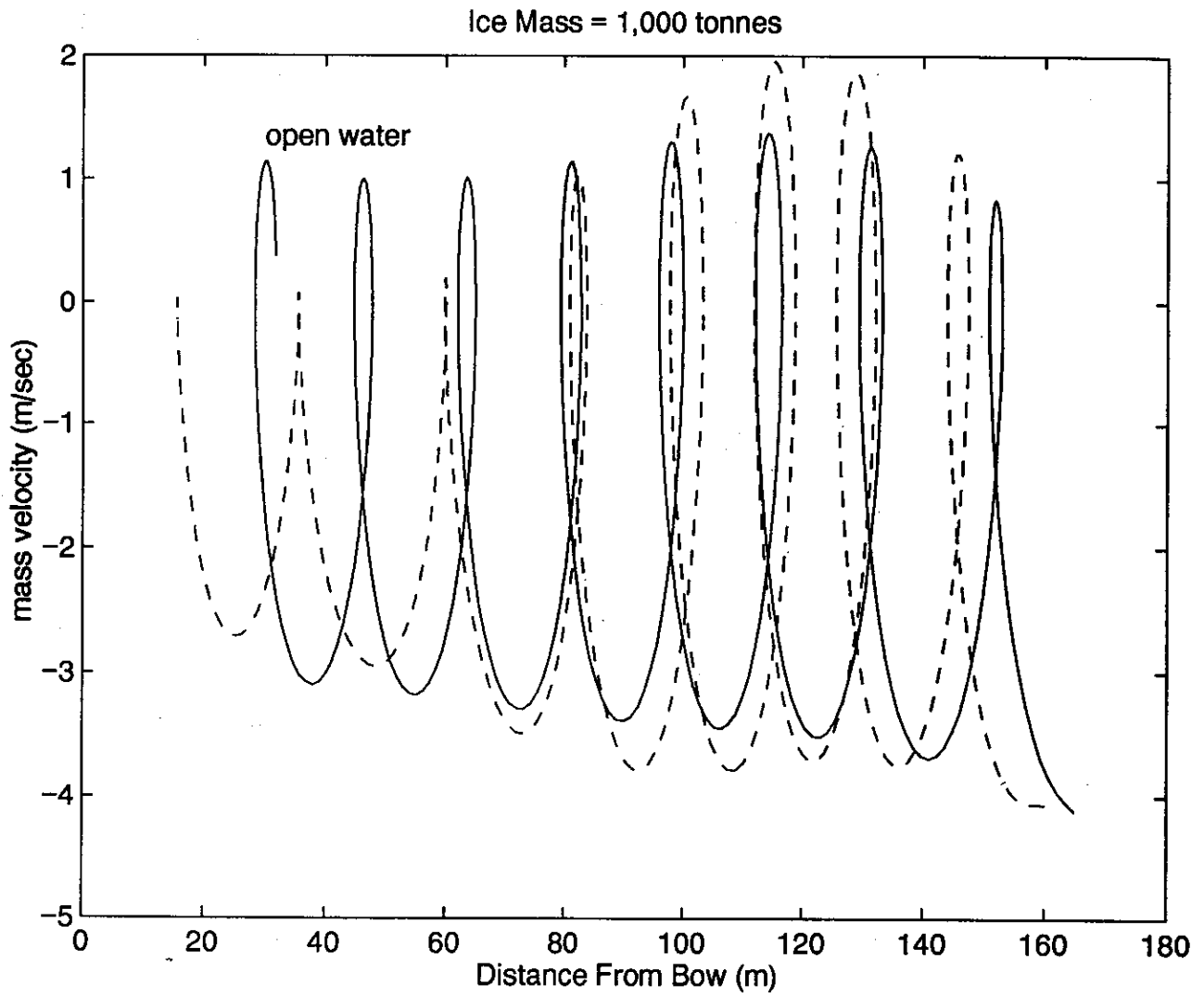


Figure 5. Comparison of Ice Mass Motion in Open Water and in the Vicinity of a Tanker

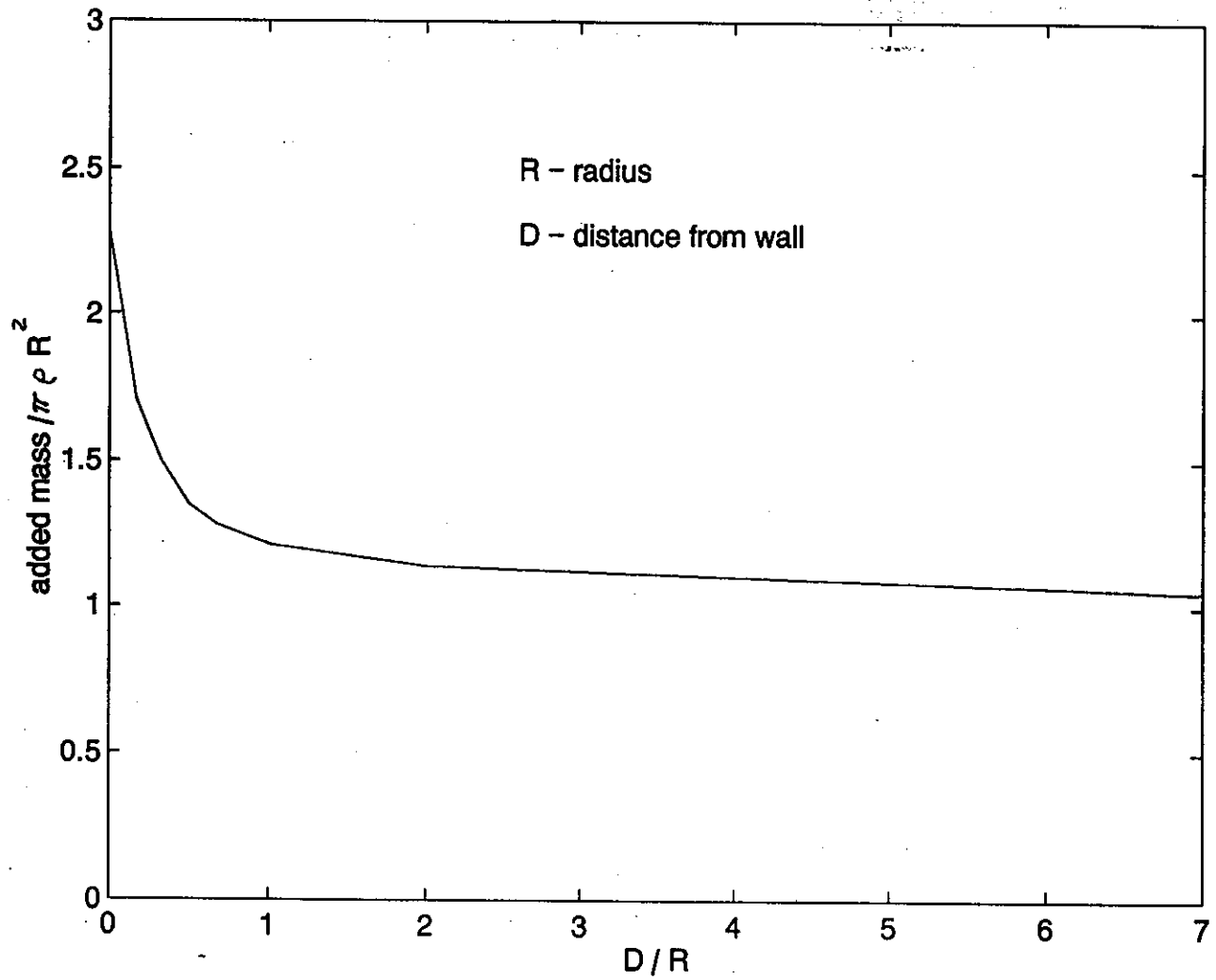
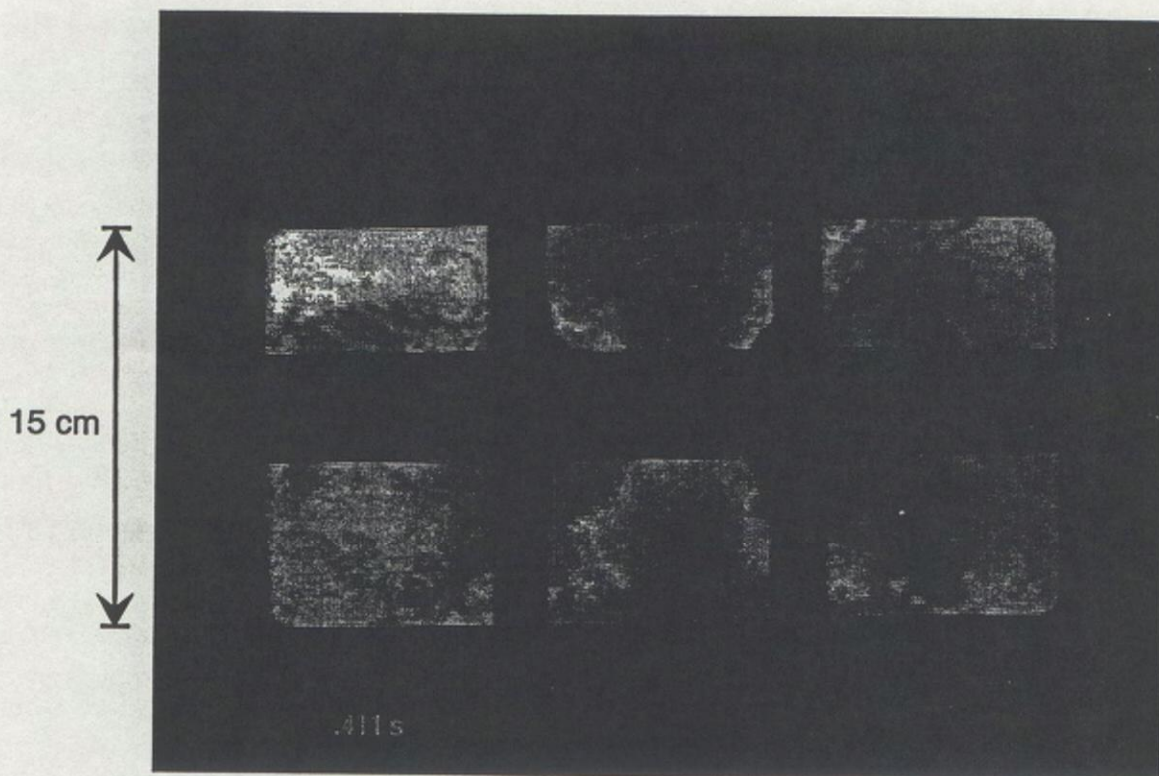


Figure 6. Proximity Effects on Added Mass Coefficient



View (black and white) of ice contact through the thick Lexan window at time .411 s into Test #4.

The high pressure 'blue' zone is the X shaped feature in the center of the view. The dark material surrounding the high pressure zone is crushed ice. Dividing the total load by the area of the X shaped feature yields a pressure of about 35 MPa.

Figure 7. View of Indentor Contact Zone